EUROHAPTICS 2001

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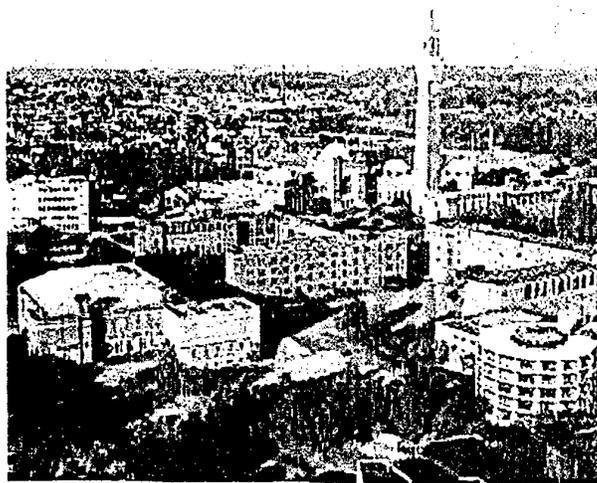
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13. ABSTRACT (Maximum 200 words)

The Final Proceedings for Eurohaptics 2001, 1 July 2001 - 4 July 2001

This was an interdisciplinary conference. Topics include research on sensorimotor and human-computer interfaces involving haptics (force feedback devices).. Specific focus is given to advances in technology (hardware, software) ; science (psychology, neurology, neurophysiology) ; applications (training, disability) ; and human computer interaction (VR, devices).

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EuroHaptics 2001

Aims

Research on sensori-motor interfaces has developed extensively in various scientific and technological fields.
The EuroHaptics 2001 conference aims to integrate these diverse lines of investigation to encourage wider communication within this community. It will provide researchers and industrial representatives with an opportunity to communicate their ideas and obtain feedback on work in progress. It is designed to facilitate networking between labs in the UK and Europe.
Additionally haptic HCI technology companies will have the chance to gain key information about current theory and research theory in the area of haptics

Topics

The EuroHaptics conference accepts papers from all areas related to haptics. The conference is themed into and is particularly interested in papers falling into the following;

◆ technology (hardware, software)
◆ science (psychology, neurology, neurophysiology)
◆ Application (training, disability)
◆ Human computer interaction (VR, force feedback devices)

Sponsors

EuroHaptics has been fortunate in attracting sponsorship from a variety of sources. This sponsorship has allowed us to subsidise student places, to invite prestigious keynote speakers, to hold a vendor's evening and to provide a range of subsidised social events. In particular, we would like to thank to following organizations and companies:
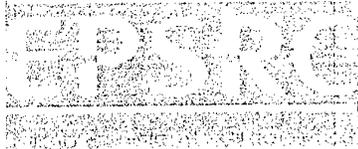
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Dr. Shumin Zhai	IBM, Palo Alto Research Centre

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SESSION SIX: MOVEMENT CONTROL

POSTERS

Using Haptics Technology to Deliver Motivational Therapies in Stroke Patients: Concepts and Initial Pilot Studies

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Abstract

Attention and motivation are two factors, which are important for motor relearning following stroke. In this paper we introduce and present the novel concepts for the use of haptics technology to deliver therapy to patients with arm impairments following stroke. The results of the ongoing initial pilot studies have shown the feasibility of the system presented here. The new approach will potentially improve the patient's attention and motivation and hence enhance therapy effectiveness.

Key Words

Motor Relearning, Robot Mediated Therapy, Virtual Environments, Perception and Haptic Feedback.

1. Introduction

Stroke is the most common cause of acquired physical disability with estimates of the annual incidence of stroke ranging from 180 per 100,000 in the USA to 200 per 100,000 in England and 280 per 100,000 in Scotland [1]. The incidence rates increase with age, doubling for every 10 years after the age of 45 [2]. Approximately one-third of the patients surviving from a stroke are left with severe disabilities [2]. Evidence has shown that early and intensive physiotherapy improves patient recovery [3] and several authors have already proposed using robots to deliver this type of physiotherapy. [4,5,6]

In the GENTLE/S project (a project under the quality of life initiative of framework 5 of the European Commission to evaluate robot-mediated therapy in stroke rehabilitation) we go further and propose a system based on haptic technology. Haptics have been widely used for different applications ranging from Surgery Simulators [7,8], Virtual Reality-Based Telerehabilitation systems with force feedback [9] to 3D painting interfaces [10].

In the context of haptics and force feedback we have already introduced and implemented a novel mathematical model directed to deliver a system capable of correcting movement in machine assisted stroke rehabilitation. This system can be used for errorless learning techniques and intensive rehabilitation treatment for patients recovering post-stroke. It allows force feedback to be delivered to the patient arm via a 3DOF haptic device (Haptic Master from Fokker Control Systems) strong enough to correct point to point movement within a virtual/real or augmented task oriented therapy.

Following initial input from members of the Young Stroke Association at Stoke-on-

1

Trent, we have enhanced movement realism by implementing a model based on the dynamics of human movement. This model allows the implementation of realistic force feedback in curvilinear 3D movement patterns [11, 12].

We are investigating new ways that will potentially improve patient attention and motivation and therefore enhance therapy effectiveness. The following sections of this paper will present the system developed, the implementation of novel theories and concepts directed to the improvement of motivation and the initial results and feedback obtained from the initial pilot trials with hemiplegic patients.

2. How can we improve patients' motivation?

Attention and motivation are two factors, which are essential for brain plasticity [13]. Plasticity is the ability of the brain to re-organise and adapt to training and experience. This ability to change has therapeutic benefit as the brain has the potential to re-map the area affected by injury/stroke in response to training of skilled tasks and hence allow motor recovery. Lack of motivation has been identified as a major cause of failure to benefit from neurorehabilitation [14]. It is also important that the tasks performed by the patient are meaningful for the patient and relate to their perceived problems [15].

The GENTLE/S system provides the opportunity for repetitive task oriented movement, a form of therapeutic intervention that has been shown to be of benefit [16,17]. In addition to this it provides the following feedback to the patient to enhance attention and motivation and hence further facilitate motor recovery through brain plasticity:

- Visual Feedback – Realistic and accurate goal oriented 3D environments. This can be anything from a virtual room, a virtual kitchen, museum, to an interactive game, etc.

- Haptic Feedback – Kinaesthetic feedback helps to discriminate physical properties of virtual objects, such as geometry. It can also be used to deliver physical therapy to a human subject using haptic interfaces. In our system it is used to guide the patients arm along a pre-set movement pattern. The amount of force used to bring the arm back to the set path can be varied to suit the individuals needs.

- Auditory feedback – Encouraging words and sounds are played when the user is trying to perform a task, congratulatory words when a task was achieved with success and comforting words when the task wasn't achieved.

- Performance Feedback – Results of previous tasks can be displayed stating the errors committed and the level of help obtained to complete the task.

We hope to be able to foster the patients' trust by developing a sense of friendship and companionship between the patient and the system. A personality can be added to the system by having a character (wizard) that interacts with the patient. Different wizards can be implemented for different personalities. These are defined and assigned to the patient once the therapist has assessed what their interests are. We hope that the wizards will further enhance motivation and attention during this therapy.

3. The System

The current prototype system (Fig. 1) consists of a frame with two chairs, a shoulder support mechanism, a wrist connection mechanism, two embedded computers, a large computer screen with speakers, an exercise table, a keypad and a 3DOF haptic interface arm (Haptic Master). The patient is seated on the chair

with their arm positioned in an elbow orthosis suspended from the overhead frame. This is to eliminate the effects of gravity and address the problem of shoulder subluxation. The wrist is placed on a wrist-orthosis connected to the robot arm using a quick release mechanism (Fig. 2).
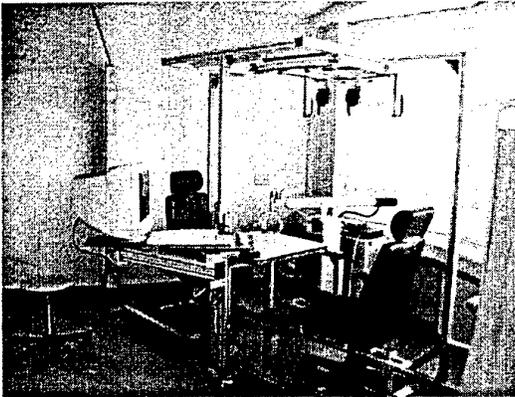
Figure 1 – GENTLE/S Prototype 1

Initial studies with a group of stroke patients at the Young Stroke Association in Stoke-on-Trent, UK, have encouraged further development and enhancement of Virtual Environments to deliver therapy [18]. *Virtual tasks* consist of a goal oriented computer graphical user interface based on virtual reality visualisation techniques. The therapist, using the task editor, can create a virtual task. The system allows the therapist to create new movement patterns in virtual 3D environments and to define how objects are related to each other and what kind of behaviour they represent to the patient. For instance, one simple activity involves the patient to reach for a can of Pepsi and move it close to a book in the table.
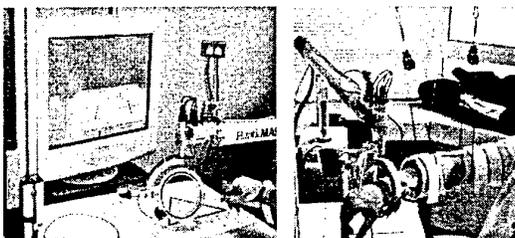
Figure 2 – Robot end-effector and arm orthosis

4. Initial pilot trials

Following ethical and safety approval, the initial pilot trials are ongoing. We have created and used 3 different graphical environments (Fig. 3) for the initial trials:

1. Empty room – A graphically poor environment consisting of white walls, a floor and ceiling, representing the 3D workspace of the system.
2. Real room – An environment that resembles what the patient sees on the table in the real world. The mat with 4 different shapes that is on the table is represented in the 3D graphical environment.
3. Joaquim's room - A high detail 3D environment of a room comprising of a table, several objects (a book, can of Pepsi), portrait of a baby, window, curtains, etc.
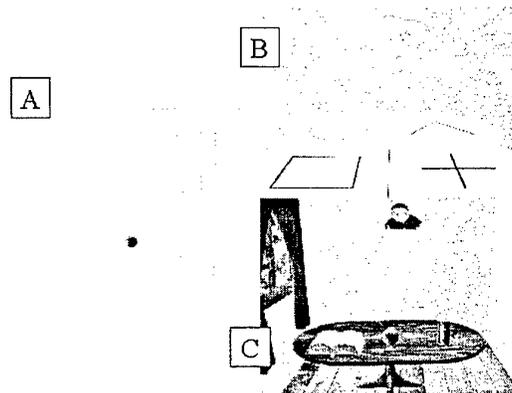
Figure 3 – (A) Empty room, (B) Real room, (C) – Joaquim's room

We have assessed the suitability and usefulness of the three different visual environments, the 2 levels of force feedback and the motivational aspects of the system using a questionnaire survey of patients with stroke using the first prototype in the pilot trials.

4.1 Perception

Several questions were asked to evaluate the patients' ability to identify and correlate his movements in the real world to what is displayed on the screen. This

information will help us to design environments that are easy to interact with. Patients completed a simple 4-point exercise (3D pyramid) in each of the three environments for 2 minutes. Four questions were asked to evaluate their opinion on the environment's look, realism, and ease of use.

4.2 Force feedback

The Kinaesthetic feedback forces were used on 2 different settings: strong (i.e. highly stiff; exerted a strong pull back to the desired path) and weak (i.e. low stiffness; allowed the patient to deviate more from the desired path and exerted a lesser force to bring the limb back to the path).

The patients exercised for three minutes on each setting in environment A (fig. 2 (A)). To evaluate the effectiveness of Force feedback, questions were asked to collect patient's opinion on whether the force feedback helped them to perform the movement, which setting made it easiest to complete the movement and which setting they preferred.

4.3 Motivation

These tests were performed to collect patient's opinion on motivational aspects of the interaction between people with stroke and the haptic interface. We collected information on the total time that they exercised for, whether exercising in the system was more interesting than their normal therapy and how long they thought they could exercise for before it would become boring.

After 10-minute intervals, patients were asked whether they wished to continue with the same exercise, change to another exercise or stop.

5. Results and discussion

The tests described in the previous section were performed by 8 respondents,

of which 1 had a Cardio Vascular Accident (CVA) more than one year ago, 3 had a CVA between 3 months and 1 year and the remaining 3 had a CVA less than three months prior to testing. Of these, 6 had left hemiplegia and 2 right hemiplegia, 6 were female and 2 were male. Their ages ranged from 50 to 81 years.

5.1 Perception

Table 1 shows that although most patients found environment C the nicest to look at, 6 of the 8 patients actually enjoyed practising in the mixed environment (B). This suggests that by providing a degree of realism we are correlating what the eye actually sees on the screen with what exist in the real world, which in turn makes the experience more enjoyable for the patient.

On the other hand, the relatively complicated graphical environments were not felt by the patients to be the easiest in which to interpret the required direction of movement from the 3D image.

Question	Environments			
	A	B	C	Undecided
1. Which room look the nicest?	1	3	4	
2. Which room felt more realistic?	0	5	3	
3. In Which room was easiest to know where you had to move next?	3	2	2	1
4. Which room did you enjoy exercising the most?	2	6	0	

Table 1 – Patient answers on perception.

5.2 Force Feedback

For this test it was required that the patient had some level of activity and were exercising in active mode (i.e. the robot did not provide any assistance in the completion of the required movement and provided a velocity dependant resistance to the patients effort).

Four patients completed this section all of whom responded that the force feedback was useful in completing the required

movement pattern. Three of the 4 patients preferred the 2nd setting (weak force). They commented that this was because on the strong setting they had to work harder. Although this may be less enjoyable it may actually be of greater therapeutic benefit and it is worth noting that 2 of the 4 patients had a better quality of movement on the strong setting. We therefore conclude that it is important to set the force to accommodate the patients needs.

5.3 Motivation

All of the six patients that completed this section felt that the system helped them to exercise for longer than they normally would in their traditional therapy session. Five of the six felt that therapy on the GENTLE/S system was more interesting than their traditional therapy session.
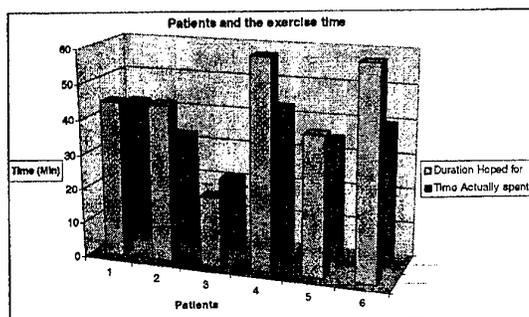
Figure 4 – Exercise time results.

When they were asked, how long they could exercise for before it would become boring; 5 of the 6 patients responded with times that were greater than the time that they had spent exercising (Fig. 4). It is worth noting that 7 of the 8 patients in the pilot trial stopped exercising because of arm fatigue rather than boredom.

6. Future Work

The initial clinical trial, which is currently taking place, involves evaluation of the prototype in terms of design, patient comfort, ergonomics and ease of use by both patient and therapist. Later in the year a full clinical trial will commence, which will evaluate the GENTLE/S system in terms of therapeutic benefit at the levels of impairment, disability and handicap.

Also we are going to look at virtual tasks allowing manipulation of objects and the haptics of manipulation of virtual and real objects in real tasks. At that point we will investigate and analyse the biomechanical data to determine if haptic technology and the development of wizard intelligence will positively contribute towards the advancement of assistive technologies.

7. Conclusion

This paper has presented the initial ideas and concepts for adapting and using dedicated haptic interfaces as part of the rehabilitation process of stroke patients. Our approach is based on the fact that attention and motivation are the keys for recovery.

The initial pilot studies have shown that the majority of the patients were positive towards the use of visual and haptic cues. Some of the results, with emphasis on visual perception, suggested that we would benefit by using augmented (mix) environments and also we would need to manipulate objects on both worlds.

Our force feedback test suggests that a patient might feel less force is more useful, although this does not necessarily means that it is therapeutic. Further investigation is necessary to prove the usefulness of haptic interfaces, especially force feedback.

Also this result allowed us to conclude that the amount of assistive force should be tuned for each individual, otherwise it might create extra impedance.

Finally, as a whole the system has proven to motivate hemiplegic patients to exercise for longer than they normally would in their traditional therapy session.

Acknowledgements

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A Fast Finite Element Modelling Tool for Surgical Simulation

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ABSTRACT

This paper present an algorithm based on finite element modelling of 3D solid volumetric, suitable for real-time animation and for haptic interaction, particularly for surgical simulator. The techniques used now by most surgical simulators are based on approximate methods that do not represent an accurate behaviour of the deformable bodies. The finite element method (FEM) is an alternative because of its accuracy, but it is computationally expensive. In this paper we address this problem by proposing the notion of ε-mesh radius in analogy with the similar notion used in the theory of adaptive meshing.

Keywords : Modelling, Finite-Element, Surgical Simulation, ε-mesh radius.

1. INTRODUCTION

The surgical simulation becomes possible, through the improvement of the computers, and some special purpose mechanisms, namely haptic interface. Various graphical based environment are being identified where the user is able to interact with such virtual environment. In these environments, the user manipulates graphical objects by using the hand interface mechanism. If the interference of the graphical object is detected, desired reaction forces are generated at the hand input device which gives the user a sense of physical interaction with the virtual objects.

Current literature in the area of haptic rendering focuses on the development of fast collision detection algorithm and some basic contact profiling [1]. For modelling the interaction with the soft tissues different approaches have been investigated [2].

Some authors proposed modelling approaches based on the spring-mass method because of their simplicity and their low cost computational [3,4]. However, such current approaches remain to be imprecise. On the other hand, The finite element method (FEM) offers an alternative. The main problem in this method is the high computational time.

Cotin & al. [5] tried to overcome this problem by using a pre-processing technique and the condensation method. Berkley and Weghrost [6] proposed to use the technique of the banded matrix. They also proposed to incorporate the whole volume of the tissue and organs for generating the finite element mesh.

This paper is concerned with determining a suitable method for defining the contact profile for constrained objects. The objective of the paper is to define suitable size and number of local grid-mesh which can represent a suitable physical recreation model for the contact profile with realistic deformation. For this purpose a number of comparisons between the traditional generation of the finite-element mesh and a new notion of ε-mesh radius is made especially in the context of piercing and cutting human tissue. As a result this study offers an approach to reduce the computation time for determining the contact profile using the notion of finite-element. In addition, such new approach can be made adaptive where, as a function of interference parameters and location of the contact between bodies, local mesh can be generated. This mesh profile can be defined optimal for computational purposes in haptic rendering. When contact is broken with the virtual object, the object representation will have its original coarse representation of mesh defined through CAD environment (or generated through MRI data-sets). The prototypes of the analysis of this study are developed using general purpose finite element environment (CASTEM 2000).

2. Overview

2.1 Mathematical formulation

In this section We briefly introduce the theory of elasticity and the finite element method.

Let us consider a body (Ω) having a volume V and a boundary $(\partial\Omega)$. At first approach, we consider that the object has a linear elastic behaviour. It is subject to volumic and boundary forces.
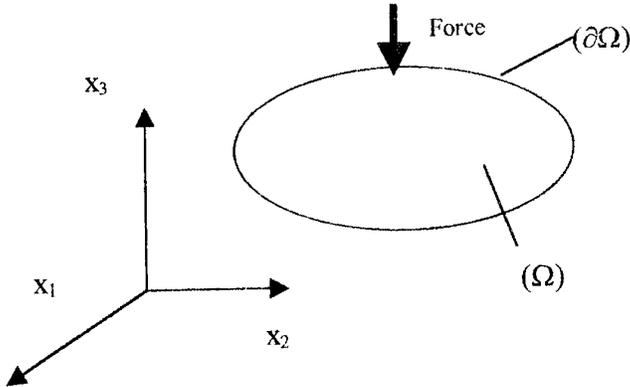
Figure 1. Description of elastic body

From the linear elasticity, the 3x3 strain tensor $\overline{\overline{\varepsilon}}$ of the body subject to a given force could be written as a function of the displacement U as :

$$\overline{\overline{\varepsilon}} = \frac{1}{2}\left(\nabla U + \nabla^{T}U\right) \qquad (1)$$

∇ is the gradient operator.

Let us note $\overline{\overline{\sigma}}$ the 3x3 symmetric stress tensor and f_v the volumic forces applied on the body . In the case of elastic behaviour, the relation between stress tensor and strain one is :

$$\overline{\overline{\sigma}} = \overline{\overline{\overline{E}}}.\overline{\overline{\varepsilon}} \qquad (2)$$

$\overline{\overline{\overline{E}}}$ is the four order tensor of the elasticity coefficients, it depends on the mechanical characteristics of the body (Ω).

When using the principle of virtual works, one can obtain, for a virtual increment of displacement δU :

$$-\int_V \overline{\overline{\sigma}}.\delta\overline{\overline{\varepsilon}}\,dV + \int_{\partial\Omega} t_n.\delta U\,dS + \int_V f_V.\delta U\,dV = 0 \qquad (3)$$

t_n is the stress vector applied on the boundary $(\partial\Omega)$.

To overcome the complexity of modelling objects based on continuum mechanics, i.e. solving equation (3), the body (Ω) is now divided into different elementary domains limited by nodes. The displacement of a given point of the body

could be approximate as a function of the nodal displacements as [7] :

$$U = [N]^T.\overline{U} \qquad (4)$$

[N] is the matrix of interpolation functions and $\overline{U}$ is the displacement column matrix of the nodes. Noting the global stiffness matrix of the form :

$$[K] = \int_V (D[N])^T.E.D[N]\,dV \qquad (5)$$

D is a differential operator. The static equation (3) becomes for the discretized body :

$$[K].\overline{U} = \overline{F} \qquad (6)$$

$\overline{F}$ here represent the column matrix of the whole volumetric and boundary forces applied on the body.

2.2 Multigrid

In the minimally invasive surgery, that we propose to simulate, the region influenced by the action of the surgeon tool is localised in the vicinity of the contacting point. The reaction force induced by this movement is mainly depending on this limited zone. To avoid solving equation (6) with a great number of degrees of freedom, we divide the object into a number of volumes. In the neighbourhood of the contacting point, we generate fine mesh. We define the size of this local mesh by the ε-mesh radius which represent a characteristic length in this volume. For the remaining of the volume, we use coarse mesh. In classical FEM, this procedure should be accompanied by the minimisation of the errors [7] in the energy norm in relation with the validity of the FEM approximation.
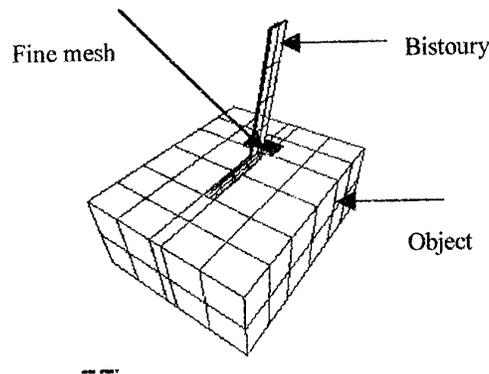
Figure 2. Modelling of the cutting problem

In haptic rendering, we have fewer constraints regarding the accuracy of the computation of the reaction force. In order to study this hypothesis, we

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will study through simulation the ratio between the reaction force given by our modelling method using ε-mesh and the one obtained through a full order 3D mesh representing the "exact" solution. The example selected correspond to the simulation of the cutting problem (figure 2).

3. Simulation results

In order to determine the relationship between the full order 3D mesh and the ε-mesh radius technique, we impose a given displacement (of piercing or cutting) to the body and determine the force needed for such task. This in general is called inverse problem.

We purpose an algorithm where we can change different parameters in the simulations and compute the ratio between the "real" reaction force computed using the full-order finite-element model and the proposed ε-mesh procedure.

1. **Input** ← (geometrical shape, mechanical characteristics, types of mesh) ;
2. **Input** ← (locations of concentration, geometry of the probe);
3. **do** ←(calculate the real reaction force to an imposed displacement of piercing or cutting);
4. **do** ← (calculate the reaction force with a multigrid referenced by an ε-mesh radius);
5. **do** ← (recalculate the reaction force with a new ε-mesh radius till the global volume of the body);
6. **back to 1** (with new parameters);

end;

Figure 3 shows an example of our study. The plots represent the ratio between the reaction force given by the ε-mesh procedure and the one obtained by a full order 3D mesh (F/F_{max}) for different values of the poisson ratio.
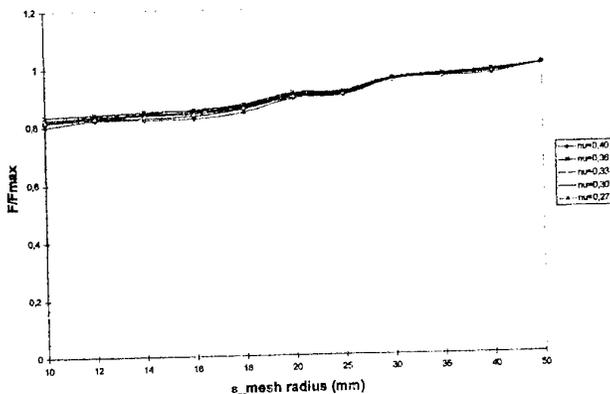
Figure 3. Influence of poisson ratio

The figure shows that for a relatively small ε-mesh radius (10mm) , we obtain more than 80% of F_{max}. This ratio remain quasi-constant when we change

different parameters of the study. Other simulations show that the ratio F/F_{max} could be considered as constant for different geometric and mechanical characteristics of an elastic body. Consequently we can develop a relationship between the results given by a full order 3D mesh issued from an off-line simulation, and those given by ε-mesh simulation. On the other hand, the computing time decreases significantly (about 50 times lesser) from the computation with a full order 3D mesh to the computation with the "ε-mesh radius" technique.

4. Conclusion

We present a method for the simulation of linear elastic deformable bodies in surgical applications. We proposed and are developing the new notion of ε-mesh radius, and have shown that it is a useful tool due its local interaction model, accuracy, and simplicity of implementation. Preliminary study shows that the results are close to those of a full order 3D mesh within a reasonable radius from the contact area.

The main contribution of the paper is to determine a guideline for developing physically based models of the object based on finite element method. The guideline suggest an approach for determining the size and number of elements involved for creating a realistic reaction force calculations which can be used in haptic rendering. The trade-offs are between the realistic sense of deformation and the computational costs.

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Rehabilitation of Musculoskeletal Injuries Using the Rutgers Ankle Haptic Interface: Three Case Reports

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Abstract

The efficacy of virtual reality-based rehabilitation for orthopedic patients needs to be determined. This paper presents three case studies in which the use of the Rutgers Ankle haptic interface for ankle rehabilitation is evaluated. The Rutgers Ankle is a computer-controlled compact robotic platform that measures foot position and orientation and provides resistive forces and torques. It has been integrated with a PC running an airplane piloting VR exercise and a custom electronic control box. The system underwent pilot clinical trials in an outpatient clinic in the State of New Jersey (USA). The goals of the pilot tests were to determine how well the current design of the interface worked in a clinical setting and to provide preliminary evidence of efficacy (whether patients benefited from incorporating the RA into their rehabilitation program). Results on three patients participating in the study showed improvements in range of motion, torque generation capacity and ankle mechanical work over six rehabilitation sessions. Objective measures obtained by the Rutgers Ankle show improvement in task accuracy to 100% for Case 1, a five-fold increase in ankle power output for Case 2, and a three-fold increase for Case 3. Both Case 2 and Case 3 reached 100% task accuracy by the end of the two-week rehabilitation training. Results from these case studies are being used in software enhancements and construction of a dual-platform system.

1. Introduction

Physical rehabilitation may benefit from the recent advances in virtual reality (VR)-based simulations. VR exercises can be used to motivate patients by providing an engaging, multi-modal, interactive rehabilitation environment [2,3]. In order to allow physical rehabilitation, such as the one needed by orthopedic and stroke patients, physical interaction with rehabilitation devices are involved. If the rehabilitation is done in virtual environments, new types of haptic input/output interfaces need to be created. One example is the Computer Assisted Rehabilitation Environment (CAREN) developed in Holland [1]. It uses a computer-controlled six-degree-of-freedom large platform to destabilize the patient standing still on it. Vision tracking is used to measure the patient's response for evaluation purposes.

Another example of a platform-based computer interface used in rehabilitation is the Rutgers Ankle (RA)[5]. The RA is designed for patients that need ankle and knee rehabilitation. It has been applied in the rehabilitation of patients with orthopedic (ankle sprain) [6] and stroke diagnoses [4].

This paper describes first the RA hardware and software system. Subsequently the outcomes of its introduction into a working clinic are presented. We describe three case studies of patients with musculoskeletal ankle injuries of different etiologies. Interpretation of the results and directions for future research conclude this paper.

2. Virtual Reality system

The Rutgers Ankle system consists of a Stewart Platform-based interface, its electro-pneumatic control box, a PC host computer and a mini-compressor, as shown in Figure 1[6].

The platform has dual-acting low-friction piston actuators, installed in parallel with linear potentiometers used as position sensors. A 3-D force sensor placed under a foot attachment measures the real-time forces and

torques applied by the mobile platform. The work envelope of the mobile platform accommodates the normal ankle motion for a sitting patient. Its force output depends on the pressure in the pistons, up to a maximum 100 psi.
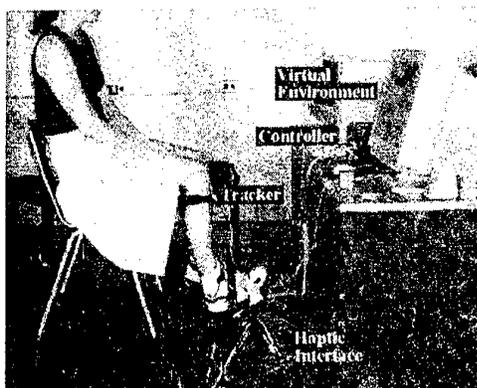
Figure 1. The Rutgers Ankle System [6]. © Rutgers University. Reprinted by permission.

The control interface uses peizo-electric valves that regulate the pressure in the actuator chambers at a bandwidth of 500 Hz. Low-level servo control is performed by an embedded Pentium board (266 MHz), based on pressure sensor information from the valve outputs. The servo control is a user-selectable position or force control loop, which runs much faster than would be possible on the PC host computer. Communication with the PC host is done over an RS232 serial line. The host PC is a single-processor Pentium 300 MHz computer running Windows NT. It displays the VR graphics, user graphical user interface (GUI), and stores data in an Oracle database

3. Exercise software

The exercise software was developed using the WorldToolKit software library for real-time graphics and the Oracle database for transparent patient data collection and analysis. The virtual reality exercise consists of a 3-D piloting of an airplane through multiple hoops, as shown in Figure 2 [4].

The movements allowed by the platform, pitch, roll and yaw, resemble the motions of the talo-crural and subtalar joints, plantar and dorsiflexion, inversion and eversion and pronation and supination [7]. The number and placement of the hoops, as well as airplane speed, viewpoint to the simulation and platform maximum force levels can be modified by the therapist. This gives the therapist the ability to adjust the level of difficulty for each exercise, on a patient-specific basis. Adjustments are

based on baseline performance on the RA and exercise performance during a training session. While the patient is exercising, force and displacement data are displayed in real time on the screen and compared with baseline information. The data are transparently and simultaneously stored in a database, which then calculates total exercise mechanical effort, peak and average forces/torques, number of hoops correctly passed, and other variables. Thus the healing process can be quantified based on objective measures, either at the physical level (range, torque, mechanical effort), or functional level (hoops entered/missed, number of hoops, exercise time/level of difficulty).
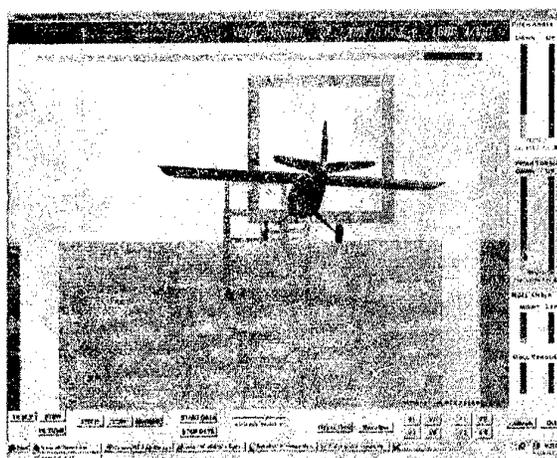
Figure 2. Ankle rehabilitation exercise in VR [4] © Rutgers University. Reprinted by permission

4. Clinical tests

In Summer 2000 the Rutgers Ankle system was installed in an outpatient rehabilitation clinic in the State of New Jersey, for a two-week trial period. The goals of the pilot tests were to determine how well the current design of the interface worked in a clinical setting and to provide preliminary evidence of efficacy (whether patients benefited from incorporating the RA into their rehabilitation program).

4.1. Subjects

Patients who participated in the two-week trials used the Rutgers Ankle to complement their regular rehabilitation program. This paper reports on three of the patients who ranged in age from 14-56 and who had varying musculoskeletal ankle injuries, time since injury

and familiarity with computer games. One of the subjects participating in the study is shown in Figure 3.
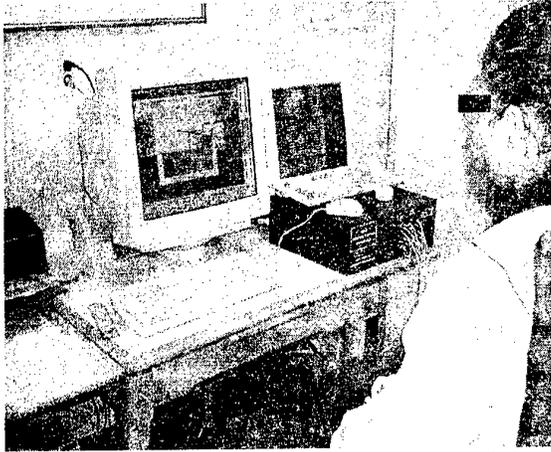
Figure 3. Subject participating in the Rutgers Ankle pilot study. © Rutgers University. Reprinted by permission.

4.2. Method

On the first day of the trial the subjects received a clinical exam, participated in baseline testing on the RA, were instructed and practiced on the RA and completed a subjective questionnaire. The clinical exam included ankle strength, range of motion (ROM), balance and functional ability measures.

Baseline testing on the Rutgers Ankle was done to measure displacement and torque for all ankle motions. Subjective evaluations consisted of questions in which participants were asked to rate their experience learning and using the interface. The participants exercised on the virtual reality system for five sessions, which lasted approximately 30 minutes each and were scheduled every other weekday. The progression of training was customized for each patient and was based on their performance with adjustments made for intensity, duration and complexity of ankle movements. Baseline performance was obtained for each session in order to update the settings of the Rutgers Ankle.

Training was supervised by a physical therapist and was a complement to the rehabilitation program for two of the three patients. To ensure consistency between sessions, subjects were positioned in the same way, their knee flexion held within five degrees of flexion, which was measured with a goniometer. The platform was held in the zero position prior to beginning the exercise. On the sixth session patients underwent a clinical exam, re-testing on the Rutgers Ankle and once again completed a subjective questionnaire. The three subjects completed the six exercise sessions.

4.3. CASE 1

The patient was a 14-year old male who was diagnosed with a Grade I inversion sprain that occurred during wrestling. He had injured his ankle two-weeks prior to beginning the trials. His goal was to return to wrestling. He had extensive exposure to computer games, which he used for recreation. The subject quickly mastered the basic virtual reality simulation, which allowed the investigators to test the upper limits of the system. Training sessions ranged between 12 and 20 minutes. Simulations were executed on average for two minutes. His longest continuous session was performed for the combination movement at a speed of 0.72 hoops/sec and difficulty setting of "medium" for ten minutes. He quickly progressed to training at the "difficult" setting and the highest level of resistance. During the final session he was able to increase from his average speed of 0.72 to 1.2 hoops/second. The subject reported enjoying the simulation, but we anticipated that he would lose interest once he mastered it. He did not appear concerned about making errors and learned to anticipate the presentation of the targets. Accuracy for the simulation improved from the first to the final session from, 36-42% for pitch, 37% for roll and 38% for the combination movements to 100% for all movements at a comparable speed, level of difficulty and resistance. Figure 4 shows the increase in task accuracy (% of hoops entered) over all simulations modalities.
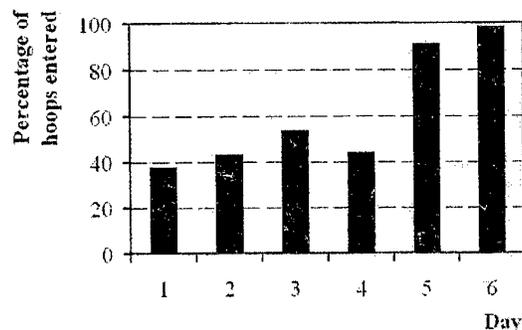
Figure 4. Subject 1 task accuracy (% loops entered) averaged over all modalities (ankle pitch, roll and combination) over the duration of therapy.

Clinically this patient presented with minor deficits in strength and balance and had some complaints of pain while walking down the stairs. After training he improved on the time he could maintain his balance on his right leg with his eyes closed from 12 to 24 seconds. He also

decreased the amount of time it took him to ascend and descend 12 steps from 23 to 18 seconds. After training he did not have any pain while climbing the stairs. At the completion of the trail he was discharged from physical therapy and returned to wrestling.

4.4. CASE 2

The patient was a 15-year old female who was diagnosed with a Grade II inversion sprain that occurred while playing softball. She incurred the sprain five months before the beginning of the trial. She used the computer for school but did not play any video games. The subject progressed from the second level of resistance to the third level. She also progressed from the "easy" level to the "medium" level, with only a couple of attempts at the most difficult level. Training sessions varied between nine minutes to as much as 24 minutes. A typical exercise span was two minutes long with her longest continuous bout at eight minutes. Figure 5 shows her affected ankle plantarflexion angles at the start and end of therapy.
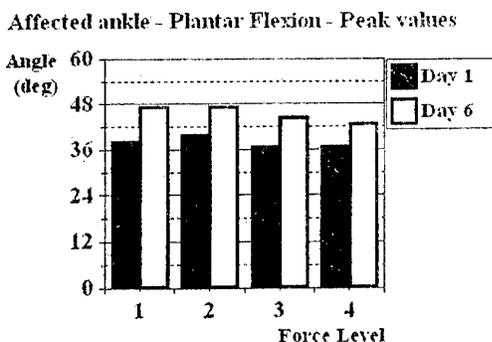
Figure 5. Peak values for plantar flexion angle of Subject 2 affected ankle, over the duration of the rehabilitation intervention. Force levels 1,2,3,4, indicate increasing platform resistance settings.

The training aggravated her symptoms and her ability to work on the system was influenced by her pain complaints. Therefore the power output fluctuated from a low of 390 watts to a high of 2020 watts. Often after the VR simulation ice packs were applied to the ankle. She reported enjoying the simulation initially, but after many repetitions she revealed that she found it somewhat boring. At the end of training her clinical exam revealed improvements in strength and balance. Strength increased by 1 manual muscle test grade from a 4 to a 5 for ankle dorsiflexion, inversion and eversion. She was able to stand on her involved leg for 60 seconds compared to 45 before training and was able to stand on her involved leg with her eyes closed for 28 seconds compared to 7 seconds before training. Recordings from the Rutgers Ankle showed that

she improved in her ankle dorsiflexion plantarflexion (see Figure 5), dorsiflexor and everter peak ROM, as well as her dorsiflexor and everter and plantarflexor torques (see Figure 6). Her accuracy with the VR simulation from the second day to the final day of training improved from 56% for pitch, from 67% for roll and from 65% for the combination movement to 100% for all the movements. Currently she is playing softball.
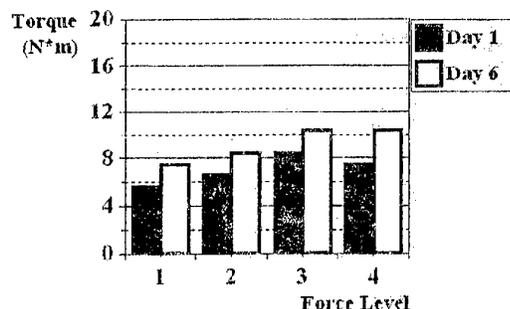
Figure 6. Peak values for dorsiflexion torque for the affected ankle of Subject 2, over the duration of the rehabilitation intervention. Force levels 1,2,3,4, indicate increasing platform resistance settings.

4.5. CASE 3

The third patient was a 56-year old female who had a bi-malleolar fracture. The fracture had been reduced with an external fixator two months earlier. Her goal was to resume recreational hiking. She used the computer in her job as a school administrator but had no experience with VR games. This patient required that some of her motions be held constant. For example, when she worked on the pitch motion, the therapist had to control the ankle yaw to avoid having the foot deviate out of position.

Early in the training the therapist had to manually guide the platform and provide verbal cues to assist the patient with the simulation. She performed at the very low speeds of 0.04 and 0.07 hoops per second on the first day on the easy ROM setting. After the simulation was modified to better represent the inversion/eversion movements she immediately increased her speed to 0.18 hoops/second. By the end of the training she was able to exercise at 0.6 hoops /second for all motions at the medium ROM setting. Her training sessions were between 15 and 22 minutes with her longest bout for a single exercise was six minutes. She reported enjoying the simulation and felt it was a good addition to her program.

Clinically she demonstrated improvements in ROM (5 degree increase in plantarflexion), balance (increased single limb support from 3 to 8 seconds), strength (1/2 grade increases for inversion and eversion) and speed (50% decrease) at which she climbed the stairs. Results from the Rutgers Ankle showed that she made gains in

ROM of the ankle everters and plantarflexors, which corresponded with clinical measurements. Her ROM increased for plantarflexion (50%) and eversion (55%). The amount of torque she could generate increased for ankle everters (60%), and dorsiflexion (25%). At the end of training her power output (calculated from the variables collected by the RA) increased from 175 watts to 475 watts for the affected ankle and surpassed that of the unaffected ankle. This is illustrated in Figure 7. Accuracy of the movements increased from 22% for pitch, 28% for roll and 26% for the combined movements on the first day to 100% for all movements on the sixth day. During the training period she returned to hiking.
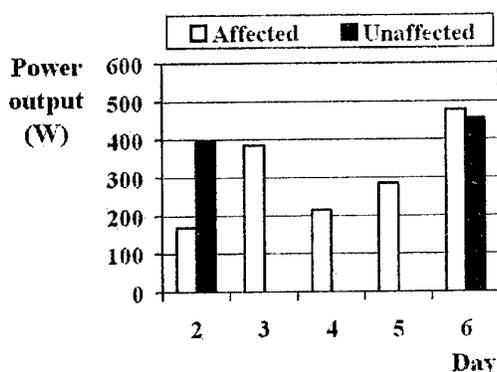
Figure 7. Peak values for ankle mechanical power for the Subject 3, over the duration of the rehabilitation intervention.

5. Interpretation /Discussion

The RA was successfully introduced into a clinical setting. Patients with varying diagnoses and ages were able to learn the simulations and train on the device. The greatest improvements were found for the patient with bi-malleolar fracture who presented with hypomobility and strength deficits. The patients with the sprains were functioning at a higher level and would have benefited from having their rehabilitation done in standing position. Clinical improvements were noted for strength and range of motion as well as for balance ability. Clinical exams and VR-related measures showed that all subjects had some degree of improvement and reported that they were able to use the device and enjoyed it as a complement to their regular rehabilitation program. Only one subject (case 2) was not receiving concurrent physical therapy, so it is difficult to conclusively attribute the clinical and functional gains to the VR training alone.

All three subjects were able to complete their exercises sessions without any prolonged adverse effects. Although the RA was installed in an open area with treatment tables on one side and an exercise area on the other, the three subjects were able to concentrate on the VR simulation. They were immersed in the virtual environment, and were not distracted by other patients exercising in the vicinity. The mapping of the foot motions to the RA was modified based on subjects input and observed difficulties with selected motions. Specifically, the degree of yaw, and roll movement that accurately corresponded with the inversion and eversion motions had to be adjusted. Difficulties with using the system were encountered with maintaining the pressure in the pistons during longer exercise spans. The compressor often became overheated, which resulted in a drastic reduction in its output pressure, requiring that exercise bouts be interrupted. In addition, the seating system was cumbersome when making adjustments for patient positioning, taxing the therapist. Finally, the calibration of the "zero" starting position will need to be refined.

6. Conclusion and Future Work

The case studies described here constitute the first clinical data indicating preliminary evidence of efficacy of the Rutgers Ankle system as a rehabilitation device for orthopedic patients. As a result of these trials several improvements are planned to the RA controller, in order to increase reliability, reduce vibrations and increase force output capabilities. It became clear that pneumatic control needs accurate temperature compensation of the pressure sensors, otherwise unwanted vibrations result. The compressor needs to have sufficiently large storage in order to avoid frequent starts under load, which in turn result in overheating and the subsequent inability to maintain high pressures.

Furthermore, a dual-platform system that would allow the patient to exercise while standing is being designed. This will allow the addition of virtual exercises in standing, followed by more clinical trials. In addition, more simulations are being developed with the goal of providing greater variety as well as increasing the ecological validity of the exercises. By providing several kinds of VR simulations the patient boredom may be alleviated. Studies in which the RA replaces selected aspects of rehabilitation such as strength, balance and proprioceptive training will assist with further evaluating the efficacy of the RA.

Acknowledgements

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Comparison of Simulated Ovary Training Over Different Skill Levels

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Abstract

This paper describes an initial attempt to compare performance levels of users of different skill levels on the Glasgow Horse Ovary Palpation Simulator (HOPS). Experimental participants were asked to identify the position and size of follicles on the surface of virtual horse ovaries. The two experimental groups were made up of expert and novice users. Experienced large animal veterinarians were chosen as expert users, and second year veterinary students were chosen as novice users. The initial results of the study suggest that novice users perform better than expected. Some possible reasons for this are discussed.

Keywords

Haptic, force feedback, medical simulation, virtual reality training.

Introduction

Virtual Reality is increasingly being recognised as a potential tool for providing training in medical procedures. It offers a safe controllable, environment for medical personnel to practice and learn new skills with no risk to patients. However, validation of a medical simulation proves difficult. Ethical considerations often prevent doctors who are trained using untried methods from working on patients. Particularly as a simulator may provide no training, or may even have a negative effect on training. Studies have shown that simulators can be used to improve performance on the simulator, as well as psychomotor skills [8], but there is little evidence to suggest that these improvements carry over to actual surgical procedures. O'Toole et al. [10] describe an experiment where experienced surgeons perform significantly better than medical students on a surgical simulator. They conclude that their simulator may be useful in quantifying surgical skill.

Although Virtual Reality simulation is a relatively young area in medical training, simulation is already a well established method of providing training in medicine. Students gain experience in certain techniques through use of plastic or rubber models, but these often lack realism and provide no useful feedback to the trainee. Surgical and diagnostic skills can also be improved in the anatomy labs that are incorporated into the medicine and veterinary medicine courses. Again, there are problems since cadavers are a scarce resource, and are not generally reusable. Living tissue can also have noticeably different haptic properties than cadaver tissue. VR medical simulators have the potential to present anatomical and physiological information to the user simultaneously on reusable models. Simulations currently developed can be divided into those that provide training for minimally invasive surgery (MIS), surgery, or palpation procedures. MIS simulators are by far the most common. In a MIS procedure, surgeons view their interaction with the patient through a monitor, and hence, it lends itself to a virtual simulation. The Preop endoscopic simulator [4] developed by HT Medical Systems is one example of a system combining a force feedback MIS training system with anatomical and physiological models. Other systems exist to simulate other MIS procedures such as arthroscopy or laparoscopy. SKATS [1] and VE-KATS [11] present knee arthroscopy training systems.

Surgery simulations cover a wide range of techniques using different surgical instruments. Cathsim [2] is an example of a commercially available training system for venipuncture. Berkley et al. [3] present a simulation for training in wound suturing.

The development of a palpation simulation presents different problems than development of a surgery simulation. During surgery, a medical practitioner interacts with the patient through surgical instruments, so the haptic feedback from the tissue to the surgeon is mediated by the instruments. In palpation procedures, the doctor is in direct contact with the patient. Burdea et al. [5] describe one of the few examples in the literature of simulation of a procedure involving palpation. Their comparison of rubber and virtual prostate models indicated that although rubber models provided better recognition, the virtual tumour models were also recognisable by experienced doctors. Dinsmore *et al.* [7] also describe the development of a palpation simulator for training in detection of sub surface tumours.

This report describes an ongoing experiment that uses the Horse Ovary Palpation Simulator (HOPS) developed at Glasgow University to compare the performance of experienced and novice veterinarians in horse ovary palpation.

Ovary Palpation

Traditionally, students are taught horse ovary palpation through books, lectures, and practical experience. However, the high cost of keeping horses often leads to a large ratio of students to horses. As ovary palpation is a stressful procedure for the horse, ethical considerations limit a student's opportunity to gain experience. A horse ovary examination can be difficult for a veterinary student to perform, but can also be fatal to the horse if performed incorrectly. Students are only exposed to conditions that occur during their training, and may not get experience in diagnosing rare or unusual cases. Virtual Reality offers a method of providing training for any condition that has been modelled. Access can also increased for seasonal examinations, like pregnancy diagnosis, as the simulator can be used all year round.

During an ovary examination, the veterinarian inserts a gloved hand into the pelvic area of the horse through the rectum. The veterinarian must search through the pelvic region of the horse for the uterus. The ovaries are attached to the uterus, and each can be found by following either the left or right uterine horn. This is difficult in itself, since the veterinarian must perform this search through touch alone while wearing gloves. It usually requires several attempts before an inexperienced student can locate an ovary. Once located, the veterinarian will cup the ovary with one or more fingers, and palpate it using his/her thumb. In particular (s)he will look for any abnormalities in the shape or surface properties of the ovary, and through training and experience, will be able diagnose different conditions through touch alone.

For the purposes of HOPS, follicles of different sizes could be placed on the ovary models. A follicle is a spherical fluid filled sac that grows on the surface of an ovary with some of the sac existing under the surface of the ovary. It will typically grow from very small – a few millimetres – to a few centimetres in diameter. As the follicle grows, it will also tend to move towards the centre of the ovary. Depending on the size, position and feel of the follicle a veterinarian can diagnose the stage of ovulation of the horse. There may be many follicles on an ovary, but only one active follicle exists at the one time.

The Glasgow Horse Ovary Palpation Simulator (HOPS)

HOPS consists of a left and right ovary model fixed in space. The two skills that are important in ovary palpation are locating and identifying the ovaries, and palpating the ovaries. HOPS attempts to provide training to veterinary students in the palpation stage of a horse ovary examination. The left and right virtual horse ovaries can be seen in figure 1.
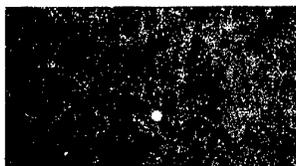
Figure 1: The Horse Ovary Palpation Simulator. This environment consists of a left and right ovary. On the bottom half of the left ovary, a spherical follicle can be seen. The user's cursor is shown as the yellow sphere in the centre.

A user can interact with HOPS through the PHANToM force feedback device from Sensable Technologies [9]. The haptic properties of the models have been developed in conjunction with experienced horse veterinarians at Glasgow University Veterinary School. A selection of veterinarians were asked to set softness, friction and damping properties for the models. Using this method a "good approximation" of actual ovary properties was achieved.

A previous study using HOPS has shown that over one training session, participants trained using the HOPS simulator perform similarly on specimen ovaries than participants trained using traditional methods [6]. Participants in this experiment were veterinary students with little or no horse rectalling experience. In this case, performance was based on the correct location and sizing of a single follicle on the virtual ovaries. This study also showed that there was a low percentage of correct identification in both cases (~11% correct), which suggests

current methods can be improved upon. This experiment will build on the previous work with the HOPS simulator.

Overview of Experiment

Training

The experiment was split into training and task stages. As none of the participants had any previous experience in using the PHANToM, they were initially presented with the standard 'Blocks' demo developed by Sensable Technologies to familiarise them with the device. The training stage focussed on training users to locate and distinguish objects by size and softness using touch alone. The training environment consisted of two spheres (shown in Figure 2).

Figure 2: The training environment consisting of 2 spheres.

In the initial training stage, the spheres had identical surface properties but varied in size. Participants had to locate these spheres in the environment, and answer whether the left or right sphere was larger or whether they were the same size. Once a participant answered, (s)he was presented with the next case. Participants had to provide five correct answers before moving on to the next training stage.

The participants were next presented with a similar training environment. In this stage, the spheres remained the same diameter, but the softness was varied. Participants were asked to judge which sphere was softer. This training stage was completed once the participant provided five correct answers.

Next participants were introduced to the HOPS environment. They were shown the models, then allowed to explore them through touch alone for five minutes. A small follicle was present on the front of the bottom left ovary. The training stage of the experiment was then complete.

All users were able to complete the training stage. The time taken in completing the training varied between 18 and 25 minutes.

The Task

The experimental task involved identifying follicles on the surface of the virtual ovaries through touch alone. Participants were presented with the same eight cases but in a random order. In each case, zero, one or more follicles were present on either ovary up to a maximum of five follicles in total. Each participant was given up to five minutes to explore the environment while identifying all follicles. Identification of a follicle involved identifying its position - either left or right ovary, front or back of the ovary, and top or bottom of the ovary - and its size. Participants were told that a follicle could be 2cm, 3cm or 3.5cm in diameter. Timing information for each case was calculated for analysis. Workload measurements were collected from all participants with a NASA TLX workload evaluation form.

There were two subject groups involved in the experiment.

- Group A consisted of second year veterinary students from Glasgow University Veterinary School. At this stage in the course, students have some knowledge of horse ovary palpation through lectures, but have no practical ovary palpation experience.

- Group B consisted of experienced large animal veterinarians. Each participant has years of experience and practice in large animal ovary palpation.

In this initial study, group A contained 10 participants and group B contained 3 participants.

Experimental Apparatus

During the experiment, users interacted with the virtual environments using a PHANToM 1.0 with the standard thimble attachment. The equipment was set up as shown in figure 3 such that a participant received no visual feedback. Participants also wore headphones to obscure noises produced by the PHANToM motors.
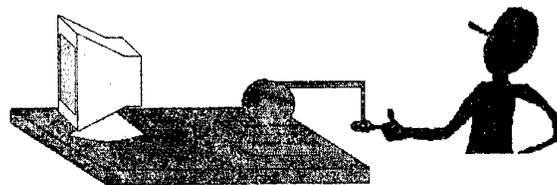
Figure 3: Experimental setup during haptic training. The screen is pointed away from the user so he/she receives no graphical feedback to feel the ovaries.

Hypotheses

1. The measured performance on the simulator of experts group would be significantly better than the performance of the novice group. This performance is measured in accuracy of identifying follicles.

2. The expert group will perform examinations significantly faster than the novice group.

3. The measured workload of the expert group A would be significantly lower than the workload of the novice group. The expert group will show a significantly higher confidence rating.

Results

Performance on the Simulator

Initial results suggest that hypothesis 1 will not be supported. Of the 22 follicles present in the experiment, both groups reported identifying similar numbers of follicles. However differences are noticed in the percentage of follicles correctly placed. Group A placed 70.9% of follicles correctly, where as group B placed 40.9% correctly. The expert group reported problems in placing a follicle on the ovary once found. In a real examination, the veterinarian will hold the follicle while palpating, and will therefore have an idea of the position of any follicle found with respect to the ovary in their hand. This is not the case in the virtual model since users are restricted to one point of contact with the environment.

	Number found per trial	% Correctly Positioned	% Correctly positioned & sized
Group A	18.8	70.9%	36.4%
Group B	17	40.9%	13.6%

Table 1: Results from both groups of performance in identifying follicles on the ovary surface.

Differences were also observed in the techniques used by group A and group B in the trials. Participants from group A tended to maintain contact with the ovary being search, and maintain a steady force to trace the shape of the ovary. Participants from group B tended to move across the ovary surface, repeatedly prodding it and therefore varying force.

Comparison of Timing Data

Figure 4 shows the comparison of timing data between the two groups. There are suggestions from Cases 6, 7, and 8 that the experienced veterinarians may complete their examination more quickly, however, a larger expert group is required before any significant results can be detected.
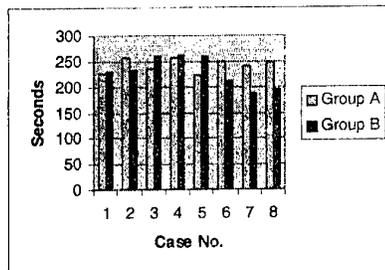
Figure 4: Comparison of the average time to complete each examination

Workload Analysis

Figure 5 shows the comparison of workload between the two subject groups.
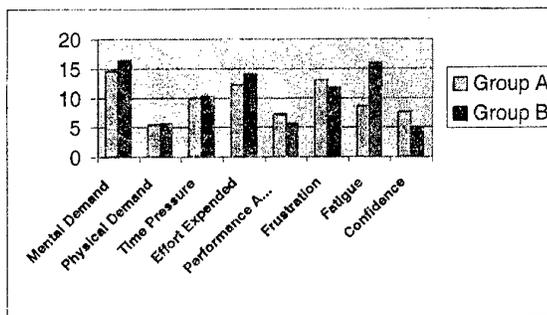
Figure 5: Comparison between the expert and novice groups of subjective workload for the task

Although the expert group is small, it is important to note that the 'Performance Achieved' and the 'Confidence' ratings are low. This is possibly down to the fact that locating follicles on an ovary is performed differently in the simulator and in the real examination. Both groups found the task very mentally demanding.

Future Work

The next stage of the experiment will be to continue with a larger number of expert users. The expert user group just now is too small to be able to draw any conclusions about the significance of results.

During the experiment cursor path and user force information were collected. Further analysis will be performed on this data. Initial aims will be to analyse the path information to detect any differences in techniques between the user groups, and look for similarities within the expert group. Information, such as force used to palpate an ovary will be examined.

We will also investigate techniques for addressing the problems raised by the expert group in positioning follicles on an ovary. Initial tests will involve incorporating two PHANToMs into the workspace. One PHANToM can therefore be used to palpate, the while the other can control the movements of the ovary. This would provide a means of reference to position the follicle on the ovary.

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The Grasp-span Weight Illusion

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Abstract

Charpentier (1891) showed that when objects of identical mass but different volume are lifted, subjects consistently report that the smaller object is heavier. This finding is preserved even when subjects are aware that the objects are of the same weight, and has become known as the size-weight illusion. More recently, Flanagan & Bandomir (2000) found that a similar effect is seen when subjects pick up weights with different grasp spans. In this case, weights picked up with a narrow grip are judged to be heavier than identical weights picked up with a wide grip. The experiment described here is an extension of Flanagan & Bandomir's work, which eliminates visual feedback. We find that the grasp-span weight illusion is present without the aid of vision.

Introduction

Flanagan & Bandomir (2000) examined the effect of the grasp span used to lift an object on the lifter's perception of its weight (note that throughout we refer to Flanagan & Bandomir's Experiments 1 and 2). They asked subjects to pick objects of different weights, and report whether the object was lighter or heavier than a reference object. The part of the object used to pick it up was rectangular, so the object could be grasped across the narrow axis (3cm) or across the wide axis (7cm). In addition, the subject could move such that the face of the object presented to the subject was the wider or the narrower face.

This study found that subjects perceived the weight to be lighter when lifted with a wide grip, and heavier with a narrower grip (Experiment 1). This finding holds whether the subject views the object from the front or from the side (Experiment 2).

Flanagan & Bandomir's study did not exclude the classic size-weight illusion as their subjects could see the objects that they were lifting, instead the object was rotated such that a wider or a narrower face of the object was visible to the subject. The study presented here corrects this, and tests the presence of a grasp-span weight illusion without vision.

Method

We recruited 20 able-bodied subjects, who did not report any difficulty with using their preferred hand at the time of the experiment. 15 men and 5 women were tested, between the ages of 18 and 23 years. Subjects were not rewarded for their participation.

Following Flanagan & Bandomir we used a forced-choice paradigm, in which blindfolded subjects lifted a test weight, selected in random order from weights of 80g, 94g, 101g, 108g, 115g, 123g, 130g, 137g and 151g, then lifted

a reference weight of 115g. Subjects were then asked to report whether the test weight was lighter or heavier than the reference. Each weight could be lifted using either a narrow grip or a wide grip, giving a total of four conditions.

A standard lifting platform was used for each weight, with a central, narrow grasping site (3.2cm) and an outer, wider grasp site. The size of the wide grip could be varied according to the size of the subject's hand, and was either 9.6cm or 11.35cm. We chose the grip size such that the subject was just able to pick up the lifting platform. The two groups performed statistically identically (data not shown), and will be treated as one group. The grasp sites had strips of sandpaper attached to provide a high-friction surface, and to reduce the grip force needed to lift the object (Flanagan & Wing 1997).

The subjects were instructed to lift the platform using the thumb and the ring and middle fingers. No instructions were given as to how to lift the weight, but all subjects were observed to lift the weight by about 10cm, hold it momentarily then place it down again.

Analysis

The responses for 20 subjects were pooled, and for each test weight in each condition we found the proportion of trials where the test weight is reported as being heavier than the reference weight. Each subject lifted each weight twice in each condition, so there are 40 estimates per point in each

condition. The point of subjective equality (where the two weights are judged to be identical) was found for each condition by fitting a sigmoid function to the observed data.

We performed F-tests on pairs of curves to determine whether or not the underlying populations were significantly different.

Results

We find that when both weights are lifted with the same grip width (narrow-narrow or wide-wide), the curves fitted to the response data are not significantly different to each other [$F(2, 14) = 1.16$, n.s.], and the halfway points of these curves are close to the true value of the reference weight.

However when the weights were lifted with different grip sizes (wide-narrow or narrow-wide), subjects report that the test weight is heavier when it is lifted with a narrow grip, and lighter when lifted with a wide grip. The fitted curves are significantly different [$F(2, 14) = 347.76$, $p<0.001$], with the curve representing the narrow condition shifted to the left, and the wide condition to the right.

Figure 1 shows the proportion of subjects who reported that the test weight was heavier than the reference, for each weight in each condition. It is clear from the data and from the fitted sigmoids that the subjects were more accurate when the weights were lifted with the same grasp size than with different grasp sizes.
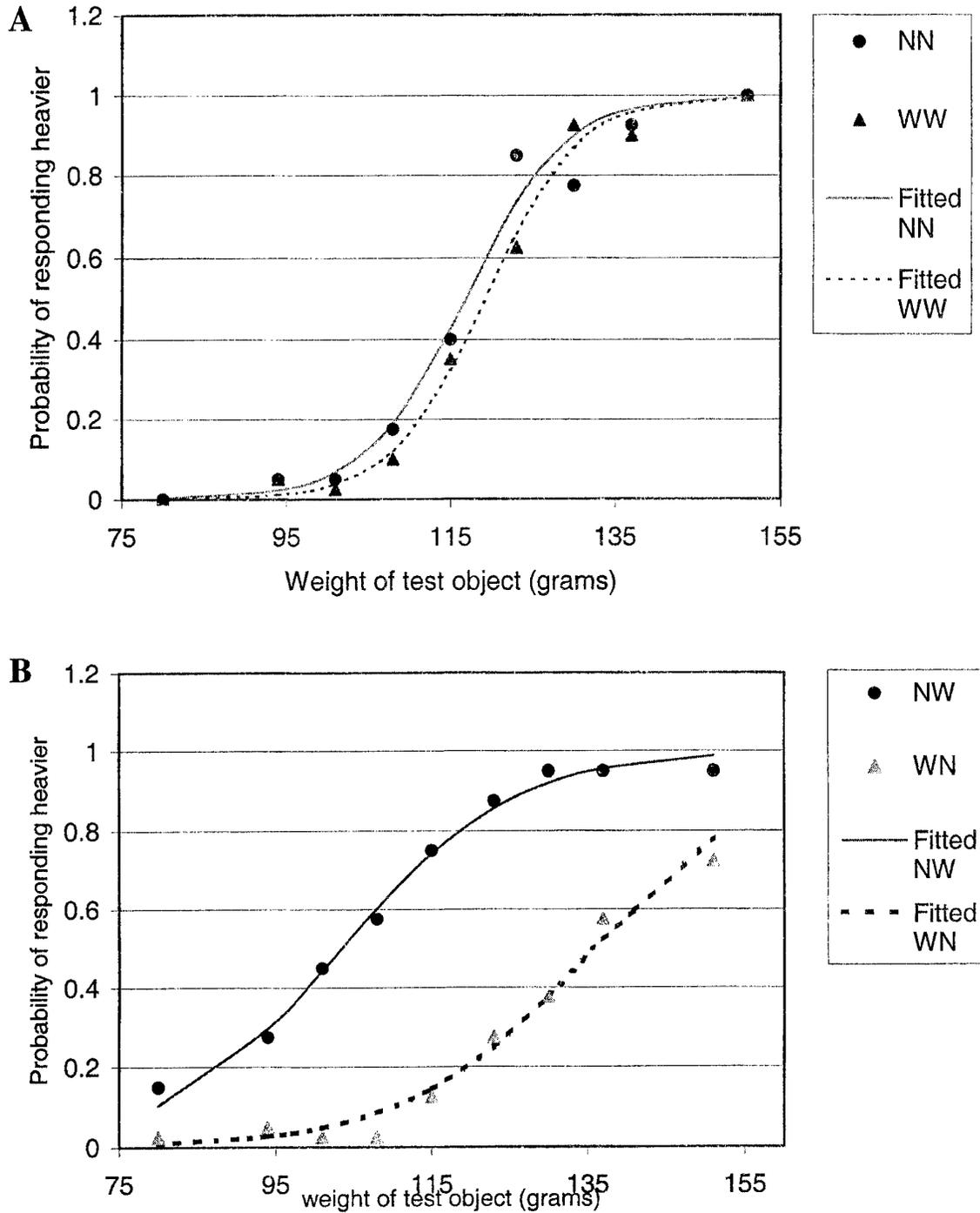
Figure 1. These figures show the proportion of subjects who reported that the test weight was heavier than the reference weight, for a given test weight. Figure 1A shows the conditions where the two weights were lifted with the same grasp span (W = wide, N = narrow), with the fitted sigmoid shown. 1B shows the conditions where the grasp spans were different (NW = test weight narrow grasp, reference weight wide; WN = test weight wide, reference weight narrow).

The midpoints of the fitted sigmoids away from the true value of the reference weight give the points of subjective equality for the different conditions. In the condition where the test weight was lifted with a narrow grip and the reference weight with a wide grip (narrow-wide condition), the midpoint is shifted to the left by 11.5g, suggesting that for a given weight, the perceived weight was 11.5g heavier than the true weight. For the wide-narrow condition it is shifted to the right by 20.9g, suggesting that it is perceived as being that amount lighter.

Discussion

The experiment described here demonstrates that the grasp-span weight illusion has a purely haptic or kinaesthetic cause, since we eliminated the ability of subjects to use vision to pre-judge the properties of the object to be lifted.

Since the only parameter of the experiment that is being manipulated between conditions is the grasp span, the illusion must arise either from perception of the grasp size, or from the perception of the work required from the hand muscles.

Van Doren (1998) found that as grasp span increases, the amount of work required of the hand muscles decreases, for a given grip force. Our grip spans were larger than those that Van Doren measured (up to 8cm). We believe that the trend should hold for larger grip spans, however this study did not measure muscle activity during the task. We suggest that this differential pattern of muscle activity is the best candidate for the substrate of the grasp-span weight illusion.

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Results from a Tactile Array on the Fingertip

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Abstract

Data from a 100-contactor tactile array on the fingertip (1 mm × 1 mm matrix) suggest that it may be possible to target different receptor populations in the skin by using different frequencies of vibratory stimulation (40 Hz and 320 Hz). Results from perception of a moving target within a uniform "background" vibration indicate that there is greater spatial acuity for perception at 320 Hz than at 40 Hz. In the absence of a background vibration, discrimination between moving-bar stimuli presented at resolutions of 1 mm, 2 mm and 3 mm is difficult, particularly at 40 Hz, suggesting that a 100-contactor tactile array may offer little advantage over a 25-contactor array (2 mm × 2 mm matrix) in some contexts.

1. Introduction

In "natural" touch perception, sensations are produced by spatiotemporal patterns of mechanical disturbance at the skin surface. At Exeter we have developed a stimulator array which is designed to simulate such sensations on the fingertip by artificially generating the appropriate patterns of tactile stimulation. The spatial resolution required for stimuli is determined by the density of touch receptors in the skin – around 1 mm^{-2} on the fingertip. To achieve this, the array has been designed with 100 contactor pins arranged on a 1 mm × 1 mm square matrix over an area of 1 cm^2 which covers the fingertip (see Figure 1). Each contactor is driven by a piezoelectric actuator (see Figure 2) – the 100 drive waveforms can be individually specified in software and are delivered via a purpose-built interface.

In previous tactile arrays, such as the widely used Optacon device, the stimulus waveform from each contactor has generally been limited to a fixed frequency (~250 Hz) at a fixed level, with stimulus patterns produced by simple on/off keying. The Exeter array has a significant advantage in this respect: within the working bandwidth of 25-400 Hz, a wide variety of stimulus waveforms is possible from each contactor. This allows, for example, targeting of different receptor systems in the skin, which differ in terms of their frequency response [1].
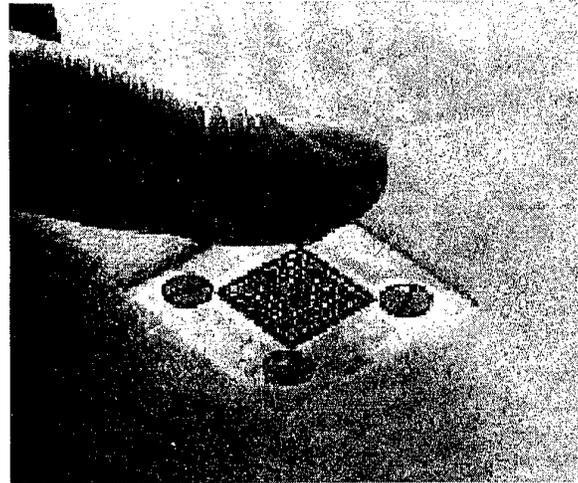
Figure 1. The array has 100 contactors over an area of 1 cm^2. The displacement waveform of each contactor can be individually specified.
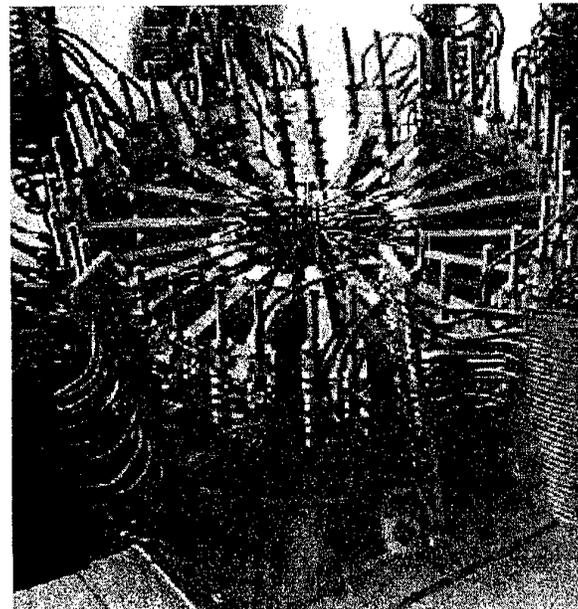
Figure 2. The underside of the array: 100 piezo-electric drivers are arranged in five tiers.

2. First experiment

This is an investigation of the perception of a moving target (created by contactor pins driven at amplitude S) against a uniform background (created by the remainder of the array driven at amplitude N, with $N < S$).

2.1. Method and results

Subjects are required to identify the direction of motion: up, down, left or right. The target is in the form of a line of L array elements (L = 1, 3, 5, 7), moving across the array in a direction perpendicular to the line: a horizontal line moves up or down and a vertical line moves left or right. (For $L = 1$, the "dot" moves in any one of the four directions.) In all cases the target moves from one side of the array to the other in one second, i.e., at a speed of 1 cm per second. In this experiment, all the contactor pins (both target and background) are driven with sinewaves at the same frequency f. Half of the test blocks were run with $f = 40$ Hz and the remainder with $f = 320$ Hz. These frequencies were chosen in the hope of targeting non-pacinian and pacinian touch receptors, respectively.

With the target amplitude S held constant, discrimination scores were determined for 8 subjects as a function of the background amplitude N. Curve fitting with a suitable psychometric function was used for each of the 8 test conditions (4 values of L with two values of f) to obtain in each case an estimate of the critical background amplitude at which the targets are just discriminable. This was specified as the value of N corresponding to a discrimination score of 62.5 % (i.e., halfway down the psychometric functions, which run from 100 % to the chance score of 25 %). Figure 3 shows these values of critical background amplitude (in arbitrary units, with $S = 120$ in the same units).
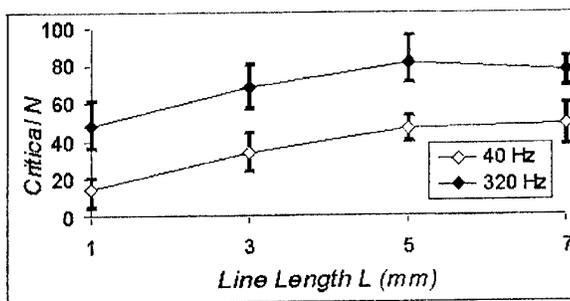
Figure 3. Critical values of background amplitude N (at which the direction of movement of a target of amplitude S = 120 is discriminable with 62.5 % success rate [chance = 25 %]) as a function of length of the target line. Data are shown for stimulus frequencies of 40 Hz and 320 Hz.

At 320 Hz, amplitude 100 corresponds to around 4 microns peak-to-peak, hence the target at amplitude 120 corresponds to around 5 microns peak-to-peak; at 40 Hz, amplitude 100 corresponds to around 40 microns peak-to-peak, hence the target at amplitude 120 corresponds to around 50 microns peak-to-peak. The conversion between displacement amplitude and sensation level is not straightforward – the detection threshold varies with stimulation area (and presumably varies differently at the two stimulation frequencies). However, the bar stimuli are all at a "comfortable" sensation level and the 1:10 ratio of the amplitudes at 320 Hz and 40 Hz means that corresponding 40 Hz and 320 Hz stimuli are at roughly the same sensation level.

2.2. Discussion

Both data sets flatten at a line length of 5 mm (i.e., $L = 5$). This value may relate to the size of the receptive fields involved in the task. There is a significant difference between the data at 40 Hz and at 320 Hz. This suggests that different receptors may have been targeted with the two different stimulus frequencies. Certainly, the sensations are very different: 40 Hz stimuli produce a much better approximation to "real" touch sensations than do 320 Hz stimuli. However, there is a problem with this interpretation in terms of different receptor populations: there are suggestions in the literature that non-pacinian receptors have greater spatial acuity [2], and so it might be expected that discrimination in this "signal-in-noise" task would be easier at 40 Hz than at 320 Hz. However the experimental data suggest that the converse is true: equivalent performance is obtained with much higher background amplitudes at 320 Hz than at 40 Hz, suggesting that spatial acuity is greater at the higher frequency.

3. Second experiment

Future plans include construction of a device to address four fingers and thumb on one hand, each digit with a 5 × 5 array of 2 mm pitch. It is thus of some interest to predict the difference in performance between the present 10 × 10 array and a 5 × 5 array, each addressing 1 cm² on the fingertip. Here we describe an experiment on perception of stimuli at different spatial resolutions.

3.1. Method

Test stimuli are in the form of a line of 10 array elements moving across the array at a speed of 1 cm per second in a direction perpendicular to the line. The active contactor pins are driven with sinewaves at frequency f. Stimuli move across the array via 9 increments of 1 mm,

4 increments of 2 mm, 3 increments of 3 mm, 2 increments of 4 mm or 1 increment of 6 mm. For each stimulus, subjects are required to identify the spatial pattern of the motion.

Eight volunteer test subjects were trained and subsequently tested for their ability to distinguish between stimuli at the different spatial resolutions. Each subject was presented with eight test blocks; half with $f = 40$ Hz and half with $f = 320$ Hz. At each frequency f, separate test blocks were run for each direction of movement: up, down, left or right. Each block consisted of 20 test items, distributed between the 5 different spatial resolutions. Noise masking via headphones was used to eliminate any acoustic cues.

3.2. Results and discussion
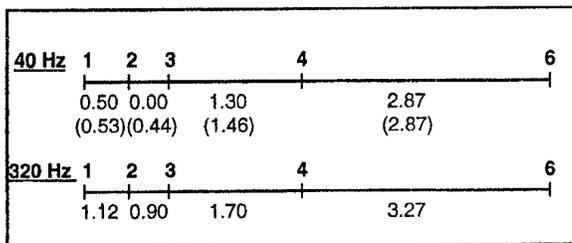
Figure 4. Representation (not to scale) of discrimination index between the five stimulus resolutions. (Data pooled over stimulus direction; upper line: 40 Hz stimuli; lower line: 320 Hz stimuli.) The labels above the tic marks indicate the stimulus resolution in millimetres. The numbers below each line indicate the calculated discrimination index d' for neighbouring stimulus types. At 40 Hz the d' between 2 mm and 3 mm resolution was calculated as being very slightly negative – this d' value was thus forced to zero. A second set of data at 40 Hz, taken in a pilot experiment with a different group of subjects, is shown in brackets.

Data from the identification task were obtained in the form of confusion matrices, indicating the extent to which the five spatial resolutions were distinguishable. No significant differences in performance were observed between the four directions of movement. Hence data were pooled over direction of movement and, using a method similar to that described by Braida and Durlach [3], the pooled confusion-matrix data were processed to obtain values for discrimination index d', as shown in

Figure 4. (Note: A d' value of less than 1 indicates that discrimination is difficult; d' values are cumulative, e.g., the d' at 320 Hz for stimuli at 2 mm and 4 mm resolution is $0.90 + 1.70 = 2.60$.)

These data show poor discrimination between stimuli at 1 mm, 2 mm and 3 mm resolution, particularly at 40 Hz. This is an important result, since it suggests that a 10×10 array (1 mm pitch) offers little advantage in this context over a 5×5 array (2 mm pitch) – and the 10×10 array has significant disadvantages in terms of cost, control and ease of construction.

The better performance for 320 Hz stimuli, compared to that for 40 Hz stimuli, can be related to the fact that discrete "jumps" in the moving 320 Hz stimuli are reported to be clearly detectable at all resolutions, whereas these jumps are only apparent in the 40 Hz stimuli at the lower resolutions.

4. Conclusion

Each experiment provides evidence, albeit indirectly, that the position of moving stimuli on the skin is more accurately perceived at 320 Hz than at 40 Hz. It is possible that this relates directly to the nature of the stimulus provided by the array. However, the design of the array provides no obvious mechanism for this, and hence we believe that differences between results at 40 Hz and 320 Hz are attributable to differences in the perceptual mechanism at the two frequencies, and may be explained in terms of the involvement of different populations of receptors.

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Feeling Rough:
Multimodal Perception of Virtual Roughness

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Abstract

The texture of a real or virtual surface can both increase the sense of realism of an object as well as convey information about an object's identity, type, location, function, and so on. It is crucial therefore that interface designers know the range of textural information available to them through current interaction devices in virtual environments. We have examined roughness perception of a set of force feedback generated textures (conveyed via a PHANToM device) in order to better understand the range and resolution of textural information available through such interaction. We propose that the addition of audio stimuli will increase further the potential for conveying more varied and realistic texture percepts through force feedback interaction. We are currently examining roughness perception of a set of auditory stimuli and will use both sets of unimodal results to test the potential benefits of combining haptic and auditory textural stimuli.

Keywords

Haptic, auditory, force feedback, texture, roughness perception, multisensory, multimodal interaction.

Introduction

Despite the increasing prevalence of haptics in today's computing environments, the effective representation of such information is still a relatively new design problem for human computer interaction research. Force feedback interfaces in particular pose a variety of design questions such as what can and cannot be communicated convincingly via such devices.

In human sensing and manipulation of everyday objects, the perception of surface texture is fundamental to accurate identification of an object [5]. In a virtual world also, texture information can both increase the sense of realism of an object as well as convey information about what the object is, where it is, and what it is for [4]. Through force feedback interaction in particular we can provide textural information that we can literally feel through the haptic modality. Given that it is often argued that touch is the 'reality sense' [2], being able to feel the texture of a virtual object should surely lead to increased realism of the object.

Previous work investigating the perception of real surface textures has shown that the physical properties of textures are complex and that an overall understanding of texture perception remains somewhat elusive [e.g. 3,4,5]. Textures are therefore proving difficult to reproduce successfully in virtual environments. It has been accepted however that roughness (along with hardness) is certainly one of the primary properties of a surface used to identify and classify an object. We have chosen therefore to focus our research initially on this dimension of roughness of virtual surfaces.

Simulating textures with force feedback devices in particular has proved an interesting research problem. Force feedback devices convey texture by actuating kinesthetic forces on the users' finger, hand, or body. This type of interaction relies on forces created through kinesthetic movement or displacement of the device and user limbs or joints while much of the texture perception we are used to comes through tactile stimulation of the mechanoreceptors on or just below the surface of our skin [5]. We have found in our previous work that such 'gross' or large textures can perturb the users' movements so much that the ability to stay on the textured surface is adversely affected [7]. More careful design of such force feedback based textures is required if these devices are to reach their full potential.

High fidelity force feedback devices (such as the PHANToM) are becoming increasingly realistic

interaction tools in a variety of applications where the texture of a virtual surface may be of great importance. Medical research for example can exploit such interaction in surgical and diagnostic simulations where the texture of tissue or organs may provide crucial information or feedback to the surgeon during a procedure.

Force feedback interaction is also improving the ability to design and prototype a variety of products ranging from the commercial (e.g. cars) to artistic and historical artifacts (e.g. sculptures and jewelry). E-Commerce will also benefit in that companies can provide their customers with a close representation of the feel of their products before they buy. The textile and fashion industry in particular could anticipate increased online sales if the texture of the clothing could be felt before purchasing [1].

It is crucial therefore that interaction designers know the potential range of textural information available through each modality and indeed each device available to them. With the increasing prevalence of force feedback interaction, it is particularly important to establish this for the haptic modality and high end of the range devices such as the PHANToM (SensAble Technologies).

Past research suggests that texture representation is possible through force feedback interaction but that the ideal solution is yet to be found. This is due in part to the mismatch between real texture perception (which involves both cutaneous and kinesthetic sensation) and virtual texture perception (which normally relies on either cutaneous sensation through tactile devices or kinesthetic sensation through force feedback devices). The problem could potentially be solved by advancing the currently available devices in order that the devices better suit real texture perception [e.g. 8]. This hardware-based solution is inevitable as the technology advances.

Another solution may be to improve the physical and mathematical modeling of real textures to produce the optimum algorithms for generating realistic virtual textures. This method currently has mixed results, as it cannot be assumed that the virtual exploration of texture matches that of real texture perception. Exact physical modeling therefore may be pointless if the interaction used to experience the texture differs significantly from that assumed by the physical model.

Proposed Solution

Our approach offers a cost-effective approach that makes use of the currently available devices and even the simplest physical models of texture. We propose a multimodal solution that exploits the human ability to combine and integrate information from multiple sensory modalities into a fused and meaningful and whole percept.

We hypothesise that presenting combined haptic and audio percepts of roughness will increase the quantity and quality of textural information available through force feedback interaction alone.

Overview of Experiments

The current work involved: (1) the evaluation of the effect of texture frequency on perceived roughness of a set of force feedback generated textures, (2) a follow up study extending the range of frequencies used and examining the possibility that there were two distinct notions of roughness emerging from the range of textural stimuli used, and (3) the evaluation of the effect of texture frequency on perceived roughness of auditory textures created from the profiles of the force feedback textures. This perceptual classification process will serve as a basis from which to test the eventual effects of systematically combining the haptic and auditory texture stimuli.

The Force Feedback Device

The PHANToM 1.0 force feedback device by SensAble Technologies (Figure 1) was used to generate the virtual textures. Optical sensors detect changes in the device's configuration and mechanical actuators apply forces back to the user. Users interact with the device by holding a pen-like stylus attached to a passive gimbal on the device.
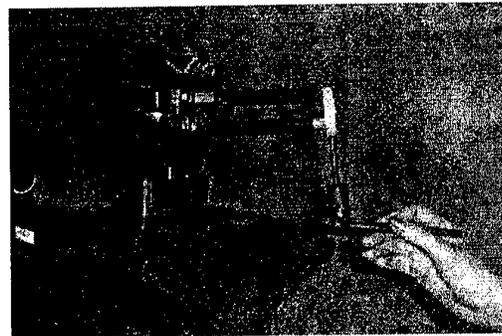
Figure 1: The PHANToM 3D force feedback device from SensAble Technologies.

By scraping this stylus/probe back and forth across the textured area the appropriate forces can be calculated from the positional information of the tip of the probe and the stored algorithmic models of the textured surface with which the user is interacting.

Haptic Textures

Haptic textures were generated as sinusoidal waves or gratings on a rectangular patch on the back wall of the workspace. Figure 2 shows a diagrammatic view of the profile of a texture and the forces generated as a result of this profile.

(a)   (b)
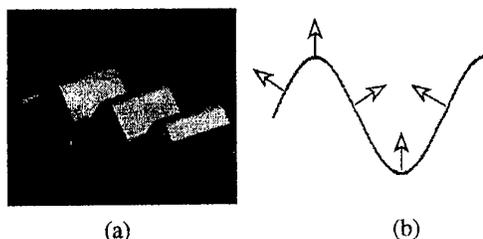
Figure 2: (a) diagrammatic view of the profile of the texture; (b) indication of forces resulting from amplitude and frequency of texture wave.

The resulting texture profiles depend therefore on the amplitude and frequency of the sinusoidal waves. The textures had fixed amplitude of 0.5mm and variable frequency (cycles per 30mm). The frequencies used varied from 5 – 45. Higher frequencies were more tightly packed waves and lower frequencies were more loosely packed waves. The result of these textures was a bump felt at the peak of each wave.

Auditory Textures

Auditory textures were generated from the same sinusoidal waves on a rectangular patch on the back wall of the workspace. The resulting profile still depended on the amplitude and frequency of the waves. The result of these textures was a single MIDI note generated from and heard at the peak of each wave. No experimental forces were experienced through the device.

Roughness Comparisons

Participants in Experiment 1 could rate the textures as the same, the one on the left as rougher, or the one on the right as rougher. Participants in Experiment 2 were given the same options but with the additional response option of rating the textures as not comparable on the same roughness scale. This set of responses allowed us to evaluate (a) whether the participant perceived the two textures as the same or as different in terms of roughness, and (b) the number of times each texture was rated as the roughest of the pair.

In addition, the added response in Experiment 2 allowed us to evaluate (c) which textures participants felt were different but not comparable along the same roughness scale. This was added as it was observed in experiment 1 that people often perceived a haptic difference but that they could not decide easily which one was in fact rougher.

Procedure

Participants (Experiment 1, N=12; Experiment 2, N=10, Experiment 3, N= 12) were instructed to drag the probe of the device over each of the indicated textured surfaces and make a judgment on the roughness of the pair of textures. Participants compared each texture to itself and to each of the others twice (in a random order). In experiment 1, subjects compared 6 textures. In experiment 2 the frequency range was extended to include 9 textures.
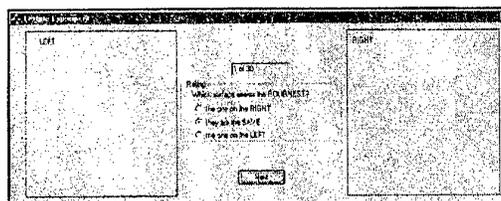
Figure 3: Interface for roughness comparisons

Participants were allowed to explore each of the textures during that trial for as often as they liked and could switch between exploring the one of the left to exploring the one on the right as often as they liked to compare the two textures. They were instructed however that it was their initial response to the textures that mattered most and that there were not necessarily right or wrong answers for each of the trials. Participants made their response by clicking the switch on the probe of the PHANToM to select the response that reflected their roughness judgment for each trial.

A training session identical to the experiment but with less trials allowed the participants to become familiar with the device and the interface. Importantly, it also allowed them to adopt an exploration strategy for experiencing the textures comfortably and successfully.

Hypotheses

Independent Variable: frequency of texture (cycles per 30mm).

Dependent Variable: Perceived roughness, operationalised as the number of times each texture was judged as the roughest of the pair.

Exp. 1: The frequency of the haptic texture (or number of bumps) will have an effect on the perceived roughness of the texture.

Exp. 2-a: Increasing frequency of haptic texture (or number of bumps) will lead to an increase in the perceived roughness of the texture.

Exp. 2-b: There may be a bimodal function of roughness with a frequency from either end of the scale being perceived as the roughest of the set.

Exp. 2-c: Textures compared from either end of the frequency range are more likely to be rated as not comparable on the same roughness scale than textures compared within the high range or within the low range.

Exp. 3: The effect of frequency of audio texture (or number of notes) will have an effect on the perceived roughness of the virtual texture.

Haptic Results (Experiment 1)

Effects of Frequency on Perceived Roughness

The frequency of the texture was shown to have a significant effect on perceived roughness. That is, there was a significant effect of frequency on the number of times a texture was judged as the roughest of a pair (F=9.73, p<0.01). The number of times each (frequency of) haptic texture was judged as roughest tended to increase as the frequency of the texture increased (see Figure 4).
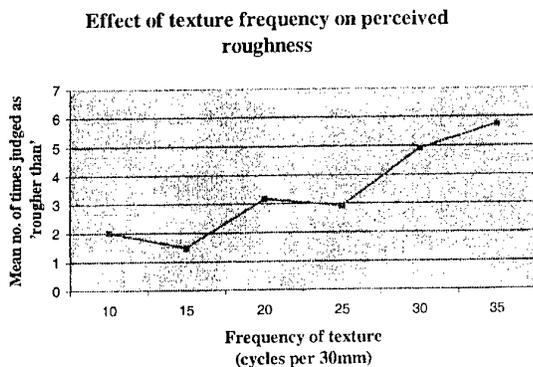
Figure 4: Effect of frequency on perceived roughness.

It is likely however that the range used in the experiment is only a sample from a more complex function. In fact, the graph shown may not be part of a simple monotonically increasing function at all. Instead it may be part of a quadratic function of perceived roughness as suggested by people such as Lederman *et al.* [6]. At the very least, it may be likely that there is more than one maximum roughness generated from the set of frequencies.

Two distinct notions of haptic virtual roughness?

Participant comments began to suggest that the lower frequency of 10 was considered very rough 'like corrugated material'. The higher frequencies of 30 and 35 however were also labeled as very rough but 'like sandpaper'. It is possible then that 2 frequencies from opposite ends of the scale can be perceived as equal in roughness magnitude but from different roughness scales.

Experiment 2 extended the range of textures (5-45 cycles) to evaluate whether the increasing frequency leading to increasing perceived roughness relationship still held beyond the range used in Experiment 1 and whether the bimodal peak roughness points emerged. This follow up study also evaluated our suggestion from Experiment 1 that comparing two textures from either end of the frequency range would increase the likelihood that they would be judged as different but also increase the likelihood that they would not be able to compare the textures on the same roughness scale. Final results from this evaluation will be presented at the workshop.

Identical Haptic Stimuli

Textures with equal frequency were judged as the same roughness on an average of 64% of the trials. It appeared that higher identical frequencies were more likely than lower identical frequencies to be successfully judged as the same. This could perhaps due to the interaction between probe size and texture-profile size - lower frequencies being more susceptible to differences in hand force and exploration speed. Further statistical analysis of exp.1 and exp.2 will investigate this hypothesis further.

Different Haptic Stimuli

A frequency separation of 5 cycles was not sufficient to significantly separate the perceived level of roughness for the haptic textures used. That is, textures separated by a frequency difference of 5 cycles were often judged as the same roughness. As frequency differences increased participants found it increasingly easy to decide whether the textures felt the same or different but increasingly difficult to decide which of the two was in fact the roughest. These results will be discussed in more detail at the workshop.

Auditory Roughness (Experiment 3)

The audio virtual roughness experiment is currently underway and the effects of frequency of notes on perceived roughness of the audio textures are being evaluated using the same experimental paradigm. The MIDI instrument being used is piano although this will be compared to other instruments in the future. Our main concern for the initial audio experiment was purely to explore the effects of frequency of an arbitrary sound or note on the perceived roughness of the auditory texture. Results from the auditory roughness experiment will also be presented at the workshop.

Future Work

The results of the haptic studies suggest that larger frequency differences lead to more easily distinguishable textures but also to difficulties in using the dimension of roughness in comparing textures. Large textures have also been found to throw users off of some textured areas [7]. The addition of audio information to such force feedback textures might ameliorate some of these restrictions.

We propose that the combined (multisensory) presentation of haptic and audio textural information will increase the range and/or resolution of textures available to the designer without disturbing interaction through force feedback devices. Results from the unimodal haptic and audio studies will be presented at the workshop. Our future multimodal (haptic – audio) experiment will also be discussed in more detail.

Acknowledgments

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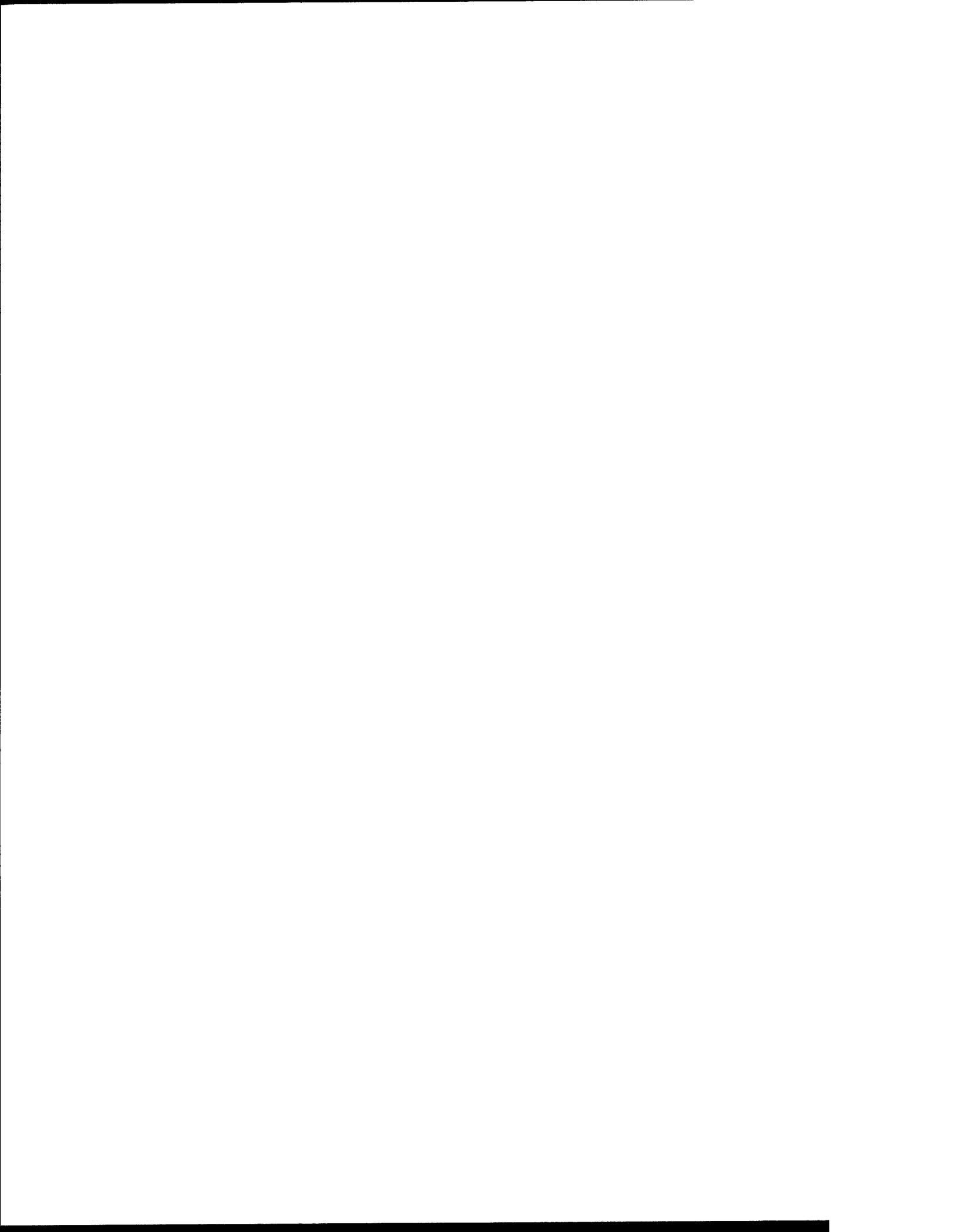
THE ROLE OF FRICTION AND THE RATE OF TANGENTIAL FORCE CHANGE IN THE SUBJECTIVE SCALING OF ROUGHNESS.

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Although friction was originally thought to be an important parameter in the subjective scaling of roughness [1], subsequent experiments by Lederman and Taylor [4] found no evidence to support this view and current opinion has ruled out friction as a significant determinant [2]. However, a recent study by Meftah et al [3] found a close correlation between the distance between rows of surface asperities and subjective roughness, again raising the question about whether friction co-varied with spatial period and roughness. The objective of the present study was to examine how normal and tangential forces at the fingertip were deployed in active tactile exploration of textured surfaces in order to determine the contribution of friction to the subjective magnitude estimations of roughness. In the first experiment, six volunteer subjects were asked to scale the roughness of 8 surfaces using a single stroke of the middle finger. The surfaces were 7.5 cm x 2.4-cm polymer strips embossed with truncated cones 1.8 mm high with a spatial period of 2.0 mm in the transverse direction and 1.5-8.5 mm in the longitudinal, scanning direction. The surfaces were mounted on a 6-axis force and torque sensor that measured the perpendicular, contact force, normal to the skin surface, and the tangential force along the axis of stroking. The results confirmed the findings of an earlier study that magnitude estimates of perceived roughness increase approximately linearly up to a longitudinal spatial period of 8.5 mm. Despite stroking speeds that ranged from 10 mm/s for the slowest subject to 157 mm/s for fastest subject, there was no discernable relation between the stroking speeds and the roughness estimates. The mean tangential forces varied from 0.42 to 1.28 N and the mean normal forces varied from 0.29 to 1.01 N. However, there were no correlations that were consistent for all subjects between perceived roughness and either the mean tangential or normal force alone for each spatial period. In contrast, the correlations between roughness estimates and mean friction (the ratio of the tangential to normal force) varied between 0.65 and 0.88 for the six subjects, and were all statistically significant (p<0.01). Examination of the trial-by-trial tangential force traces revealed oscillations whose amplitude increased with the longitudinal spatial period and the frequency was determined by a combination of the spatial period and the stroking velocity. These oscillations were even more conspicuous in the rate of change of the tangential force which was quantified as the root mean square (RMS) of the tangential force rate. The mean normalized RMS proved to be strongly correlated with subjective roughness averaging 0.88 for all subjects. In order to dissociate the fluctuations in tangential force from the mean kinetic friction, a second experiment was performed on 6 additional subjects who estimated the roughness of identical lubricated and unlubricated surfaces. Lubrication with liquid soap respectively reduced the mean kinetic friction, the RMS of the tangential force rate and also the subjective estimates of roughness. Taken together, the results suggest that in tactile exploration, the RMS of the tangential force rate may be an important determinant of subjective roughness and

a significant parameter in guiding tactile exploratioin. According to these results a physiological study of the sensitivity of glabrous skin mechnaoreceptors to the rate of change in tangential forces would seem warrented. Research supported by the Canadian Institutes for Health Research.

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Friction and curvature judgement

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Abstract

*Local shape is an important attribute that can
be sensed by exploratory movements of the
finger. Normally this involves a blend of tactile
and proprioceptive cues. A curved surface will
deform the pad of a single finger and so tactile
cues can indicate whether a surface is convex
or concave or whether it slopes one way or
another. When more subtle discriminations
must be made between different degrees of
curvature, scanning motions are made in
which the finger sweeps along the surface. In
this case the cue to curvature is the change in
position of the finger tip over time and here
proprioceptive input is important. We have
been examining how curvature judgements are
affected by the force reflected back from the
curved surface during scanning. Normally
when you run your finger over a surface, you
experience resistance to motion due to friction.
This resistance creates a force vector which
varies in direction with friction. But the vector
also varies in direction with the curvature of
the surface traversed by the finger. We used a
two-alternative forced-choice (2AFC) task in
an adaptive staircase in which subjects made
comparisons between various test curvatures
and a reference curvature in order to find the
point of subject equality (PSE) between the
two. Differences in friction between reference
and test stimuli were found to alter the PSE in
a consistent manner. In particular, we found
that the reference curvature was only closely
matched when no frictional disparity existed
between reference and test surface. Reference
surfaces that exerted high frictional forces
produced smaller curvatures as PSEs while
surfaces with low friction produced high
curvature matches. These results suggest that
forces experienced in palpating a surface may
be utilised in the comparison of curvature.*

1. Introduction.

Curvature is an important local shape
descriptor that may vary continuously across
the surface of an object. In terms of the
sensation of touch, curvature may be assessed
by either the cutaneous receptors of the
glabrous skin (finger pads or palm) of the hand
or through proprioception supported by several
types of receptors in the muscles of the hand,
or both. Evidence for the former type of
sensitivity to curvature has been provided by
LaMotte et al (1998); see also Bisley et al
(2000) who showed that slowly adapting type
1 mechanoreceptors in the monkey hand
respond to the curvature of a raised bump on
an otherwise flat surface. Psychophysical
experiments have also shown that human
subjects are very good at judging curvature
using only the finger pads (Goodwin et al,
1991; Goodwin & Wheat, 1992). Evidence for
the ability to perceive curvature through
proprioception has been studied using
psychophysical experiments on humans. Such
experiments involved curvature discrimination
based on active touch or passive deformation
of the whole hand (e.g. Vogels et al, 1999;
Pont et al, 1998). Surface curvature, it seems,
may be assessed equally well by both static
placement of the hand across the surface or by
active touch with the hand or fingers (Pont et
al, 1999). However, it has been argued
elsewhere that active touch is better than
passive touch in the discrimination of shape
and recognition of objects because the former
can yield continual pick-up of information
from the surface (Gibson, 1966). Differences
in the discrimination of curvature in different
parts of the hand were also studied by Pont et
al (1997) who found that the palmar side of the
hand is more adept at this task than the dorsal
side. Pont et al. attribute this to the
preponderance of cutaneous input from the
palm although the task clearly involves both
(cutaneous and proprioceptive) types of input.

A notable feature of the visual sense is that
of maintaining shape invariance or shape
constancy. That is, a shape may be encoded in
geometrical terms equally well regardless of
which visual cues are being used to depict it.
There is active debate in the vision community
whether this is the case with human vision and
we may ask whether such an ability is found in
active touch as well. So what physical factors
might influence the perception of shape from

visually unaided active touch? Imagine that a convex bump on a flat surface is being stroked by a single finger that does not provide cutaneous input. Both the horizontal, scanning and vertical velocity of the finger and the reactive force of the surface acting on the finger may be affected by the object impeding motion of the finger. These physical variables may be encoded by the mechanoreceptors to the muscles of the upper limb and therefore, if curvature can be encoded by through proprioception, then it may be through changes in these variables. Surfaces of real objects also exert an additional, frictional force on the finger in a direction opposite to the direction of motion. If the force applied through the finger is greater than the tangential force exerted by friction the finger starts to slide across the surface. In this case, dynamic frictional forces act on the finger to impede its motion. This resistive force depends on the normal force at the contact surface but is also a function of the coefficient of dynamic friction of the surface. It is therefore possible that the perception of surface curvature is influenced by the frictional properties of the surface.

We isolated proprioceptive cues to curvature by using the Phantom haptic interface. The Phantom is essentially a robot arm controlled by three motors and connected to a computer that can control the exertion of reactive forces to a single finger placed in a thimble. These forces can be used to simulate solid objects, friction and viscosity. The useful feature of using the Phantom is that sensory input is provided by active palpation without local tactile information and this in turn allowed us to focus on the contribution of proprioceptive cues.

2. Method.

2.1 Simulation of Solid Shape.

The Phantom is a haptic rendering system that uses 3D force feedback to generate the impression of 3D solid shape, viscosity, friction and surface texture. The haptic rendering process is similar to that in computer graphics (Salisbury et al. 1995; see also Ho et al, 1999). For instance in the rendering of solid shape the position of the cursor or stylus is tracked at a frequency of 1 kHz until an intersection with a virtual surface is detected. Once an intersection is detected various forces can be applied to the finger to give not only the impression of solidity but also of surface compliance, texture and surface friction. It should be noted that the perception of solid shape is generated only as a function of the

observers active movements of a single finger inserted into a thimble. If there is no movement (and therefore no exerted force) then no haptic feedback can be provided. This allowed us to isolate the proprioceptive sense that results from active movement.

As well as generating the impression of solid shape the Phantom can also be programmed to simulate static and dynamic friction (Salisbury et al. 1995). Friction is simulated by detecting the collision between the finger/stylus and an object in the scene and applying an appropriate tangential force to the finger. The tangential force serves to restore the finger to an initial position as the finger attempts to slide across the surface. Thus the finger sticks on the surface. If the tangential force required to restore the finger becomes greater than the normal force times the coefficient of static friction then sliding occurs. During sliding a tangential force (proportional to the coefficient of dynamic friction) is applied to the finger in the direction opposite to the direction of motion, which provides the sensation of dynamic friction. In this manner, the surface is made to feel either slippery like ice (i.e. low friction) and feels sticky like rubber (i.e. high friction).

2.2 Stimulus definition.

The curvature (or more correctly the normal curvature) of a surface at a point is the curvature of a section of the surface in a given direction and perpendicular to the tangent plane at that point. On a sphere the normal curvature is the same in all directions. On a cylindrical surface, which is what we shall be using here, the normal curvature is zero along the elongated axis and maximal in a direction perpendicular to this axis. Cross sections of a right circular cylinder are circular in form and the maximal normal curvature of the cylinder is therefore given by the curvature of a circular section which is inversely dependent on the radius.

The stimulus in this experiment was a virtual cylinder that the subject was allowed to stroke twice. This virtual surface was generated by the Phantom force-feedback system. This was implemented using the application programming interface GHOST. The Phantom was programmed to generate cylinders with variable cross-section and it was the radius of these cross sections that served as the independent variable in these experiments. The cylindrical surface was defined within a virtual space measuring 5cmx20cmx20cm (see figure) with the X axis set as the horizontal axis perpendicular to the desk at which the

subject sat. The Y axis was the gravitational vertical axis and the Z (depth) axis defined the forward-backward direction with respect to the subject. The principal axis of the cylindrical segment was oriented along the X axis and the subject stroked the segment from the top in the forward-backward (Z) direction. Movement in the X direction was restricted so that strokes across the surface followed a similar trajectory each time.

Virtual button
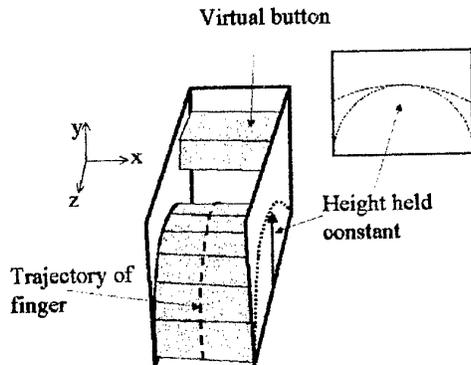
Figure 1: Schematic representation of object surfaces created by haptic rendering.

2.3 Task.

The aim of this experiment was to determine how well a subject could discriminate between the curvature of two circular strips and to test whether this ability is affected by friction. The only curvature information was through proprioceptive sources arising from the Phantom. We measured the point of subjective equality (PSE) for two curvatures (0.013/cm and 0.008/cm). The curvature was manipulated by varying the radius of the cross sections of a circular cylinder (i.e. 75mm and 125mm) however for a constant position of the centre of curvature this manipulation of radius would have resulted in an additional height cue in the y direction (see Figure 1). This was controlled by allowing the centre of curvature to move up or down in the Y direction so that the maximal height of the cylinder remained constant.

The subject was asked to determine which of two (sequentially presented) curvatures was greater. One of the two stimuli was the constant reference (radius = 75mm or 125mm) and the other varied according to a 1-up/1-down adaptive staircase. After having stroked both strips the subject had to respond using a computer keyboard which had the greater curvature. Using this method the PSE was

estimated as the average of six reversals. In order to bring the test stimulus quickly to the PSE each staircase measurement was preceded by 4 'reducing reversals' in which the increment or decrement of the test was varied as a function of the reducing reversal number.

The influence of dynamic friction was tested by introducing disparities in simulated friction coefficient between the reference and test stimuli. Two friction coefficients were used ($\mu=0.2$ and $\mu=0.8$) for both the reference and test stimuli. The $\mu=0.2$ stimuli felt slippery, rather like moving ice on ice. The $\mu=0.8$ stimuli felt rubbery. In both cases the friction coefficients were low enough that smooth and uninterrupted movement of the finger across the strip was still possible.

2.4 Design.

The two sizes of reference stimulus and the two friction values for both test and reference resulted in 8 distinct conditions in a balanced design. That is, each condition consisted of a unique value of reference radius (either 75mm or 125mm), reference friction (either 0.2 or 0.8) and test friction (either 0.2 or 0.8). Mean PSEs were collected for each of these 8 conditions in random order and repeated 5 times for each subject.

2.5 Subjects.

Four subjects participated in this experiment and were rewarded with gift vouchers. All subjects were spent several minutes training on the task prior to the actual data collection. Subjects' view of their hands was occluded during the experiment and they were asked to close their eyes.
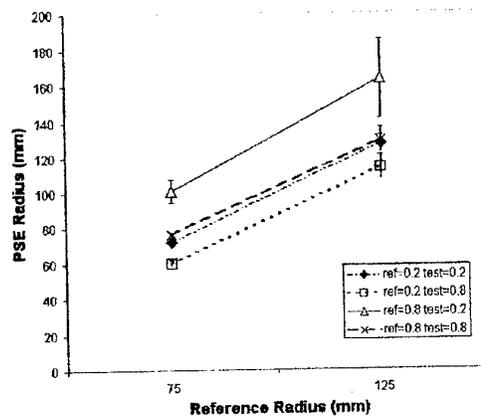
Figure 2: Effects of reference radius and surface friction on point of subjective equality (PSE)

3. Results.

The dependent measure for this experiment was the PSE radius which is defined as the radius of the test surface that subjects equate with the magnitude of a given reference radius regardless of frictional differences. We report results mainly in terms of the radius of curvature because it involves more intuitive and manageable dimensions of size in terms of millimetres rather fractional curvature quantities although it should be remembered that a smaller radius of curvature produces a larger surface curvature. Figure 2 shows the PSE radius averaged across all 4 subjects and plotted as a function of the reference radius. The four lines correspond to the four conditions used. The reference radius was matched closely only when the friction coefficients for test and reference stimuli was the same (i.e. when $\mu_r = \mu_t$). When there were disparities between the test and reference stimulus friction systematic errors in mean PSE were observed. For example, when the reference friction coefficient was greater than the test stimulus friction (i.e. when $\mu_r > \mu_t$) the mean PSE radius obtained was at least 25% higher than the actual reference radius which meant an underestimation of the radius of curvature of the reference stimulus (that is the reference appeared more curved than it really was). For trials in which the reference surface friction was less than the test surface friction (i.e. when $\mu_r < \mu_t$) the mean PSE radius was found to be at least 11% lower than that of the reference stimulus. These results mean that the radius of curvature of the reference stimulus was underestimated for high friction surfaces and overestimated for low friction surfaces.

An analysis of variance was performed on the data with three repeated measures (reference friction μ_r, test friction μ_t and reference radius) and mean PSE radius as dependent variable. Assuming an $\alpha=0.05$ as our level of significance we found a significant main effect of reference friction [$F_{1,3} = 11.42$, $p<0.05$], an almost significant effect of test stimulus friction [$F_{1,3} = 11.42$, $p=0.09$], and a highly significant main effect of radius. None of the interactions (i.e. between μ_r and radius) was significant.

In terms of repeatability, we use the standard deviation of settings to assess differences in relative difficulty. Standard deviations were calculated for the five repeated settings made by subjects for each of the 8 data points. The mean standard deviations (averaged across all subjects) for the 75mm and 125mm circular segments were 11mm and 21mm respectively. A paired comparison students t-test showed that this difference in means was significant. The increased variance of settings for the 125mm radius strip reflects greater difficulty in assessing a shallower curvature (larger radius of curvature).

4. Conclusions.

We have described an experiment in which subjects made curvature comparisons between sequentially presented curved strips, simulated using the Phantom haptic interface. The results show clearly that simulated curved strips can be accurately discriminated using kinesthetic information derived from the hand joints as the finger is deflected by the surface during stroking. Our results also highlight the importance of friction, and consequently of reactive forces, on the curvature discrimination process. We found that the radius of strips with a higher frictional coefficient than the comparison stimulus was overestimated. The radius of strips with a lower frictional coefficient than the reference was underestimated. In terms of curvature, this means that the curvature of rough or high friction surfaces is underestimated relative to low friction surfaces and our results show that the converse of this is also true. When the friction coefficients of the reference and test stimuli were the same subjects settings of the two radii, and therefore curvatures, were a close match. It remains for us to explain exactly why disparities in friction cause under- and over-estimates in curvature in these experiments and we are investigating three potential sources:

1) The subjects use tangential forces to encode curvature and tangential forces arising from friction disrupt this encoding.
2) It is not force but change in velocity that is used to encode curvature. The frictional differences disrupt direct velocity comparisons.
3) The result is an artifact of the process of generating virtual shapes and virtual frictional forces.

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Spatial Factors in Vibrotactile Pattern Perception

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Abstract

The spatial acuity of the skin for pressure stimuli has been explored extensively, but there have been few attempts to study spatial resolution for vibratory stimuli of the type used in tactile aids for sensory disability or to augment communication. Because vibrotactile spatial acuity has never been empirically determined at such sites, pattern perception with these devices might be poorer than it could be if the stimulus parameters that optimize localization were employed. Vibrotactile localization was measured on forearm and abdominal sites used by wearable tactile communication aids. Surprisingly, stimulus frequency did not affect localization on the arm, tested on 8 Os for a given spatial arrangement; both on the arm and trunk (tested with 8 Os), fewer than half of the sites were uniquely identified. Because tactile aids should be usable throughout a person's life span, especially in the later years, older persons will also be tested in these studies of the spatial aspects of vibrotactile pattern perception.

1. Introduction

Tactile devices to augment communication are becoming more common in everyday life, especially to serve as prostheses for sensory disability or. Such systems include speechreading aids used by deaf persons (e.g., the Tactaid, worn on the forearm or chest), reading machines for blind persons (the Optacon, used on the fingertip), spatial orientation systems used by pilots or astronauts (the Tactile Situation Awareness System, on the trunk of the body), and even vibrating pagers and cell phones. In every case, vibrotactile spatial acuity has never been empirically determined at the application site,

so pattern perception might be poorer than it could be if the parameters that might optimize localization were known. We are currently exploring localization ability and vibrotactile spatial acuity at a number of these. Because it is likely that stimulus parameters such as vibration frequency might affect localization at a site, these are also being varied. The two sites we have examined initially are the trunk of the body and the forearm. In this paper we will describe localization ability and information transfer on these sites. Because tactile aids should be usable throughout a person's life span, older persons are also being tested in these studies of spatial vibrotactile pattern perception. The long-term objective of this research program is to understand better both the sensory and perceptual processes that underlie rapid and accurate performance with cutaneous communication systems.

1.1. History

Spatial acuity has been used as a measure of tactile sensitivity for over 150 years. Weber's classic 1826 work [62] describes attempts to measure tactile acuity on a number of body sites. The two primary methods used then (and now- e.g., [63]) are to measure the minimal separation required to discriminate one versus two points touching the skin, the 2-point threshold, and error of localization, which is the accuracy with which the location of a touch can be identified. Over the years, it has become clear that methodology plays a large role in determining the threshold levels obtained [6], [18], [40]. Johnson [34] and Stevens [53, 54] describe improvements in the methodology and the devices used for testing that reduce subjective biases and more appropriately measure the minimum distance that can be perceived between two durative points touching the skin. Nevertheless, serious

problems remain. Tawney [55] and, then one hundred years later, Johnson [35], argued that the two-point threshold cannot measure tactile spatial resolution because spurious cues such as intensitive differences are inherent in the presentation of single versus paired points. Even a pin-prick has a spatial quality, and produces a sensation of tactile "extensity" ([55] p. 592). The traditionally-obtained thresholds therefore may only represent "the categorical perception of a distance at which separation between two points is no longer ambiguous" [64].

The history of the study of tactile acuity, rarely has included the minimum separation on the skin required to resolve vibratory stimuli, perhaps because it is so difficult. Kirman [37] elaborated on a number of demonstrations of the apparent inability to resolve simultaneous vibrotactile stimuli, as did Craig [16]. Yet, the simple question - "How close together can we place vibrating tactors before their loci become indistinguishable?" - is still often raised by designers of wearable multi-tactor arrays. Typically the two-point limens for touch are cited to support a particular spatial design for vibrotactile arrays. Yet, one must assume that vibratory stimulation will extend well beyond the limits imposed by contactor boundaries. Analyses of the waves
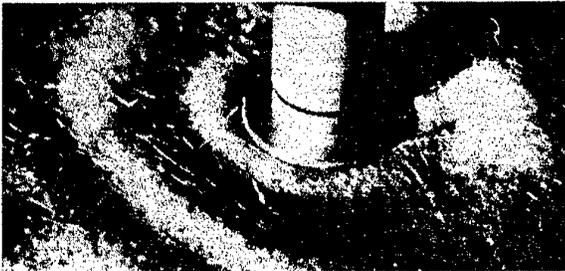
Figure 1. Mechanical wave propagation on the skin of the dorsal thigh produced by a 68 Hz vibration (From Franke [21]).

propagated on and in the skin from vibratory stimuli like those shown in Figure 1 by Franke [21] and Keidel [36] suggest a number of parameters that can influence the skin's resolution for vibratory stimuli. A static surround may damp the spread of surface waves [26], but not those passing through deeper tissues, where many of the cutaneous receptors lie, as shown (for hairy skin) in Figure 2. The velocity of traveling waves in the human skin not only depends on the viscoelastic
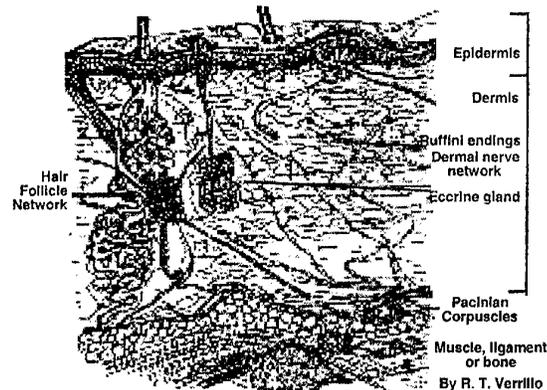
Figure 2. Cross-section of human hairy skin. (From Greenspan & Bolanowski [32]).

properties of the skin itself, but also on factors as varied as vibration frequency, skin temperature, and whether underlying tissue is bone, fat, muscle, or a combination.

Clues to the relevant variables in any study of vibrotactile spatial acuity can be found in studies in which two (or more) stimuli were used to examine other aspects of tactile processing. Profound interactions are revealed among stimuli, particularly when presented close together in space and in time [37]. For example, Békésy [2, 3] described increases *and* decreases in apparent location and perceived magnitude of the stimuli when two vibrating points are brought close together spatially and temporally (within cm and ms). Geldard, in his studies of sensory saltation [24, 25] demonstrated a number of ways in which the apparent locations of tactile, visual, and auditory stimuli shift with larger temporal disparities. Similarly, Gilson [29], Sherrick [51], and others have examined the "masking" interactions that occur when two vibratory stimuli are presented close together in space and/or time, finding that the closer the two are to one another (on either dimension), the more the sensation magnitude of the test stimulus will be reduced. Furthermore, in studies of tactile masking, where the accuracy of identification of complex two-dimensional patterns is reduced in the presence of a masking stimulus [12, 14], error analysis shows subtle spatial interactions between pattern and mask [11, 15]. Similarly, Craig [17] demonstrated that the ability to localize patterns on an array was influenced by the presence of preceding stimuli, especially when test and target were at two different locations. Even physiological data indicate varying degrees of interaction between stimulated loci [23, 31]. These findings of simple and complex vibrotactile spatial effects warrant further exploration of the bases of the interactions that could affect the encoding of information from tactile communication aids and devices.

There are only a few studies of tactile resolution in

which the ability to localize vibrotactile stimuli has been specifically examined (notably, [58]). In attempting to determine the appropriate spacing for tactors in the Tactile Vision Substitution System, Eskildsen [19], explored simultaneous and successive two-point thresholds on the lateral back near the scapula for 2 sec 60 pps stimuli, finding that threshold could be as small as 11 mm for pairs of 1 mm contactors (Weinstein's [63] static two-point thresholds were c. 4 cm). Rogers [49] examined spatial resolution on the fingertip, with two constantly-vibrating tactors. For frequencies of 10 and 250 Hz, resolution was a function of separation with poorest performance at 2 mm. Sherrick, Cholewiak, and Collins [52] used carefully-controlled 25 or 250 Hz stimuli to appeal to high- and low-frequency sensitive cutaneous channels. Observers indicated the location of a burst of vibration on the hypothenar eminence of the palm (the edge opposite the thumb). Accuracy was generally above 75%, with low-frequency stimuli only slightly better localized. The absence of parametric vibrotactile spatial acuity data needs to be addressed directly, in order for tactile communication systems to be used efficiently.

1.2. Pattern perception & spatial localization

The history of device design illustrates that the resolution of displays has rarely been determined empirically. Rather, designers have resorted to the data published in Weinstein's oft-cited 1968 paper that describes error of localization and 2-point threshold obtained over many body site. As an example, Bliss [4] carefully analyzed the spatial resolution of cameras used to record text for direct-translation aids for blind persons, relating the resolution of the device to the spatial frequency bandwidth of the images to be processed. However, to determine the resolution of the vibrotactile *output* device, he used Weinstein's static two-point data as a measure of the skin's acuity. As a guide to the development of *vibro*tactile patterns and devices, these measures, obtained with static patterns, are being inappropriately generalized to vibratory stimuli. The relationship between two-point touch thresholds and performance on durative patterns such as Braille cells seems more intuitive. Indeed, Stevens [54] argues that the reduction in static tactile acuity with age they measured has serious consequences for blind persons trying to read Braille characters. It is likely, however, that the active movement of the fingers over the cells in normal Braille reading adds a level of richness to the tactile pattern that may compensate for the inherent mismatch between static stimulus and aging receptive systems. In contrast, vibrotactile arrays in devices like the Tactaid, Optacon, TVSS, or TSAS, described earlier, cannot be actively explored. These have tactor arrays designed for passive reception. In none of these arrays has there been a

quantitative measure of their ability to accurately present vibrotactile patterns that have spatial characteristics matching those of the application site.

The accuracy with which persons can process tactile patterns, given appropriate temporal factors, ultimately comes down to an interplay between the spatial acuity of the skin and the spatial resolution of the patterns and display. Some have argued that the poorer performance often seen with tactile patterns is a natural consequence of the inferior acuity of the skin, at least in contrast to the visual system [41, 42]. Recent tactile data have shown differences in pattern identification performance between old and younger subjects that appear to be directly related to poorer spatial resolution in the older group [9, 10].

1.3. Aging & spatial localization

We will also be examining vibrotactile pattern processing in elderly persons to compare their performance against that from the younger population. This exploration into aging is warranted for several reasons. Hearing acuity decreases rapidly after the age of 60 irrespective of specific otological disease [20], while 88% of visually-disabled persons are over the age of 60 [28]. Consequently, understanding the capabilities of the sense of touch in the older individual has great importance, since it may often be the only alternative system available to supplement remaining sensibility. Furthermore the study of tactile pattern processing in this group, because of the known changes in the peripheral nervous system, should help us understand the mechanisms involved in tactile perception, and show how these findings might be incorporated into better devices for sensory substitution or augmentation.

Basic research on processing of tactile stimuli has demonstrated significant changes with age revealed when a single touch or a burst of vibration is presented to the skin [53, 59, 60]. Typically these studies have been concerned with measuring tactile or vibrotactile thresholds [22, 46, 80]. In most cases there is a decline in the capacity [30]: thresholds increase, or discriminative capabilities are poorer, in older individuals. A few notable studies have found similar declines in performance when the effects of aging are examined in complex measures of tactile pattern processing, such as haptic or form exploration [1, 13, 38], spatial acuity [53]), or temporal processing [57]. The underlying cause of the progressive loss has usually been attributed to physiological changes in the skin itself [53, 59] or neurological factors [39, 43, 61]. The functional decline in tactile perceptual skills also parallels age-related anatomical and morphological changes in the skin and its receptors. In aging skin, the size, shape, and number of

cells in the upper layers become quite variable and glands often atrophy or become inactive [44]. Dramatic age-related alterations in some mechanical properties of the skin such as compliance, surprisingly, do not appear to be tied to reductions in tactile sensitivity [65]. Changes with aging in the receptors themselves have also been fairly well documented. In general, while the number decreases, structural complexity increases. For example, there are one-third as many Meissner corpuscles in some body sites in 70-year-old individuals as in 20-year-old persons [50]. In addition, there are fewer Pacinian corpuscles, and those that remain undergo dramatic distortions in shape and size, while Merkel's disks and free nerve endings undergo less-obvious changes with age [7]. Because these structures and others have been related to different aspects of tactile sensitivity [5, 33], a correlation would be expected between these changes and variations in tactile acuity. Although tactile pattern perception requires a combination of both spatial and temporal processing abilities, we are primarily studying spatial processing abilities to provide a measure of the change in this sensory capacity in older subjects relative to a younger population.

But how well does the skin appreciate spatial stimuli? We are probably familiar with illustrations like the next one – showing the considerable variation in sensitivity over the surface of the body for simple touches, or pressure stimuli (from Weinstein [63]).
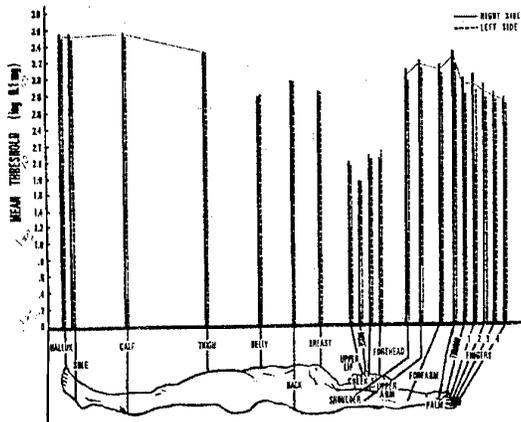
Figure 3. Variation in pressure threshold over the body (From Weinstein [63]).

Similar pictures have emerged when pairs of such points were used, but, as discussed earlier, there is are
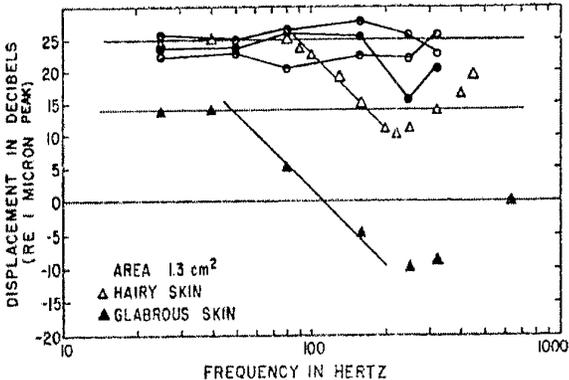
Nevertheless, there is little question that tactile sensitivity varies considerably over the body's surface, whether measured by one or two touches. But what about vibration? As we saw earlier, the patterns of activity resulting from vibration on and in the skin can be quite complex and widespread, as shown in Figure 1. Such a pattern can also result from more natural stimuli such as rubbing or stroking of the skin, although stretch components are also introduced.

So what happens when we look at the skin's sensitivity to vibration? Observers judged stimuli that

Figure 4. Vibrotactile thresholds on hairy and glabrous skin. Circles represent 3 sites on the back. (After Verrillo [59]).

varied in vibratory frequency over the normal range of sensitivity of the skin – from about 20 to about 300 Hz, of varying intensity. They indicated when they just felt the stimulus. When we compare the results on the palm of the hand versus the arm (smooth versus hairy skin), we have seen impressive differences (Figure 4). Hairy skin is less-sensitive over the whole range. A few additional data points are shown in the graph from a single observer in my lab. These are thresholds taken on the costovertebral angle of the back. Depending on where one places the stimulator, within a range of a few cm, a high-frequency dip can be recorded – or not! These data suggest the presence of different underlying physiological systems – receptor channels that differ across body sites, within body sites, and over the age span.

Physiological data certainly support these notions – 40 years ago, Sato, von Bekesy, and others indicated that at least one component of these curves, the high-frequency dip – reflected the operation of one known receptor, the Pacinian Corpuscle – which is found to be sparsely distributed in hairy skin (Figure 5). Anatomical

Figure 5. Properties of 2 deeper-lying glabrous skin receptor structures (after Vallbo [56]).

exploration has shown even more structures that could be involved in tactile sensitivity, and, more recently, these
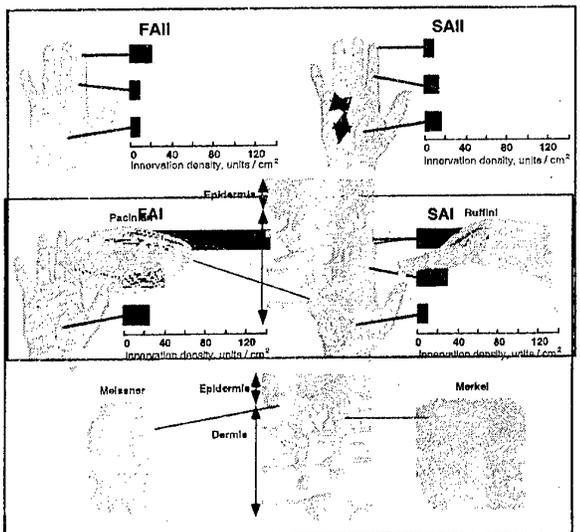
have been related to specific perceptual experiences when the glabrous skin of the hand was stimulated [48].

Figure 6. Properties of 2 superficial glabrous skin receptor structures (after Vallbo [56]).

Other research has shown that in the human hand, the superficial receptor structures (Figure 6) have extremely high densities in the fingertip skin, much greater than that of the deeper structures. Nevertheless, recall that the most dramatic variations in sensitivity were in the high frequency ranges where the Pacinian determines threshold. Remarkably, given the extraordinary sensitivity of this receptor system (less than 1μ at 250 Hz), it is the deepest-lying of all of the structures. When we try to decide which of these subserves spatial pattern processing, single unit data suggest significant differences in their ability to resolve spatial detail when presented with patterns even as simple as Braille cells.

2. Spatial localization on linear arrays

How does vibratory *spatial* sensitivity vary over the surface of the body? There are no data in the literature like those we saw for the two-point thresholds. We have collected some data that address the accuracy of resolution of spatial vibrotactile stimuli on two body sites: the forearm and the trunk of the body. In the first case, eight subjects were asked to identify 7 locations of 150-msec bursts of 100 Hz or 250 Hz vibration on a linear array, equated in perceived intensity. Stimulus frequency was varied in order to appeal to different underlying receptor systems, since they also have been reported to have different spatial sensitivities. Examining the distributions of correct responses and errors to each site in the first session of 5 blocks of 70 identification trials, (in Figure 7), we see that when sites are 25 mm apart, accuracy is
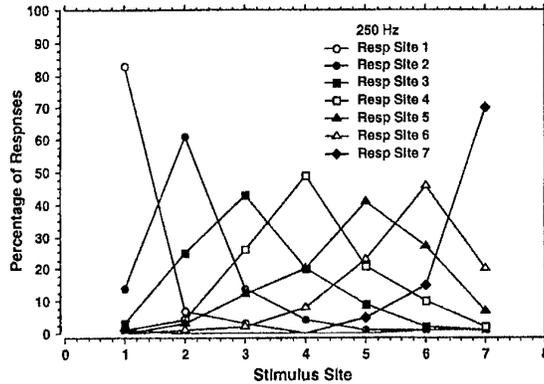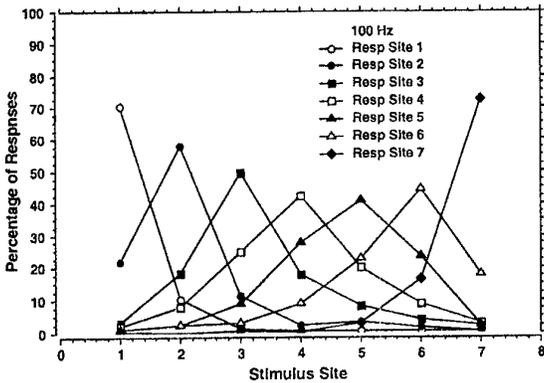
Figure 7. Localization of sites on a 7-tactor linear array on the forearm; 25 mm separation, 100 Hz (upper graph) and 250 Hz (lower).

quite poor for this task, particularly in the mid-range of loci. The higher accuracy at the ends of the range has a number of sources we could discuss (specifically related to "anchor points" [6]). Remarkably there is no meaningful difference between the functions obtained for the two frequencies.

What would happen if we expanded the separation and used fewer tactors (since the forearm has a fixed length)? The next sets of data were taken from one of our studies in which the 100-Hz stimuli were presented at 4 sites separated by 50 mm to younger (college-age) and
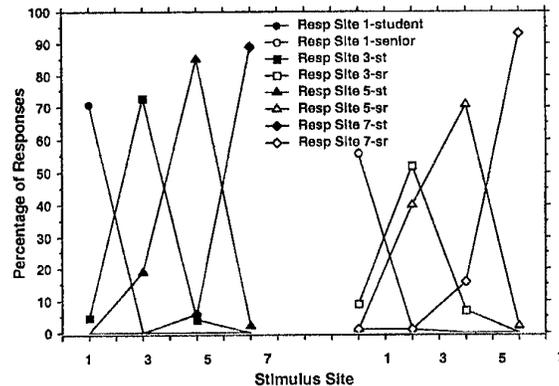
Figure 8. Localization of sites on a 4-tactor linear array on the forearm by students (left) and seniors (right): 50 mm separation, 100 Hz.

older (60+ yrs) subjects. The results plotted as a confusion matrix in Figure 8, indicate that students were more precise, making fewer errors particularly for sites more than 50 mm away from the target. Although performance was quite good overall, the students were particularly accurate in the interior sites. These studies are continuing, and will be expanded to other body sites.

Finally, we examined the accuracy with which spatial vibrotactile stimuli are resolved on the trunk of the body. In this case, seven subjects were asked to identify the locations of 150-msec bursts of 250-Hz vibration presented on a belt of 12 vibrators spaced at equal intervals around the lower abdomen, at a level just above the umbilicus. Here, trained observers responded on a 3-dimensional cylindrical keyboard, as shown in Figure 9. They were instructed to encode the stimuli (and key positions) as though they represented hours on the clock face, with 12 o'clock located at the navel and 6 o'clock at the spine. The data were collapsed over two sessions of 300 trials, and responses plotted as before, as a function of the stimulus location, in Figure 10. Again, average performance was very good, but note that optimal identification occurred at what might be defined as "anchor points" at the front (12 o'clock) and rear (6 o'clock) of the trunk – the navel and spine.

Finally, despite the apparent accuracy of identification

Figure 9. Participant working with the 12-site 3-dimensional tactor keyboard.

identification, even for 250-Hz stimuli, it is helpful to examine the amount of information transferred in each case. In fact, analyses of the data represented in Figure 7 indicate that for 250 Hz stimuli, overall correct identification was only at the 56% level, with only
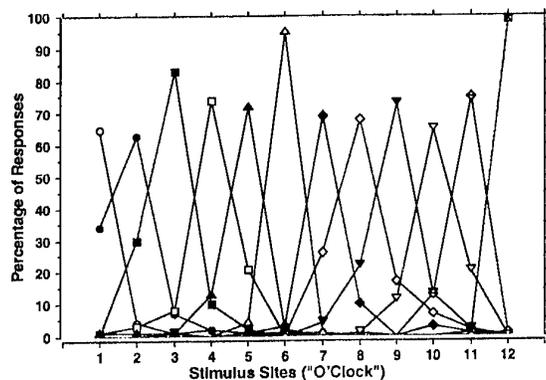
Figure 10. Correct responses and errors by response sites as a function of locus on a 12-tactor belt: 250 Hz.

1.11 bits of information transmitted (representing 2.15 tokens) out of the 2.807 bits potentially available in the 7 stimulus tokens. Similarly, when the stimulus frequency was 100 Hz, overall percent correct was 54%, and only 1.01 bits of information were transmitted (representing 2.01 tokens). When 12 tactors were tested (Figure 10), overall percent correct was 75%, and 2.52 bits of information were transmitted out of a potential 3.58 available in the stimuli, encoding 5.74 of the 12 tokens.

Further studies are being conducted to better explore the stimulus parameters that might influence vibrotactile localization., including, in particular, a parametric examination of stimulus frequency and tactor separation. Our intention is to optimize vibrotactile localization at each site so as to determine the design parameters for arrays used in cutaneous communication systems.

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Menu Interactions in a Desktop Haptic Environment

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Abstract

Since the importance of haptic interaction in virtual environments grows, the relevance of good haptic UI widgets becomes more important too. This papers shortly discusses a framework for building 3D widgets in general and more specific 3D menus. The usage of these menus was assessed in a formal user test. The surplus value of using haptic feedback in 3D widgets and the difference in performance of clicking versus pushing were evaluated. This experiment and its results are explained in this paper.

1. Introduction and motivation of the research

Haptic interaction is becoming more important in 3D environments. Since the user typically holds a haptic device, such as the PHANToM [14], in the dominant hand, it is not convenient to use a mouse for menu interaction. Although a minority of the users are capable of manipulating a mouse with the non-dominant hand, it is likely that another 3D input device, such as a space mouse is used for camera navigation. Such a two-handed input metaphor is common in many 3D applications, such as 3D modelling [3, 15]. Furthermore, a menu paradigm should be developed that also supports users who are not bimanual. Therefore, we chose to use the haptic device to interact with a menu. This opens the possibility for placing a 3D menu inside the virtual world.

Although menu interaction has been thoroughly explored in (traditional) VR research [2], the implications and most effective use of 3D menus in a haptic context are not yet known. Different approaches to incorporate menus in a virtual environment can be identified. In JDCAD [6, 8] Spherical and ring menus are used, while pie menus are utilized in HoloSketch [4]. The latter approach can also be found in Alias|Wavefront's Maya [7], where a radial menu, called the Hotbox is placed around the user's mouse cursor. This is, however, a 2D solution. Lindeman et al. [9] used hand-held windows to provide a passive feedback for manipulating 2D widgets in a 3D world with the user's finger.

Active force feedback, using a PHANToM device, has been applied in various 2D desktops. Force feedback has been incorporated in the X desktop by Miller et al. [10, 11] while Oakley et al. enhanced the Microsoft Windows desktop [12]. Some research into 3D haptic user interfaces has has also been conducted: Anderson et al. [1] have created a interface builder for graphical and haptic user interfaces (GHUIs) for FLIGHT (FLIGHT is now called e-Touch [5]) in which several interfacing components are present. Since, to our knowledge, no research exists in which the usefulness of haptic menus in investigated, we developed a 3D haptic menu and performed a formal user experiment in order to assess the effectiveness of our solution.

This paper presents a technical overview of the menus that we provide in our haptic environments and discusses the user experiment.

2. Haptic interfacing elements

All 3D interfacing elements, such as menus, toolbars and dialogs, have to provide a common functionality. For instance, they have to support the haptic device and should allow the developer to place descriptive texts on them. We call these objects "haptic UI elements".

2.1. Placement

Another problem with 3D UI elements is the fact that they sometimes obscure the element of interest: a dialog, which asks to confirm the deletion of an object, should not be placed in front of this object. Likewise, if an object
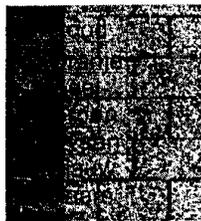
Figure 1. Semitransparent menu

Figure 2. Opaque menu

were to obscure a haptic UI element, the haptic UI element would be unusable. Therefore, a haptic UI element should be placed rather in the foreground of the virtual environment than in the background. However, it must not hinder the user in interacting with the virtual objects. Hence, we have developed haptic UI elements that can arbitrarily be positioned in the virtual environment, but are typically placed in the foreground. The haptic UI elements are semitransparent, thus not obscuring the virtual objects [16]. When the virtual pointer approaches the haptic UI element, it fades in to become opaque. As the pointer moves away, the haptic UI element fades out again. Figures 1 and 2 show a menu in its semitransparent and opaque form.

2.2. Implementation

In order to use haptic UI elements in a virtual environment, we have written an abstract C++ class, which supports the above-mentioned functionalities for 3D UI interaction. When the first haptic UI element is instantiated, it makes a series of OpenGL display lists in which the alphabet is stored. All haptic UI elements can then use these display lists to display their textual contents. Likewise, the abstract class is responsible for placing a haptic constraint in the virtual environment. This haptic constraint represents the haptic UI element and calculates where the virtual pointer, representing the haptic device's position and orientation, is located with respect to the haptic UI element.

Currently, a class is derived from the abstract class, which implements a 3D menu: a 2D menu object, which can be arbitrary positioned in 3D space. Each menu item in this 3D menu is indicated by a text, e.g. "Exit". Optionally, a descriptive icon can be depicted in front of the menu item. In order to make the menu recognizable for the user, it employs the Windows colour scheme. Two different interaction methods are provided by the menus: "point and click" and pushing against the menu item. The first method makes use of the standard method for accessing 3D menu's, although a 3D pointer is used in this case, while the latter is based on real life interaction with buttons and switches.

3. User experiment

The usefulness of the menu interactions was assessed in a formal user experiment. We wanted to assess if the "point and click" metaphor is better than the push metaphor and if force feedback improves menu selection. A scene representing a room, containing a cube and menu, was shown to the users. The menu items indicated 7 colours; the name of each colour was preceded by a square in the same colour, so that the user could easily match the colour of the cube with a menu item. We choose to add this square instead of depicting the text in the colour it describes, because not all colours are equally readable. Figure 3 depicts the experimental scene; since our test persons were native Dutch speakers, the colours are indicated in Dutch. The test subjects had to indicate the current colour of the cube, which was randomly chosen, in the menu. The performance of the users when using haptic feedback, provided by a PHANToM device, was compared with a condition where no haptic feedback was present. In each condition, a test person was presented with 5 practice trials and 15 measured trials.
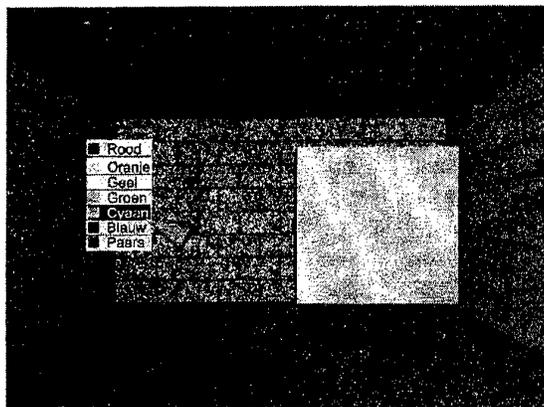
Figure 3. Experimental scene

Twenty-four test persons, twenty males and four females with an average age of 30, participated in a counterbalanced

repeated measures design. In order to avoid negative transfer effects, the test persons where evenly distributed into two groups according to age, sex and experience with computers. One group of 12 test subjects was presented with the "point and click" interaction (click condition), while the other group had to push against the menu items (push condition).

The dependent variables we measured were: elapsed time (in ms), needed to select a menu item, the distance covered by the virtual pointer (in mm) and the number of erroneous selections. The elapsed time was further divided in the approach time, needed to come in the vicinity of the menu and the homing time, needed to select the item within the menu. A trial was considered complete, when the correct menu item was selected. After completing the test in each particular condition the subjects were asked to answer a series of questions. After completing the second condition, a comparing questionnaire was presented. This questionnaire presented the test persons some questions about their subjective feeling of performance and frustration.

4. Results

The results for both conditions were analysed using two-way ANOVA over all measurements (click and push conditions). This analysis reveals that the use of force feedback only significantly reduces the number of errors that were made by the test subjects. When no force was applied, the results were better for all other dependent variables, though not significantly. Table 1 summarizes these results.

Table 1. Statistical analysis of all results

	Without force	With force	P-value
Avg. approach time	2053.7	2112.1	.86
Avg. homing time	3167.4	4076.5	.14
Avg. total time	5221.1	6188.6	.11
Avg. distance	60.7	74.8	.11
Total errors	150	68	< .001

Furthermore, the trade-off between precision and speed is confirmed by our results, since a negative correlation between the approach and homing time can be found (see table 2).

However if the two selection mechanisms are compared, a significant difference can be found in favour of the clicking with the stylus switch (see table 3). At first sight, this

Table 2. Correlations

	Avg. approach time	Avg. homing time	Avg. distance
Avg. approach time	1.0		
Avg. homing time	-0.27	1.0	
Avg. distance	0.27	0.76	1.0
Total errors	0.06	0.40	0.35

seems to be contra intuitive: in real-life, selecting a button, e.g. a button on a microwave oven, is done by pushing against the button, not by clicking with another device. However, in real-life people push against buttons with their fingers, not with a pen, while people are used to the "point and click" interaction when working with a computer. As an alternative, we could have chosen to use the PHANToM thimbal, because it allows the user to push against objects with the index finger. However, most of our applications require 6DOF input, which can only be provided with the encoder stylus. Furthermore, most 3D interaction benefits from having a switch on the encoder stylus (e.g. to select objects in the virtual world).

Table 3. Comparing the click with the push condition

	Click	Push	P-value
Avg. approach time	1387.6	2778.2	< .001
Avg. homing time	1894.9	5348.9	< .001
Avg. total time	3282.5	8127.1	< .001
Avg. distance	42.7	92.8	< .001
Total errors	79	137	< .001

Within the click condition, no significant difference was found in the time needed to complete the condition with haptic feedback and the condition without haptic feedback. The approach time was slightly better when no haptic feedback was present. However, this was compensated by the better homing time in the condition with haptic feedback,

leading to better over all performance in the condition with haptic feedback. Video recordings, from the user test, suggest that this difference is caused by a slight hesitation when approaching the haptic menu because the test subjects searched the haptic plane, whereas in the condition without haptic feedback, the test subjects just located the pointer in the vicinity of the menu. However, as soon as the virtual pointer hit the haptic plane, the test subjects could use this plane as a guide and worked faster and more precise. The fact that haptic feedback aids the user in being more efficient is supported by the results of the error measurements (see table 4). In both cases 180 (12 test persons x 15 trials) correct clicks were recorded. In the condition without haptic feedback another 63 erroneous errors were made; hence, 26% of all clicks were wrong. Haptic feedback, however reduces this figure: 8.2% of all clicks (16 out of 196) were erroneous. This result is statistically significant. We reckon that this difference is caused by test persons, who overshoot the virtual pointer when no haptic feedback is present. Furthermore, if the encoder stylus does not rest against a virtual plane, clicking on the switch will sometimes cause the stylus to move downwards before the click is registered.

Table 4. Analysis of the click condition

	Without force	With force	P-value
Avg. approach time	1365.3	1409.8	0.82
Avg. homing time	2038.4	1751.4	0.35
Avg. total time	3403.8	3161.3	0.41
Avg. distance	42.8	42,5	0.94
Total errors	63	16	$< .001$

No significant difference was found in the results of the post experiment questionnaire, although a number of test subjects in the push condition were visibly frustrated during the experiment.

5. Discussion

Our experiment shows that selection of a menu item in a haptic scene can be best performed by using a "point and click" metaphor. We believe that these results are valid for a number of selection widgets, such as toolbars and lists. In our setup, pointing can be accomplished in a reliable and fast manner. It is reliable because the menu item that can be selected lights up when the pointer is near to the item (but

this is also true for the pushing mechanism). It is also fast, because the user does not have to touch the menu, lighting a menu item by coming in the vicinity is good enough. However, the menu lets the users rest their hand against a haptic plane, which helps to reduce errors. We noticed both behaviours during the test.

Of course, the haptic case still does not provide perfect selection, so usual error correction mechanisms, such as a confirmation for critical operations (e.g. clearing the virtual scene) and an undo mode for other operations, must be provided.

A problem that arose, when working with the haptic menu was the fact that it was only touchable from the front. We allowed to push trough the menu, when approaching it form the back in order to enhance the push condition. Sometimes, the test subject would get lost and ended up behind the menu. In order to push against the menu, the user must be in front of it. In this case the test person would have to go round the menu with the pointer If the back of the plane would also be touchable. We choose to keep this effect in the "point and click" condition, in order to minimize the differences between both conditions. The test persons in the push condition where happy with this feature, but the test persons in the "point and click" condition that ended up behind the menu reported that they would be more efficient if the menu would be touchable from two sides. This is an extra argument in favour of the "point and click" condition, since the use of a menu that is touchable from both sides is consistent with a haptic virtual environment. However, further research is needed to support this thesis.

Although the usage of semi-transparency allows us to place the menu in an arbitrary location, it would be better if it would not be visible if the user does not want to use the menu. We have already explored the use of head-tracking in a desktop virtual environment [13]. With this setup, users can virtually enlarge their workspace and can look at the virtual world from different viewpoints in an intuitive manner. If a menu would be placed just outside of the users view, than the menu can be easily accessed without being intrusive. Of course, semi-transparency would still be desirable, because it is still possible that the user just wants to examine an object.

6. Conclusions

As a first conclusion, we can state that haptic 3D menus in a virtual environment should use the "point and click" metaphor for selection and not a pushing metaphor when using an encoder stylus, although the latter seems to be obvious from real-world experiences. Secondly, haptic feedback is invaluable in this interaction, in order to reduce the number of errors that arise due to overshooting. We believe that similar conclusions can be drawn for other haptic UI

elements, such as dialogs and toolbars, although further research is needed to support this hypothesis.

7. Acknowledgements

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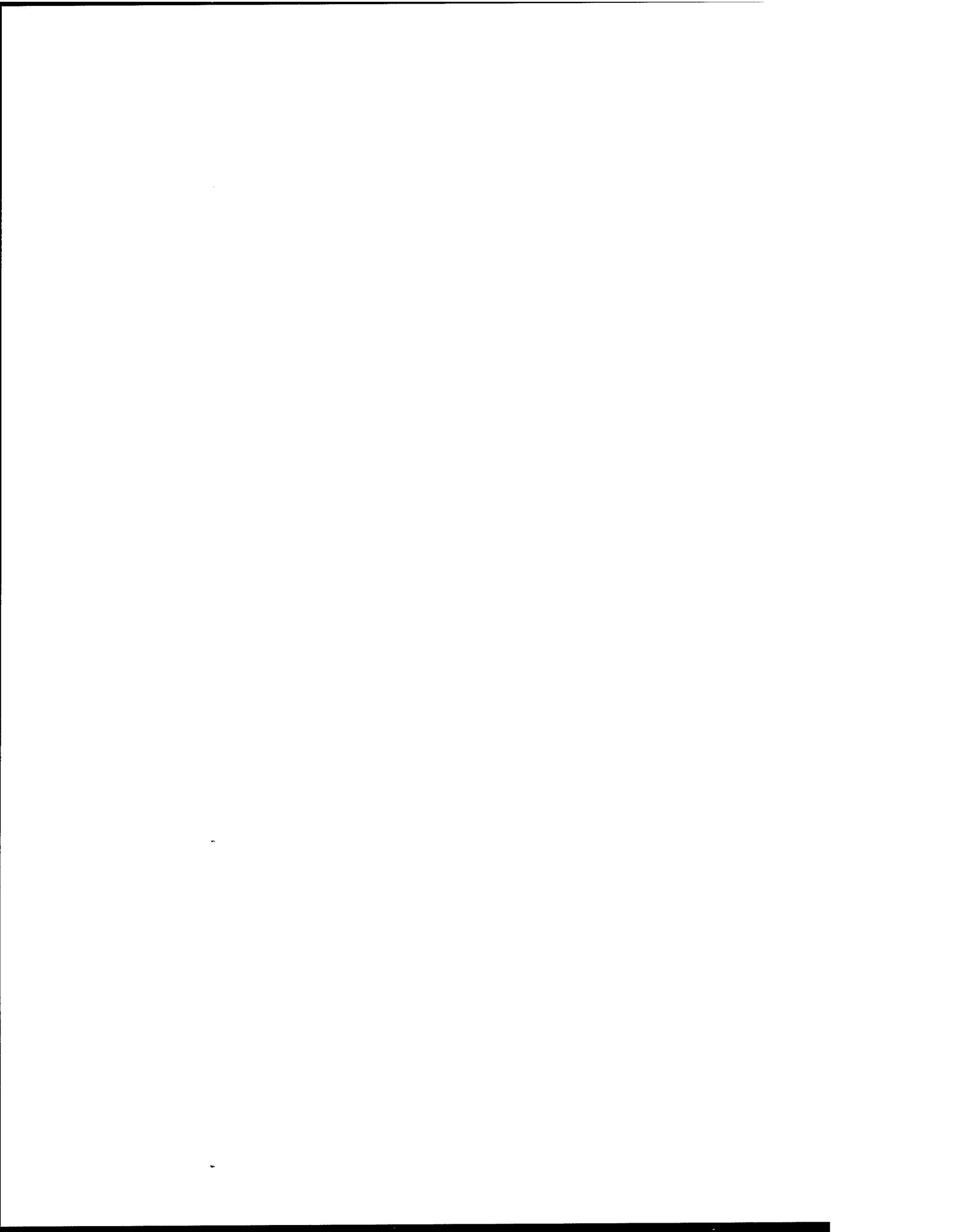
Can You Feel the Force?
An Investigation of Haptic Collaboration in Shared Editors

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Abstract

Users of collaborative systems are typically restricted to communication through voice and video links. Users find this difficult — it does not encompass the richness of communication they are accustomed to in the real world. Attempting to address this problem we describe the implementation of a novel mechanism for haptic communication based around interactions between users' cursors. An initial, and mainly observational, evaluation is described, along with some promising results. We show improvements in subjective experience and suggest several, more formal, avenues for future research.

1. Introduction

With the advent of the World Wide Web (WWW), distributed, collaborative technologies have begun to gather momentum. Real-time collaborative tools are becoming more common, and there is growing acceptance that such tools may be able to reduce travel costs and facilitate group and team based work. However, these systems still face problems. Crucially, the communication that takes place between users does not reflect the richness of communication in the real world. Even assuming high quality video and audio links, information pertaining to sources such as bodily gestures, eye gaze, and background noise is typically lost.

Consequently, users of these systems experience difficulty communicating effectively with one another. Users typically find it difficult to maintain awareness of the actions of others, and to meaningfully coordinate their work activities. Users find it hard to infer where a co-worker's attention is directed, and the use of gestures, both as aids to conversational token passing and as indicators of topic or information, is less effective than interactions in the real world.

There is a large body of research that attempts to address these issues. Much of it focuses on the addition of information through novel means. There is extensive work investigating the impact of video systems that allow participants to maintain eye contact [12], and various researchers have looked at the possibilities of displaying images of the hands and arms of remote users [8]. Audio information, in the form of auditory icons [4], has also been shown to be an effective addition to these systems. However, despite the improvements suggested by this research, the problems faced by collaborative systems still remain.

Here we consider how haptics could be used to address these problems. Previous literature concerning haptic communication in dedicated, standalone devices has suggested that it provides a strong interpersonal link between users, and raises levels of presence [2, 3]. More recent work investigating the cooperative performance of physical tasks in virtual environments has shown significant performance benefits and an increase in the sense of "togetherness" and presence achieved between participants [1, 15].

However the majority of collaborative tasks are not physical. Here we describe an approach that attempts to take the benefits of haptic communication – not only increases in performance, but perhaps more importantly, a greater sense of engagement and presence – and apply and evaluate their effects in a realistic collaborative task. We focus on trying to augment the communication between users of synchronous shared editors. Shared editors are a common collaborative tool and allow multiple users, often situated at different locations, to simultaneously work on the same document.

2. Implementation

2.1. Haptic Communication

Synchronous shared editors typically include graphical avatars, known as telepointers. These are additional cursors used to represent the position of other users in the workspace. In accordance with the haptic communication described by Oakley *et al.* [13], we base our haptic communication on enhancing interactions between these cursors. Oakley *et al.* define five different mechanisms for haptic cursor communication. Firstly, a push effect, which transforms cursors from a purely graphical representation into tangible objects – they can be felt, knocked into and pushed around. Secondly, a gesture effect which allows cursors to pull each other around. One user can pick up another user, causing that user to be constrained to follow an accurate representation of his or her path. Thirdly and fourthly, locate and grab effects,

which let users activate forces to guide themselves towards another user and to guide other users towards themselves. These effects differ from the gesture effect in that they make no attempt to represent a path, merely a position. Finally Oakley *et al.* describe a proximity effect, which varies the viscosity of workspace according to the proximity of other users, and is designed to provide a basic sense of the presence of others.

2.2. Haptic Simulation

The haptic simulation was implemented in C++ under Windows NT and for the PHANToM (from SensAble Technologies). As we focused on desktop editing tasks the PHANToM was given control of the cursor to provide a standard pointer interface. However, as the PHANToM is an absolute position device, there were some discrepancies with normal mouse operation. The most important of these was that stiff walls lined the edges of the PHANToM's range, preventing users from further motion. The PHANToM's button was mapped to a left mouse click. The workspace itself was presented as a vertical plane.

The gesture, locate and grab effects all require an explicit command to initiate and halt. All commands were mapped to the PHANToM's single button. To gesture, a user moved over another user and depressed the button; to end the gesture the button was released. This control mechanism was designed to support the metaphor of taking hold of, and pulling along, another user. The locate effect was activated by pulling backwards from the workspace and depressing the button. Releasing the button stopped the effect. Finally the grab effect was initiated by pulling backwards from the workspace, performing a double click and keeping the button down after the second click. Once more, releasing the button stopped the effect. All other buttons presses were passed to the system as normal mouse events. The rational for using the PHANToM's button in this way was to ensure that the haptics could only be activated while the PHANToM was being held.

2.3. Implementation of Networked Haptics

Haptic feedback in general requires high update rates, typically of 500 Hz or more [11]. Most modern networks, for instance ethernet or the Internet, do not provide a quality of service at anywhere near this level. Several researchers are working to address this issue [16]. The goal of this research, however, is to investigate the potential, for a user, of collaborative haptics. Consequently, a high performance, loss-less transmission medium was required. To achieve this we first analyzed the refresh rate requirements for the haptic cursor communication.

In general, high update rates are required to support the production of stable stiff objects [11] and, in the haptic cursor communication, only the push effect involves the production of an object at all – the other cursor. The proximity effect does not require any such representation, merely modifying the viscosity of the workspace based on the distance to other

cursors, and as such should be fairly insensitive to low update rates. Changes in the viscosity from one millisecond to another are relatively unimportant and should fall well below the perceptual threshold. The locate, grab and pull interactions all regard the other user's position as the target of a homing force and as such, when the range to the target is small, so is the magnitude of the targeting force. Lower forces can be adequately represented by lower update rates [11]. Conversely when the distance to the target is large, the targeting force is also relatively large. However in this instance the distance that the target must move to cause a substantial change in the targeting force is also large. These factors all combine to make the haptic communication relatively tolerant of low update rates.

Furthermore, an analysis of the total network demands of haptic cursor communication leads to the conclusion that even assuming a high update rate, a low total bandwidth is sufficient. This is because the only remote information of significance to the simulation is the position and state of other cursors – for instance whether they are engaged in a gesture. This can be expressed in a handful of bytes (16 bytes per PHANToM per update in the current implementation).

Finally, to further simplify development some of the requirements of a collaborative system were relaxed. Firstly we choose to consider a system consisting of only two users and secondly we decided to implement the communication through a dedicated streaming connection rather than across a network. Both of these choices are commonly seen in groupware research [e.g. 4, 8] and typically reflect the intention of the work - to evaluate the potential of the communication for a user, not to investigate underlying network performance.

With these analyses in mind, the haptic communication was implemented running over serial cables and providing a dialogue between two machines at 100 Hz. This implementation suffers from the restrictions of being simple for two users, but more complex for more, and of being confined to machines positioned only a few metres from one another. Due to the update-tolerant nature of the cursor communication, this refresh rate provides a subjective experience that is both stable and of an acceptable quality.

2.4. Collaborative Editor

To provide a flexible platform for evaluating this haptic communication, we turned to GroupKit [14], a high level tcl/tk based groupware toolkit. GroupKit provides support for the management, including the creation, manipulation and mediation of access to, shared information, and basic groupware aids such as telepointers.

The product of coupling the haptic communication with GroupKit is CHASE (Collaborative Haptics And Structured Editing), a synchronous, Relaxed What You See Is What I See (RWYSIWIS) structured drawing tool, pictured in figure 1. It provides telepointers and allows users to simultaneously work on a large canvas while each maintaining a separate view of it. CHASE allows users to create and edit four types

of object: text items, rectangular groups, oval groups, and links. Text items can be placed in group objects and links can be made between them. All items can be freely moved, edited, resized and otherwise manipulated.

One consequence of the combination of the haptic cursor communication and a collaborative RWYSIWIS workspace is that users can feel forces that attempt to move them outside of their current view of the workspace. To resolve these forces intelligibly, the haptic workspace was restricted to only allow cursor movement within the window of the GroupKit application; walls were presented at the edge of the CHASE window. When users pushed into these walls, as they would if forces were pulling them off the workspace, the workspace scrolled in the direction that they are pushing, gradually changing their view until their target was on screen. This solution had the consequence of providing a new mechanism for scrolling – simply pushing into the walls of the workspace.

The haptic simulation communicated with CHASE through mouse events and also through a socket connection. The mouse events formed the main part of the interface, and functioned simply as a consequence of using the PHANToM as a cursor control device. The socket connection was used to communicate all other information, such as the scroll position of the CHASE workspace, and to transmit scrolling events when the PHANToM pushed into a wall. A diagram of this architecture is shown in figure 2.

3. Evaluation

3.1. Design

Evaluation in collaborative systems is a more challenging process than the evaluation of single user systems [6]. Frequently a metric such as time to complete a task, or even quality of output, is less important than the somewhat ephemeral "quality" of the communication between the users. Furthermore, the use of collaborative systems is arguably much more dependant on context than single user systems. There is less guarantee that a feature which appears to work successfully in a laboratory situation will transfer that success to real world use.

This evaluation was also further restricted by the preliminary state of this work. Lacking foundations on which to build, and combined with the challenge presented in the evaluation of any collaborative software, we decided that the most important issue to address was one of acceptability. We choose to address the question of whether or not users would adopt this novel form of communication and, if they did adopt it, what effects it would exert on their subjective experience. Furthermore, although the haptic communication was designed with a purpose in mind, we felt that, if users did adopt it, they were likely to develop unforeseen uses for it. A secondary goal was simply to detect any novel uses of the communication. Finally, as this software represents a prototype, we wanted to discover any problems users experienced with the communication.
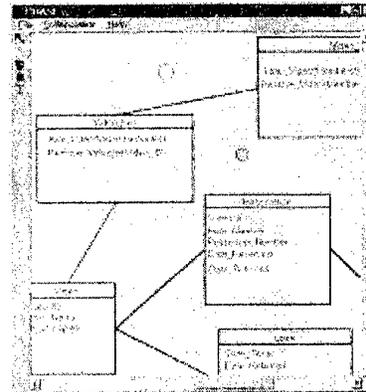
Figure 1. Telepointers and structured objects in CHASE

Designing our initial evaluation to reflect these considerations we chose to perform an observational study of users performing a high level task. This allowed us to observe whether or not participants adopted the communication, what uses they put it to, and the problems they had with it.

3.2. Participants

Sixteen users, all computing science students, in eight pairs, participated in the experiment. Four pairs, forming the Haptic condition, solved a problem with the aid of the collaborative haptic feedback; four pairs, the Visual condition, worked without it. Both sets used the PHANToM in the same restricted workspace, and had access to the same novel scrolling technique. None had previously used a shared editor, nor had anything more than trivial experience with haptic interfaces.

3.3. Task

CHASE was used as a simple CASE (Computer Aided Software Engineering) tool. Participants were required to read a problem statement and design a set of Unified Modeling Language (UML) diagrams to solve it. The advantages of using CASE are that it is an established domain for collaborative tools (e.g. [5]), and that problems, ideal solutions, and semi-expert users are easy to find in an
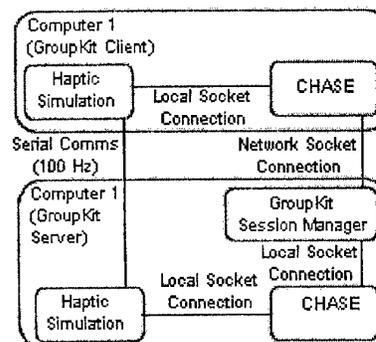
Figure 2. System Architecture for Collaborative Haptics

academic environment. While CHASE cannot represent all the objects in the UML specification, it does allow the development of a basic diagram.

3.4. Measures

Users were observed, with both audio and video recorded, throughout the experiment. No formal dialogue analysis of this data is currently planned. Four questionnaires were administered at the end of the experiment. Firstly, NASA TLX [7], an established questionnaire designed to measure subjective workload. Secondly, QUIS [10], a standard questionnaire for assessing the usability of computer systems. Thirdly, the ITC Presence Questionnaire [9], designed to measure presence in virtual environments. The final questionnaire was created specifically for this experiment to assess collaboration. It consisted of ten items, to be rated on seven-point scales (the questions are included as part of Figure 6, in the results section). The use of this custom questionnaire reflects the lack of an accepted tool for this purpose. This questionnaire data was intended to allow us to gain a measure of the influence of the haptic communication on subjective experience. Objective measures of time to complete task and quality of model were also gathered, but little weight has been attached to them.

3.5. Procedure

For simplicity participants were seated in the same room, separated by a screen. They could not see one another, and no video link was provided. They could talk freely. A disadvantage of this setup is that audio information from the environment, such as the sound of keys presses, which is not typically passed between subjects at different locations, was present. Participants in both conditions went through an extensive training phase. A manual to CHASE, and in the case of the Haptic condition, to the haptic cursor communication was provided and each feature explained and demonstrated. Participants were then required to copy a printed UML diagram into CHASE. At this stage it was clearly explained that the example diagrams consisted of acceptable UML constructs. The recording equipment was then switched on and subjects then began to solve the UML problem. There was no time limit imposed on the task; subjects were instructed to stop when they believed the problem had been solved satisfactorily. This typically took an hour.

4. Results

4.1. General Observational Results

There was substantial variation in the use of the haptic communication. One pair of users in the Haptic condition did not use the communication at all, while others embraced it, using the various effects regularly. This may reflect the fact that touch is a very personal sense. Individual differences and

social factors may well exert a strong influence over the adoption and use of this kind of communication. Furthermore it seems likely that communication of this sort breaks new social ground. Most users prefixed use of the haptic communication with a verbal warning, even when the communication would not affect the other user, as with the locate effect. Users have not previously been able to communicate in this way and appear unsure what protocols should mediate their interaction.

Users also appeared to find the interface to the haptic communication difficult. We attribute this to the fact that the communication was completely controlled through the haptic device; it was simply overloaded. A final crucial point is that the majority of the users appeared to find the haptic communication engaging and helpful, rather than annoying or intrusive.

4.2. Observations of Locate and Grab Effects

The majority of the participants in the haptic condition immediately understood the purpose and applicability of the locate and grab effects. They used the locate effect regularly and the grab effect more infrequently. Reflecting the fact that users found it easier to find one another, pairs in the Haptic condition tended to use much more of the available screen space and created diagrams that spread over a larger area than pairs in the Visual condition. Diagrams in the Visual condition tended to be very compact, with different sections abutting one another.

Participants in the Visual condition also used many different techniques for finding one another or specific objects, which were mainly absent from the Haptic condition. They would describe their position by references to the position of the scrollbars at their location, or by naming nearby objects or diagrams. One participant in the visual condition occasionally instigated a more extreme solution. Upon finding the other user's telepointer he would endeavour to maintain a view on it for as long as possible through rapid scrolling – giving the appearance of pursuing the other user.

One pair in the Visual condition did produce a diagram that occupied a large and diverse area of the screen. They suffered from considerable confusion while discussing where to begin new elements of their solution, and in keeping track of one another when they came to review their diagrams. Such confusion was far less evident in the Haptic condition.

4.3. Observations of Gesture Effect

The haptic gesture was used infrequently. Graphical telepointer gestures, such as when a shape is described by simply moving along its contours, or more commonly, when an object is indicated by moving over it, were far more prevalent. This is probably due to the fact that there is a time cost associated with the haptic gesture. A haptic gesture involves moving over another user, picking that user up, then moving back to the item of interest. The haptic gesture also

provides little enhancement of the most common use of a graphical gesture: indicating a single object.

However, the haptic gesture was used in more complex situations. One pair of participants used the haptic gesture to indicate several objects, spread over an area of the workspace too large to be effectively displayed with a graphical gesture. This could indicate that the haptic gesture is useful for illustrating complex sets of data. Another pair of participants used the gesture in an entirely novel way - one user selected a group object that they were discussing and the other user then began to gesture to the first user, steering them (and consequently the object) towards what they thought was an appropriate location.

4.4. Observations of Proximity and Push Effects

Observing any direct usage of the proximity and push effects was challenging, as neither requires any explicit action to initiate, nor causes an observable motion. However the two effects may have combined to increase a feeling of presence in the workspace. Users appeared to be more confident about using graphical gestures in the Haptic condition, which we suggest may have stemmed from an increased sense of presence brought about by the more tangible representation provided by haptic communication.

4.5. Questionnaire Results

All analyses were conducted using two sample between groups t-tests. Figure 3 contains the results from the TLX questionnaire. Overall workload did not significantly change between the conditions. The Haptic condition, however, was significantly more Physically Demanding than the Visual ($p<0.05$). The difference in the Frustration Experienced factor approached significance ($p<0.065$) and we attribute this trend, and possibly also the increase in Physical Demand, to the difficulty users had with the interface to the haptic communication. Most users found the haptic communication hard to invoke, and this is an area that requires substantial improvement before further trials take place.

Figure 4 illustrates the results of presence questionnaire. In keeping with the observation that the haptic communication may increase a user's sense of presence, the Haptic condition

yielded significantly greater subjective ratings of spatial presence ($p<0.05$). Also, supporting the observation that users found the haptic communication appealing, it achieved significantly higher ratings than the Visual condition in the engagement category ($p<0.05$). Finally, the Haptic condition was also rated significantly higher on the naturalness factor ($p<0.05$). This factor attempts to measure how interacting with the system compares with interactions and experiences in the real world.

The results from the usability questionnaire are presented in figure 5. Overall usability was significantly improved in the Haptic condition ($p<0.05$) as were the individual factors of system usefulness ($p<0.01$) and interface quality ($p<0.05$).

Results from the custom questionnaire are shown in figure 6. While this questionnaire was developed simply for this experiment, and as such little trust can be placed in the validity of the data that it produces, it is promising to note the unanimously rated superiority of the Haptic condition.

5. Discussion

The information gained from the questionnaires supports that gained from the observation. On the negative side, users experienced problems with the interface to the haptic communication, and there appears to be substantial variation in the adoption of the communication, probably due to the personal nature of the sense of touch. On the other hand, the majority of the participants appeared to find the haptic communication engaging and used it frequently. It also significantly increased subjective ratings of presence, improved usability and appeared to facilitate collaboration.

The positive results of this experiment suggest future avenues of research. The gesture effect appeared useful when indicating complex information, for instance gesturing to encompass a variety of objects, or a complex shape. We suggest that an evaluation of this technique in such situations would yield interesting results. The locate effect was well received by subjects and it may be interesting to compare this navigation and coordination technique to other, possibly visual, aids. Finally, a direct comparison of the effect of the proximity and push effects on subjective ratings of presence might also prove interesting.

In conclusion, this work has allowed us to assess the
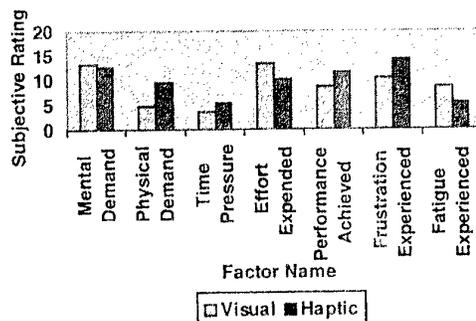
Figure 3. Results from TLX Questionnaire
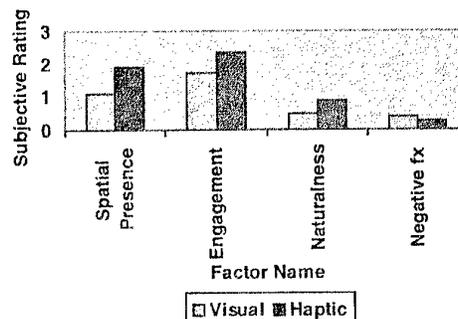
Figure 4. Results from ITC Presence questionnaire
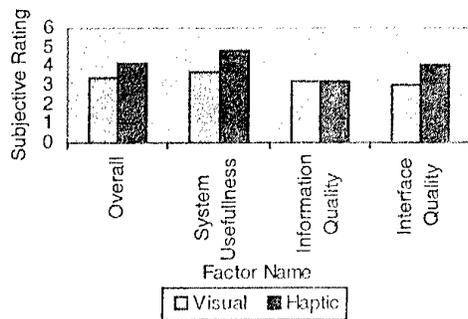
Figure 5. Results from CS Usability Questionnaire

suitability of this novel haptic communication, and to attempt to determine future research possibilities that might stem from it. We have generated several hypotheses for future work, and, more importantly, found that the majority of users regard the communication as appealing and, subjectively at least, gain significant benefits from it.

6. Acknowledgements

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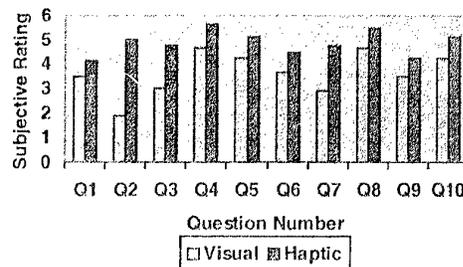
Questions used:

1. There were times when I was unable to communicate effectively with the other user
2. It was easy to find the other user
3. I found the communication in this system to be effective
4. I worked alone
5. The other user and I coordinated our actions together
6. Communicating with the other user was simple
7. I often found it hard to locate the other user
8. I was not aware of the activities of the other user
9. The system did not support my desire to communicate
10. The software made it easy to work as a team

Data has been adjusted so that higher values indicate higher levels of cooperation for all questionnaire items

Figure 6. Questions and Results from Custom Questionnaire

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Tele-Handshake: A Cooperative Shared Haptic Virtual Environment

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Abstract

A cooperative shared haptic virtual environment, where the users can kinesthetically interact and simultaneously feel each other, is beneficial for many VR simulations. We have implemented a tele-handshake system that enables the participants to shake hands over a network and feel each other's pushing concurrently. A client-server architecture has been used with a specific implementation to meet the requirements of the haptic device. The users were able to feel each other simultaneously and shake their hands in an intuitive way. An objective evaluation based on force feedback was conducted. The results showed that the force feeling induced at the remote site was very close to that felt at the remote site. Also, a subjective evaluation based on a rating questionnaire is described. The results prove that the feeling was instant without any perceptible delay.

1. Introduction

The ability to feel objects in a shared virtual environment simultaneously can markedly enhance the effectiveness of many VR applications. Haptic cooperative virtual environments, where the users can simultaneously manipulate and haptically feel the same object, is potentially beneficial and in some cases could be indispensable. It could be useful for training as in, for example, virtual surgical simulators where the team performs on the same real patient; all the other members perceive each team member interaction with the patient directly, when dealing with the patient's tissue, or indirectly because of the collisions in the limited workspace. Virtual surgical simulators offer the possibility of training surgeons without risking casualties [1] [2] [3]. However, the interaction feeling and its effect should be provided to make sure that the perceptual experience in the virtual world corresponds to that in the real world, otherwise the training would be useless, if not

dangerous. Another use of a haptically cooperative environment is in entertainment, which would allow the participants to kinesthetically interact with each other. This adds a new dimension of enjoyment and brings us one step closer to more realistic interactivity. Moreover, there will be a great benefit from such kinesthetic interaction in some sports training systems, especially the kind of multi-players sports that include direct contact between the players such as boxing, sumo wrestling, and football. The resulting virtual training system has the potential to be more realistic and efficient. In addition, there are many advantages of multi-hand manipulation that can be realized from daily life. More precise manipulation can be achieved using both hands [4]. Also, the manipulation with both hands is more efficient than one hand as has been mentioned by some ergonomic studies [5].

Buttolo et al. [6] proposed an architecture for shared haptic virtual environments where they pointed out the difference between collaborative and cooperative virtual environments. The collaborative environment is a sharing environment, in which the users take turns in manipulating the virtual object. Meanwhile, the cooperative environment is an interacting one, in which the users can simultaneously modify the same virtual object. According to these definitions most of the cooperative haptic environments that have been proposed in the last few years fall under the banner of collaborative haptic environments, as all of them cannot support simultaneous kinesthetic interaction between the participants. Takemura and Kishino [7] have built a cooperative environment using a virtual workspace by combining a head tracking display and a data glove. However, the users are not allowed to simultaneously alter the status of the virtual world. In other words, they cannot grasp the same object and manipulate it at the same time. They used what they called mutual exclusion to avoid simultaneous manipulation of the same object. In the shared virtual environment proposed by Buttolo et al. [8], one user at time, the active operator, is allowed to modify and feel the force from the environment.

Meanwhile, the other users watch the interaction but cannot modify or touch the object.

Kinesthetically linking remote users acting on the same object is a great challenge as any latency in the haptic rendering loop could bring the whole system to instability. The delay should not be more than 5-10 ms to accomplish a stable interaction with a stiff virtual object. Handshaking is a good example of simultaneous kinesthetic interaction, therefore, it is an important task to be implemented and tested. It represents a highly demanding task for concurrent interaction and quick instant feeling. As a result, achieving a rich, instant and realistic haptic sensation during tele-handshake would be an indicator for the possibility of implementing a high-quality cooperative haptic virtual environment. Another reason could be a social one related to our life communication protocol where every greeting, farewell, meeting or agreement starts and ends with handshake. Therefore, representing a handshake in any haptic cooperative virtual environment will encourage a more intuitive and natural interaction.

This paper describes a tele-handshake system with haptic sensation over the Internet. An implementation of a shared cooperative haptic virtual environment where the users, at distant sites, can shake hands and feel each other simultaneously. An architecture for kinesthetic cooperative haptic interaction in a shared virtual environment is proposed. An experiment and evaluation of the proposed system are described.

2. The experimental system

The system consists of two connected stations in client-server mode. Each machine is connected to the haptic device by which the users interact inside the virtual space, and the graphic device to display the virtual environment to the users is as shown in Figure 1. The users from different locations come to meet each other inside the virtual meeting space, which is a 3D spacious room with two graphic arms representing each user's hand as can be seen from Figure 2. PHANToM from SensAble Technologies, Inc. was used as the haptic device to represent the force feedback to the subjects [9]. The participants were asked to enter the virtual meeting space in which they can observe each other's movement, then to

shake hands as naturally as they usually do in real life. The force feedback was acquired from each site to evaluate the haptic sensation provided by the local and the remote location. Figures 3 and 4 show a snapshot of the experimental environment at each site during a real tele-handshake session.
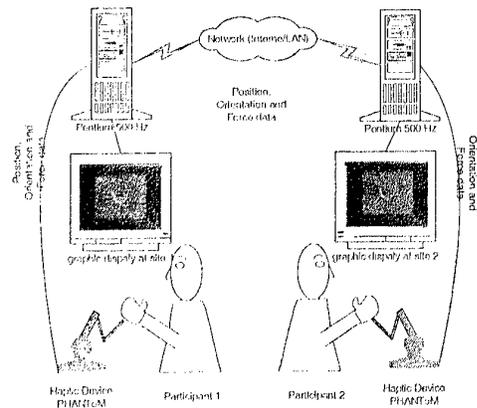
Figure 1. Diagram of the tele-handshake system
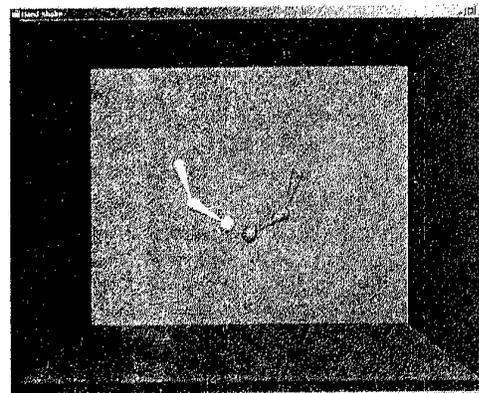
Figure 2. The virtual environment (virtual meeting space)
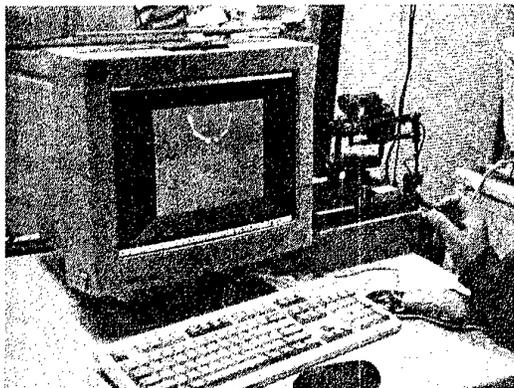
Figure 3. The experimental environment at site 1
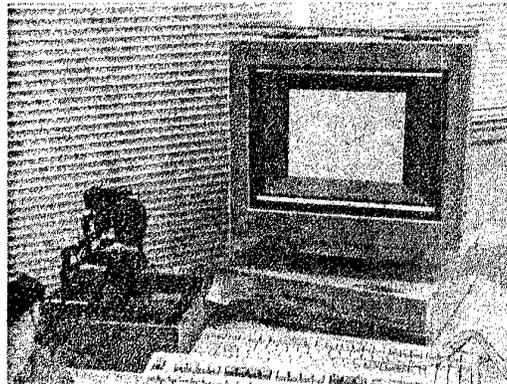
Figure 4. The experimental environment at site 2

3. The tele-handshake system architecture
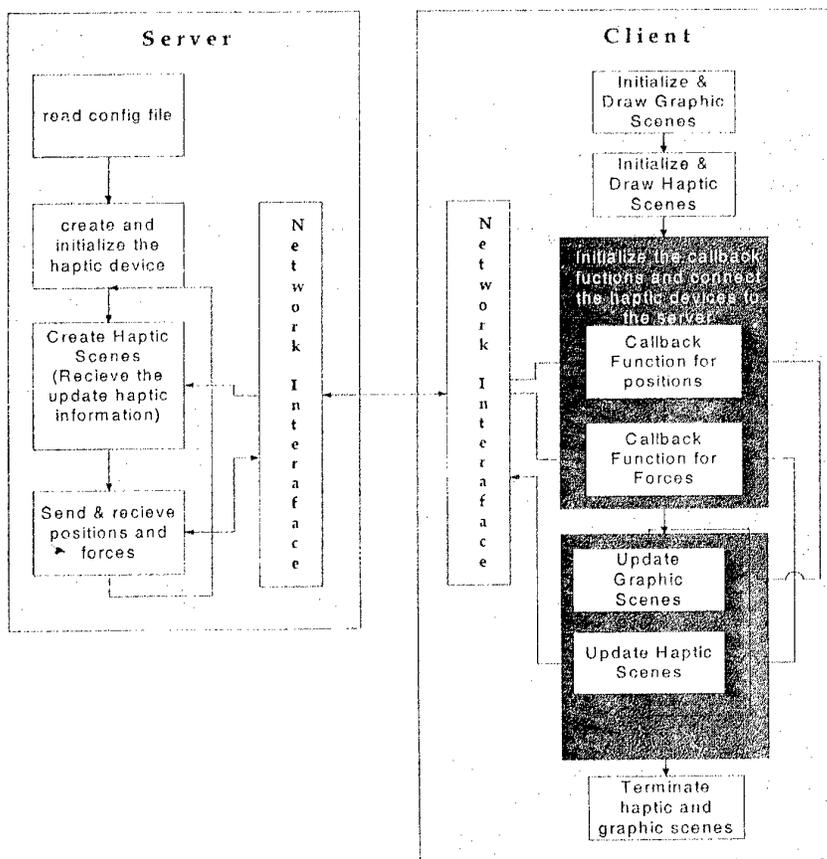
Figure 5. The system architecture

The architecture can be described as a client-server structure as can be seen from Figure 5. The system that has been used to implement the tele-handshake consists of two machines at different locations.

The server program and client program are running concurrently at each site at the same time. The server program is responsible for initiating the haptic device and passing force and position information to the client side. The client program is the application code, which initiates and draws the graphic and haptic scenes, then establishes the communication channel with the server to receive the data from the haptic device using callback mechanism. This mechanism passes only the new state information for the nodes in the haptic scene from the server side to the client side. This technique saves traversing all the nodes in the scene checking for any changes. After that, the haptic and graphic scenes are updated according to the new state information that was received from the server side.

4. Results and evaluations

4.1 Objective evaluation

Linking haptic devices over the network is a great challenge because of the small delay requirements and the high update rate required for haptic rendering. A 1000 Hz update rate was suggested by Buttolo and his colleagues to create the feeling of stiff surfaces and to prevent unwanted sudden forces [10]. Using the above architecture enabled us to meet these demands over the network. By keeping the haptic process running on the server side at a high update rate. Meanwhile, the graphic process was running at the client side and exchanging the necessary information with the haptic process, which are usually forces and positions that can be transferred efficiently through the current Internet network.

To evaluate the system we compare between the force feedback provided to the local client, who is connected to his haptic device on the local machine, and the forces provided to the remote client that is connected to the haptic device on the remote machine. Therefore, it was sufficient to obtain the forces from the local side and those from the remote side, and compare them to quantity the haptic sensation provided at each site.

The forces in the x and z directions from the remote site could provide up to 87% of the forces at the local site. Meanwhile, the forces in the y direction were up to 92% of that at the local site as can be seen from Figure 6. The results reflect the nature of the handshake task since we usually intend to shake the partner's hand up and down in the y direction.
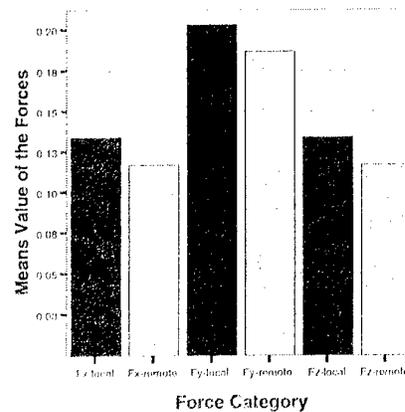
Figure 6. The local and remote force feedback evaluation

4.2 Subjective evaluation

Evaluating human interaction with any VR simulation, in general, and haptic VR simulation in particular is a complex task since there are many factors that cannot be considered. We used a simple subjective evaluation using a rating questionnaire to show to what extent the system could deliver a convincing feeling and what kind of features have been conveyed to the users. Ten subjects were asked to fill out the questionnaire shown in Table 1.

Table 1. Questionnaire rating the feel of the simulation

Convincing feeling	1–2–3–4–5–6–7	Unconvincing
Intuitive manipulation	1–2–3–4–5–6–7	Unnatural manipulation
Satisfied with the interface	1–2–3–4–5–6–7	Dissatisfied
Instant feeling of forces	1–2–3–4–5–6–7	Slow (delayed)
Haptic sense consistent with the visual sense	1–2–3–4–5–6–7	Inconsistence

As can be seen from Figure 7, the subjects thought that the system could deliver an instant feeling without any noticeable delay. Moreover, the haptic sensation was consistent with the visual sensation, up to 95%. The interface was not fully satisfactory because the Phantom is more like grabbing a pen than whole-hand grasp as in real handshake situation; only 70% of satisfaction with the

interface has been expressed. This might explain why the subjects were partially convinced with the feeling and the intuitiveness of manipulation. They were up to 62% convinced with the stimulated feeling compared with the real-life handshake's feeling.
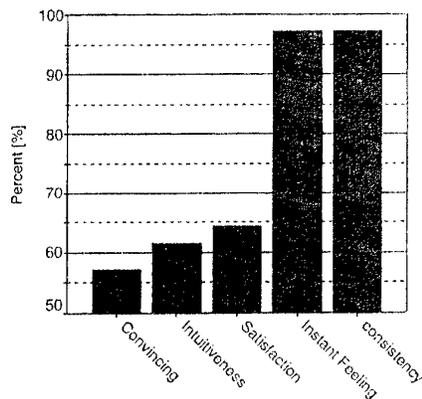
Figure 7. Subjective evaluation according to the rating questionnaire

5. Conclusions

In this paper we described a system for tele-handshake over the Internet. A client-server architecture was used to connect the users with their haptic device. Moreover, a callback mechanism was used to communicate the haptic data between the server and their clients. As a result, there is a reduction in traffic since only relevant changes are communicated.

The participants at different locations could enter the virtual space meeting and shake hands and feel each other instantly. The system, at the remote side, could provide up to 92% of the force feeling induced at the local side, which makes using the haptic devices over the network applicable and efficient. The feeling, as has been described by the subjects, was instant without perceptible delay.

The subjects expressed their desire to have the same experience but with the ability to use the whole hand, because that would deliver a more satisfactory and realistic feeling. Nevertheless, this would open up a new dimension of direct human contact and interaction over the network. The ability to touch and feel others far away would definitely start a new era in human communication and would give us access to the development of new applications over the Internet that previously only existed in our imagination.

Acknowledgment

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The tele-gesture: problems of networked gestures

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Abstract

This paper focuses on the problems of networked gestures. The tele-gesture is the achievement of a remote gesture. To reach a good sensory perception of the distant scene, it is necessary to create a specific flow for the haptic data: position, orientations, and feedback forces. This flow presents intrinsically a bi-directional characteristic. Its quality is extremely dependent on the latency of the intermediary telecom network. In this paper we will present the results of our experiments on the tele-gesture.

1. Introduction

The tele-gesture is the achievement of a remote gesture, i.e. to touch a distant object, that is real or virtual, for example, a human body, and to feel its mechanical characteristics, sensitivity specific to the bones, muscles, tendons and joints which give information about its static, balance and the displacement of the body in space, see [3], [5]. To reach a good sensory perception of the distant scene, it is necessary to create a specific flow for the haptic data: position, orientations, and feedback forces. This flow presents intrinsically a bi-directional characteristic. Its quality is extremely dependent on the latency of the intermediary telecom network. To ensure an encoding of the gesture, it is advisable to use a virtual 3D object, of which it is necessary to build a coherent visual and haptic representation. Each scene is duplicated on the two connected sites: on the local machine and on the distant machine. The haptic device frequency is too high, typically 1KHz, so it would not be possible to go forwards and backwards through the network at such a rate! On each machine, one must thus establish a local loop operating at the rate of 1KHz, from which the data is extracted and sent to the network at a desired lower rate.
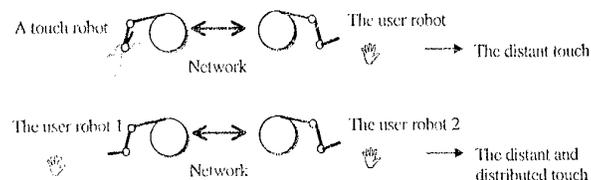
Figure 1. Distant Touch and distributed touch

A SensAble PHANToM haptic robot is used. This device has 6 degrees of freedom and renders a three-dimensional force information. It can track the position and orientation of the tool within a workspace of 16 cm wide, 13 cm high and 13 cm deep. The maximum exerted force is 6.4 Newton. We employ a second PHANToM as the distant system, i.e.: the slave system, see Figure 1. There are three main kinds of experiments of the tele gesture:

- Distributed touch like the example of the fencing,
- Touch of ballistic object, whose trajectory is foreseeable, like tennis games,
- Static touch of object, the tele-echography is an example of static touch, with a pressure sensor on the patient abdomen.

2. Local model and distant model

The 3D geometrical model of the distant scene is coded with polygonal objects. The grid is deformed under the gesture. The fine touch is the notion of touching free forms. Two approaches were studied in our projects: touch of the facets and touch of the nodes.

Touch of the facets: it is the calculation of the position of a point that is named the haptic point[1], compared to a selection of facets to touch - when the scalar product between the normal to the touched face and the vector going from the haptic point to its projection on the same face changes sign, the haptic point crosses the facet. The force will then be calculated as $F = -KX$. (K is the stiffness of the virtual object at the considered face and may be fixed or dynamically adjusted and X outdistance the haptic point to the facet). For this approach the continuity of the force is not induced and the processing of smoothing is necessary. Indeed, the force must be continuous when the user makes the handle slide along the surface of the object so that the haptic point projection changes facet.

Touch of the nodes: it is the calculation of the haptic point's position compared to a selection of points: this approach considers a sphere of radius R, the object nodes: the vertices[ ], and the haptic point. When the sphere, attached virtually to the haptic point, contains polygonal object nodes, then a force is returned proportionally to the number of touched points, and the nodes move under the gesture. A zone of forces is produced to allow a feeling as realistic as possible of the 3D scene. The effort feedback is calculated starting from a physical model of the virtual 3D form that is touched.

Table 1. Local model: the qualitative results of experiments. These tests have been performed, works in local loop i.e. without information coming from the network concerning the distant slave workstation.

Touch	Feel	Haptic rendering	Conclusion
on a set of vertices	Discontinuous	Correct	Not realistic for the fine gesture.
on one polygon	Comfortable	Good	Realistic
on one polygon and on its vicinity	Natural, comfortable	Very good	Realistic. Precise

The material point is heavy, elastic and viscous. The state of the material point is governed by mechanical equations. The 3D scene objects are flexible, deformable and their mechanical characteristics, viscosity, rigidity, and mass can be adjusted. We tried out three ways of feeling this modelling dependent on the contact with a polygonal object. The first is a calculation of force feedback based on the nodes of the geometrical 3D model. The second allows a force feedback according to the nearest polygon to the haptic point position. The third comes from the second, and allows an effort feedback

according to the polygon closer to the haptic point, but also according to its vicinity. We note the qualitative results of our experiments in the Table 1.

Gesture sequences can also be recorded to make a simulation, or to replay these sequences. We can build gesture cards. We must take into account the physiological constraints of the human gesture for the tele-gesture to be possible. The haptic loop is fed at a frequency of 1kHz, because below this frequency the gesture perception would be of bad quality, i.e.: unpleasant vibrations would be perceived in the hand.
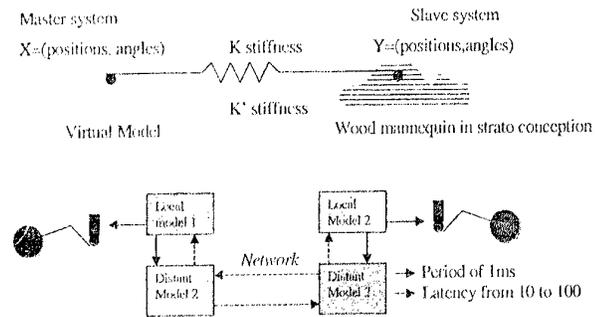
Figure 2. Distant control of the robot in position

We use the local model of the distant scene to calculate the force feedback at this rate. The network will feed this local model, see figure 1. The network is materialized as a spring. It appears necessary to have a local vision: a geometrical model, mechanical 3D from what occurs to the distant one. The local model is a precise model of what occurs locally. This model interacts at the frequency of the robot with the local robot. The distant model summarizes and memorizes for the local model all that is held within the distant one. The distant model is fed by the network messages. The distant model feeds the local model directly.

Contrary to the wave transform approach [2], we exchange haptic data directly in space of the temporal signals. Our approach is based on distant virtual mechanical model.

3. Evaluation of haptic flow

Through the network, the data are encapsulated in messages. In general, the messages contain: the positions X, Y, Z, the angles α, β, γ, and the date. The size of the messages is dependent on the workspace that is to be encoded. The working area for the handle, the workspace is 160x130x130 and the precision is of 0.02mm, for a SensAble PHANToM type desktop.

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[1] The haptic point is the extremity of the phantom arm which is the point of application of the force, in the virtual world.

Equation 1 Evaluation of number of points to encode

$$\frac{\text{maximal handle ambitus}}{\text{precision}} = \text{maximum number of points to be coded} \in D^3$$

where D^3 is the working area

By applying Equation 1, one obtains the maximum number of points to be coded : 8000 points. Then, the positions can be coded on 13 bits as $2^{12} = 4096$ and $2^{13} = 8192$.

Equation 2 Message size limits

$$\frac{\text{network flow}}{\text{sampling period}} = \text{maximum size of message}$$

The message-sampling period is one of the parameters that regulates experimentation, see Table 2. The network flow and the size limits of messages are correlated. For example, the ISDN network flow is 64 kbits per second. If the sampling period is 10ms then the maximal size of a message is 640 bits, see Equation 2.

The latency of the networks is: 30 ms for ISDN, 100 to 200ms for ADSL[2], around 10ms for the local area network LAN. The ADSL network is not recommended for tele-gesture, whereas the ISDN is adequate.

4. The predictive coding of 0, 1 and hybrid order

Messages contain at least a stamp and haptic point position coordinates through a network supposed "ideal". It means that the only disturbance applied to the data is a delay corresponding to the duration of the data's route. We use the local model of the distant patient to calculate the force feedback at a 1kHz rate. The network will feed the expert master interface device with real measurements at a lower rate. So we need to use a predictive algorithm to calculate the signal to send to the robot.

Synopsis of tele-gesture

R : received
D : distant
L : local
δ : delay of the network
t : temporal index of the local model
τ : temporal index of the distant model
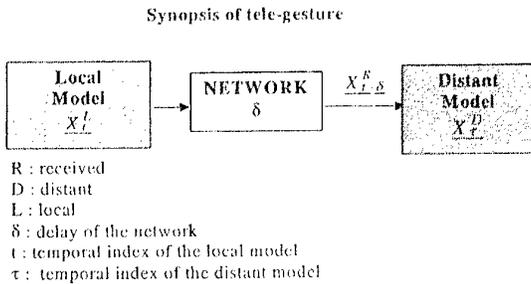
Figure 3. Synopsis of tele gesture

[2] Asymmetric Digital Subscriber Line

The network is like a delay line. It results: $X_\tau^R = X_{t-\delta}^L$. We want to evaluate X_τ^D and we dispose of the following information:

$X_{t-\delta}^R, X_{t-(\delta-1)}^R, \dots, X_{t-(\delta-n)}^R$ the serie of position vectors which transit through the network, and n the buffer's length in which the received data is written. The real time imposes the implementation of the distant model, see Figure 2. The distant model is a reproduction closer as possible to the local model, knowing that we have only the past data of the local model. This past data are separated from the present of our distant model by the incompressible network's latency, i.e. the route's duration of the information. We are going to look for creating a relation of the type:

$${}^1X_\tau^D = \Psi\left(\left({}^1X_{t-\delta}^D\right), \left({}^1X_{t-(\delta-1)}^D\right) \dots \left({}^1X_{t-(\delta-n)}^D\right)\right), \text{ for each}$$

of three position vectors.

For a predictive coding of order 0, there is a brutal modification of the distant model state when the message arrives, see Figure 4. The variable state representing the distant model is equal to the just-received data. In this case: the function ψ is the simplest, following this relation: $X_\tau^D = X_{t-\delta}^R$. From the arrival of the message we modify brutally the distant model's state, we equalize the state's variable representing the distant model to the just received data.

In a continuous haptic flow transmission case, a secure network (without loss) case and a constant transmission speed case: the distant model determines the signal, which is in fact the position of the haptic point and is equal to the signal of local model's signal but displaced in time.

Original signal
Sampling signal received from network
Smoothed signal sends to the robot
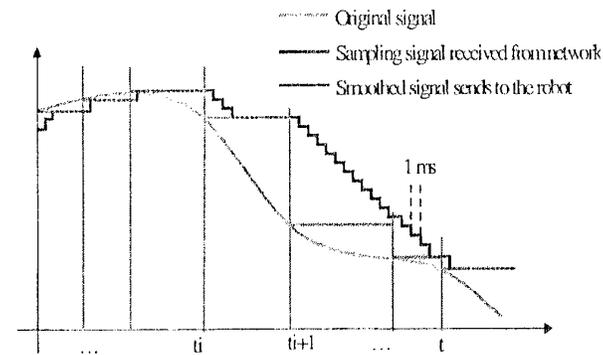
Figure 4. Predictive coding of order 0

For a predictive coding of order 1, information on the slope of the original signal is used to predict the signal between two messages from the network, see Figure 5. In

that case the function ψ is affin: $\Psi(x) = a * x + b$. The following relation is deduced: $\underline{X}_\tau^D = \underline{X}_\tau^D + \delta * \underline{P}$, with $\underline{P}(P_x, P_y, P_z)$ the slope vector composed of the slope calculated on axis X, of the slope calculated on axis Y, and of the slope calculated on the axis Z. The slope is estimated in the following way:

$$\left(P_X = \frac{{}^1X_\tau^R - {}^1X_{\tau-1}^R}{} \right)\left(P_Y = \frac{{}^2X_\tau^R - {}^2X_{\tau-1}^R}{} \right), (...)$$

By proceeding in this way, there is a weak noise of quantification on the signal representing the position of the haptic point; this noise is amplified in our construction of the predicted signal because it is multiplied by the factor δ corresponding to the network's latency. It is important to smooth the received signal to decrease the disturbance generated by this quantification's noise. We observe that the frequency of this noise was included between 150 and 200 Hz. We smooth the slope by using a temporal window of length n=10 ms.

The new slope's calculation is:

$$\left(P_X = \frac{{}^1X_\tau^R - {}^1X_{\tau-1}^R}{n} \right)\left(P_Y = \frac{{}^2X_\tau^R - {}^2X_{\tau-1}^R}{n} \right), (...)$$

This signal is better than the one predicted with the order 0, especially in the straight lines. However, it has poor results during the breaks in the slope of the original signal.
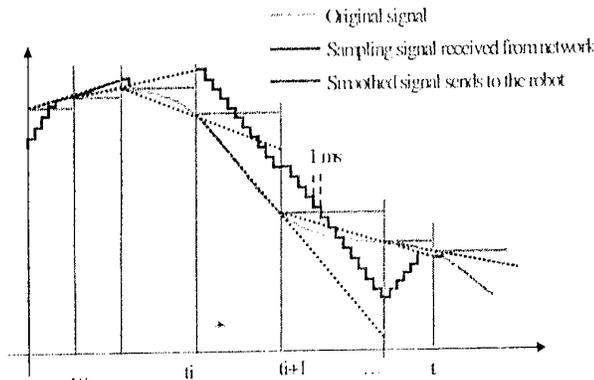
Figure 5. Predictive coding of order 1

For a predictive coding of hybrid order, the calculated signal is the half sum of the signal obtained by a predictive coding of order 0 and the one obtained by a predictive coding of order 1, see Figure 6.
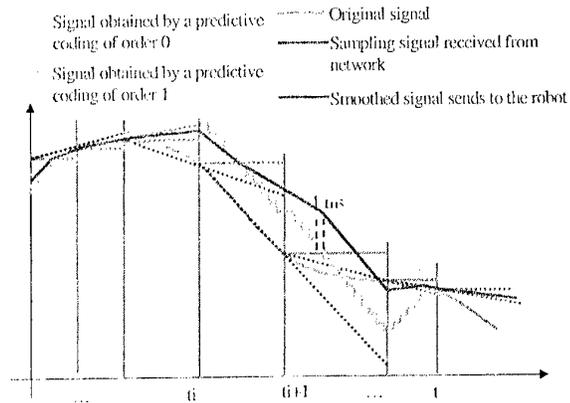
Figure 6. Predictive coding of hybrid order

We have smoothed the predicted signal as this last one results from an affin function of the input signal. The input signal arises from the digitalization of an analogical signal representing the hand movement, which acts on the robot arm. As the hand of the user vibrates slightly it appears teeth in the digitized signal, see the Figure 7, it is observed in a tenth of millimeter scale. The smoothing method consists in using a linear regression.
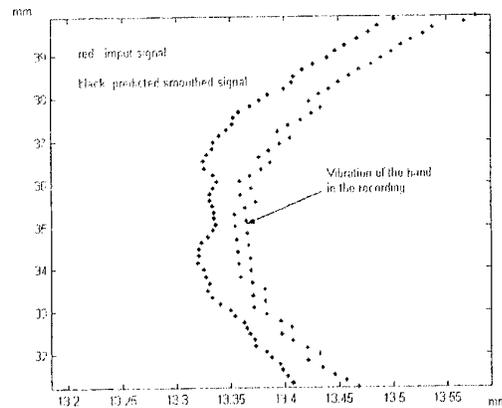
Figure 7. Example of the smoothing method

4. Tele gesture experiments

These experiments were performed using two PHANToM systems communicating through the network [1]. Each device sends its position and receives the position of the other. We tested the initialisation and shut down of the haptic session, the transmission of the position to the distant device, and the calculation of the

efforts at 1khz with a data refreshment at the reception with various rates ranging from 10 to 500ms. The first experimental results are reported in Table 2.

The case of the synchronous network (as ISDN) allows an interaction of the real gestures regularly. The up-to-date handing-over of the extrapolator of gesture is thus carried out regularly, according to a fixed period, dependent on the network.

The first experiments make it possible to test the first exchanges of gesture agility by the intermediary of the ISDN[3] network:

•Initialization of the haptic scene,

•Stopping the haptic scene,

•Sending the position of the local robot,

•Reception of the distant one at various rates: 500, 100, 10 ms,

•Calculating the efforts at a frequency of 1khz with a distant robot data refreshment at reception.

The first experiments are carried out with an ordering of position control on both sides of the network, and it was done the first time for tele-echography [4]. The predictive coding is of order 1, and the signal is smoothed. We use a second PHANToM to simulate the distant system, ie: the slave system. Each robot sends its position and receives the position of the distant robot, see figure 2.
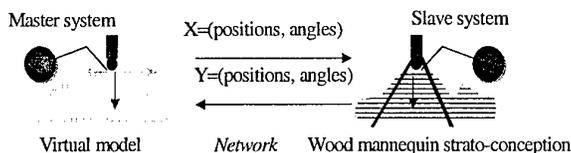
Figure 8. Position control on both sides of the network.

The mechanical model used in the first experiments is a link between the local model and the local perception of the distant model. At this point, the best way of sampling the messages must be found, the latency time due to the network, the robot 1kHz period of sampling, and to the optimal period of sampling for the gesture signal. We redefine the extrapolation algorithms of the positions and forces, and we test the predictive coding of 0, 1 and hybrid order of the distant mechanical models. Specific filtering of emissions and receptions of the gesture data is introduced. At the emission, it is a question of filtering the natural noise made by the hand. At the reception, it is a question of filtering the jitter introduced by the variable times of message transport, such as adding a low-pass filter on the speed of the gesture signals.
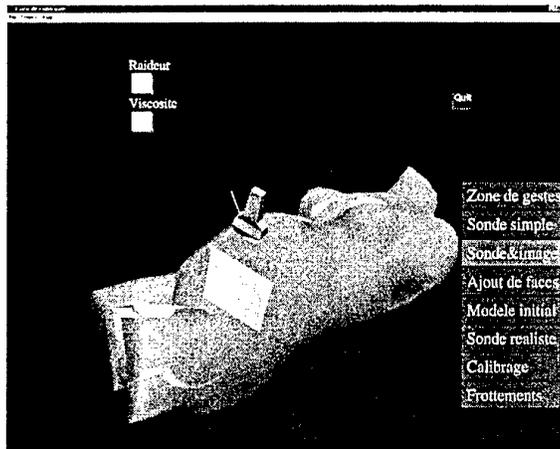
Figure 9. The tele-echography command station - a slow gesture

To improve gesture ergonomics of the expert within the tele-echography, we will create the virtual tangential forces, which increase quickly if the medical expert moves his hand too quickly, because the distant robot will have its own speed limits, see the green vectors on figure 2. The medical expert feels the force exerted on the patient and measured with a sensor, perpendicularly. Figure 3 shows the current interface of the haptic command station for tele-echography. The green segment materializes the intensity of the force perceived by the medical expert.

Table 2. Transmission experiments using the ISDN network:

Sample	10 ms	100 ms	250 ms	500 ms
Flow	100Hz	10Hz	4Hz	2 Hz
Haptic behaviour	Very good	Good	Some vibrations	Some vibrations and oscillations
Command ability	Natural	Restricted in term of the gesture speed	Difficult	Very difficult
Conclusion	Realistic	Realistic for slow gestures	Need to set up finer extrapolators of gesture	Need to set up finer extrapolator and stabilizer of gesture

The case of the asynchronous network (as internet) allows an irregular interaction of the real gestures. The up-to-date handing-over of the extrapolator of gesture is thus carried out irregularly, according to a non-fixed period, dependent on the network.

The fast gestures, such as the sword gesture, require a very low latency time of the intermediary telecom network. It should be less than 50 ms. Figure 10 shows the

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[3] Integrated Services Digital Network

example of the swords, a "game" of gestured agility. The current application calculates the intersection of two lines in space, i.e. the two swords. One of the swords is brought under control of the local robot; the local player handles it. The second sword is the local model from what occurs on the station according to the distant player.
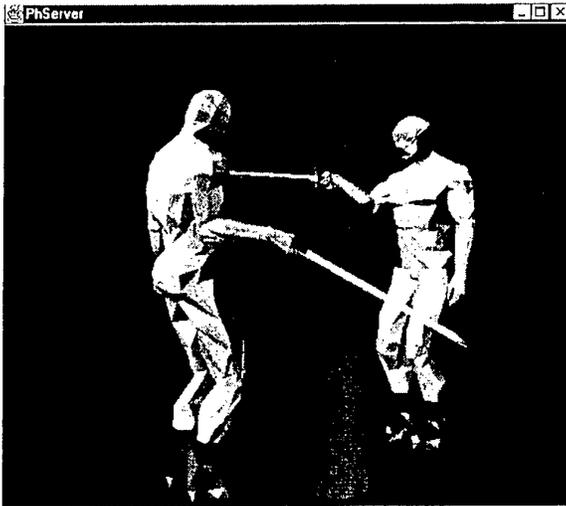
Figure 10. Sword gesture- a fast gesture

This game uses the LAN[4] network with UDP/IP[5]. The client side has to:
•Initialize the client,
•Create a socket,
•Receive messages at least at the message-sampling rate,
•Send messages to the sending message client, at the message-sampling rate 500, 100, 10 ms,
The server side has to:
•Initialize the server,
•Create a socket,
•Send messages at the message-sampling rate 10 ms,
•Receive messages at least at the message-sampling rate,
For the "game" of swords, the sampling period was 10ms. The predictive coding was of order 1, and the signal is smooth. The IP network is not a secure network and messages can be lost. It is also asynchronous network. In our experiment the latency was almost less than 10ms so, the results and the feeling were realistic and natural.

5. Conclusion

We experimented the transmission of haptic data on the ISDN network and also on local network (LAN). The results of our experiments are very encouraging and prove

that the gesture can be transported with the help of some ad hoc filtering, by ISDN network, or on IP. The transport of the gesture data via the network allows an immersion even more complete and realistic for distant manipulators.

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[4] Local Area Network
[5] User Datagram Protocol / Internet Protocol

The Perception of a Tactile Illusion in Central and Peripheral Nervous System Injury

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Abstract

Neuropathic pain patients often have lemniscal-mediated symptoms such as tactile allodynia. A novel method and device for testing lemniscal pathway integrity is described using a tactile illusion (TI) in patients with neuropathic pain resulting from peripheral nervous system (PNS) or central nervous system (CNS) injury. An unexpected enhanced perception of the TI was found in some PNS injured pain patients with mononeuropathies, in the majority of cervical spinal cord injured and in nearly half of brainstem injured central pain patients. A disinhibition of lemniscal pathway mediated TI was found in these patients. A subset of thalamic pain patients have a unique TI perseveration or persistent after-sensation despite reduced TI perception on their affected side compared to their normal side. The results of these studies indicate a unique form of sensory disinhibition not previously described.

Introduction.

Sensory illusions occur in the tactile, auditory and visual systems [1]. The tactile illusion (TI) of movement includes the phi phenomenon and is defined as the perceived movement between 2 or more fixed alternating points of vibration on the skin [2]. The TI perception is dependent on intact peripheral and central nervous system pathways including lemniscal pathways. The lemniscal pathway to the cerebral cortex is necessary for tactile discrimination. Cortical integration of peripheral stimulation is needed to form the TI of perceived movement between points of vibration that form symbols such as numbers "written" on the skin. This is distinguished from graphesthesia, defined as the ability to recognize numbers traced lightly on the skin with a stylus or pencil. Both lemniscal (pressure, touch, and vibration) and reticular (pain and temperature) neural pathways can be affected by a disease of the peripheral and central nervous system. This is due to the close anatomic proximity of these pathways so that pathologic injuries, such as diabetic neuropathies, traumatic nerve and spinal cord injuries, strokes to the brain, etc., primarily affecting one pathway can often affect the other. Injury to a single peripheral nerve can result in a perversion of the tactile sense, called allodynia, in which normally innocuous light touch (mediated by lemniscal pathways) is perceived as noxious or painful. Noxious stimuli are normally only mediated by reticular pathways. Disease or injury to the central nervous system (CNS) may produce similar distortions of lemniscal and reticular pathway-mediated sensations.

In these studies patients with CNS and peripheral nervous system (PNS) injury were tested using a device that produced the TI of numbers "drawn" on the skin across several dermatomes. These studies are described below and details have been recently published [3, 4].

Methods.

In the 2 studies described, patients were identified from the authors' [GRG] clinical practice, Mayo Clinic, Scottsdale, Arizona, U.S.A. An institutional review board protocol was submitted and approved for these investigations, and informed consent was obtained from all patients and controls. A room that was free of distractions was used in testing all subjects in both studies. The tactile device holds solenoids that vibrate and stimulate discreet cutaneous points and produce the illusion of "drawing" complex symbols (i.e. numbers) on the skin where the device is applied (see Figure 1).

In the first study, 27 patients with unilateral central pain resulting from a CNS injury to the cervical spinal cord, brain stem, lateral thalamus, or suprathalamic brain regions were studied using this device. The device is applied to the volar wrist on the unaffected, normal side first and then to the affected, painful side. In a second study, 8 subjects with PNS injury were tested using the same study procedures. The magnitude of the learning effect of delivering sequential stimuli was determined by testing the device on 10 normal, testing-naïve individuals. The learning effect, L, was expressed as $L=(T_1/T_2)\times100$, where T_1 is the total number of attempts to identify the 10 random digits presented on the first body side tested and T_2 is the total number of attempts to identify the 10 random digits presented on the second body side tested. The first side was tested immediately after testing the second side.

Tactile Illusion-Producing Device
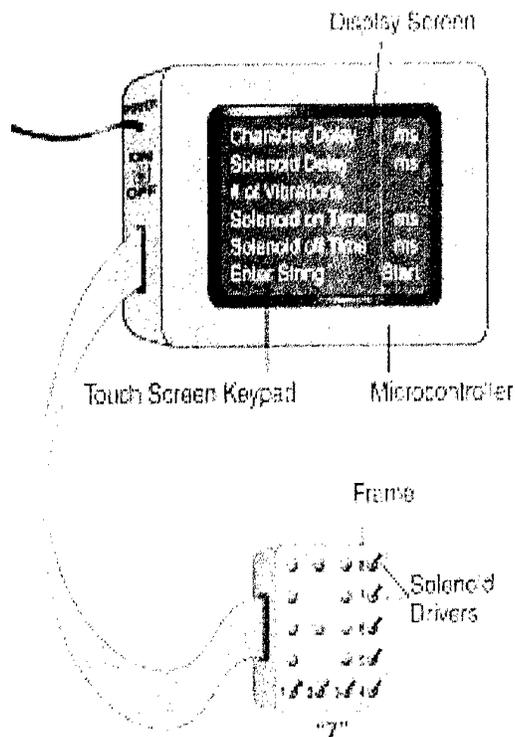
Figure 1. The tactile illusion-producing device with solenoids protruding demonstrating the number "7". The frame holds 18 solenoid drivers with vibrating cores in an array measuring 27mm x 33mm against the wrist. The sequence of solenoid protrusion for each of the 10 numbers delivered can be found in reference [3]. The fixed settings on the tactile device include, 5 protrusions/solenoid driver; 5 msec interval between protrusions; 10 msec solenoid on-time and 10 msec solenoid off-time

Results. In measuring the learning effect, 9 of the 10 normal subjects improved in that they required fewer trials to identify correctly the 10 randomly delivered numbers on the second side tested. The median learning effect, L was 1.23%. This constant, L, was then applied to the number of trials on the affected side of the patients with pain from CNS and PNS injury to yield the *Affected Side, Adjusted-for-Learning* values=1.23x, where x=the number of trials on the affected side.

As expected, in the first study, 8 of 10 patients with thalamic and suprathalamic central pain had decreased TI perception on the affected side. Unexpectedly, 7 of 10 patients with cervical spinal cord central pain, and 3 of 7 patients with brainstem central pain had better TI perception on their affected side. In other words, fewer number of trials were needed for them to correctly identify the number presentation when their abnormal side was compared to the normal side. The enhancement of the perception of the TI in the majority of patients with cervical spinal cord central lesions and in nearly half of the brainstem-injured patients was unexpected. Another observation from this study was that 2 of 4 patients with thalamic injury had a unique phenomenon of TI perseveration, despite a decreased TI perception on the affected side. This perseverance was maintained and more than one number could be felt simultaneously even after subsequent stimulation to that body part was discontinued [3].

In the second study, performed on 8 patients with PNS injury and mononeuropathy with tactile allodynia, 3 of 8 patients unexpectedly had better TI perception on the affected side compared to their unaffected side [4].

Discussion. Lesions within the PNS and CNS that cause pain are often associated with lemniscal pathway injury as well. For example, a mononeuropathy caused by a traumatic injury to the ulnar nerve will often injure motor and sensory fibers. The injured sensory fibers are destined for both the pain- and temperature-mediating reticular, spinothalamic pathways as well as touch-, pressure-, and vibration-mediating lemniscal, posterior column pathways in the spinal cord. Lesions in the CNS, in particular those above the spinal cord level, are associated with both reticular and lemniscal pathway injury due to the close proximity of the pathways in brainstem, lateral thalamic, and suprathalamic regions. Spinal cord lemniscal pathways are located in the posterior spinal cord whereas reticular pathways are located primarily in the anterior spinal cord. None-the-less spinal cord injuries from conditions such as infarcts, trauma, multiple sclerosis plaques and others will often times produce injury to both sensory pathways.

Even though spinal cord, brainstem and suprathalamic lesions can cause central pain without thalamic injury, central pain is dependent upon thalamic modulation [5]. The accentuated perception of the TI in some PNS and CNS neuropathic pain patients are consistent with a proposed central disinhibition theory. This theory posits that "tonic activation from net descending facilitation of supraspinal sites" [4], results in improved cortical

Fingertip Tactile Illusion-Producing Device
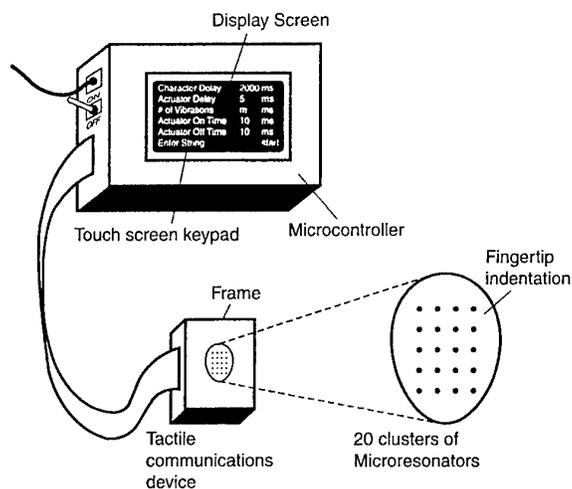
A.
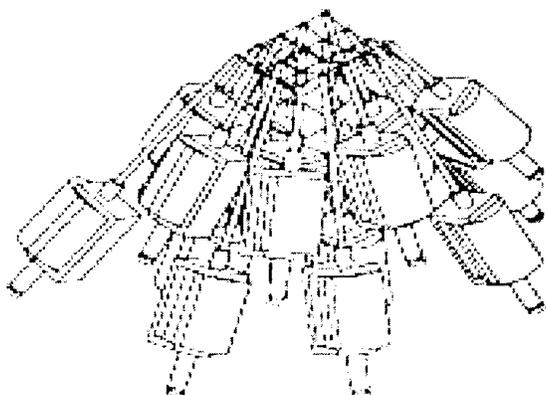
B. Microsolenoids

Figure 2. Microresonators in A. fit below the surface of the finger indentation of the frame. The resonators may be clusters of microelectrical mechanical systems (MEMS) or hexagonally stacked, splayed array microsolenoids as shown in B.

processing of the TI [5, 6]. In the thalamic injured central pain patients with TI perseveration, the possible mechanism of this phenomenon may include TI aftersensations released from the disinhibited cortex or thalamus, similar to the tactile movement aftereffect mechanism proposed by Hollins and Favorov [7].

The device in Figure 1 produced cutaneous stimulation over several dermatomes. Theoretically a device that would stimulate a single dermatome will provide more

precise determination of peripheral inputs needed to produce this illusion, which is ultimately caused by brain cortical activity. Newer devices in development will activate a smaller area of skin on the "tactile rosette" of the index finger, in a single dermatome, and will spatially reduce the area of CNS somatotopic activation (see Figures 2A and 2B).

The index fingertip is also known to have a higher density of Pacinian corpuscles than more proximal cutaneous sites and has a greater primary, and possibly secondary, parietal cortical representation than more proximal cutaneous dermatomes. Localization using a single dermatome TI device on the fingertip will assist in the interpretation of CNS imaging using functional magnetic resonance imaging (f-MRI). Therefore, this type of device will be helpful in determining factors that may modulate TI discrimination as well as injury associated sensitivity changes of the lemniscal system. This may also help define whether the newly described observation of TI perseveration in subsets of patients with central pain is dependent on multiple peripheral nerve or dermatomal activation, or spatial summation in a single nerve or dermatomal distribution.

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The Potential Importance of Perceptual Filling-In for Haptic Perception of Virtual Object Form

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Abstract

The aim of this paper is to discuss the possibilities of Perceptual Filling-In to be useful in haptic displays, especially for perception of 3D form. Examples of the functioning of this mechanism in vision and natural haptics are reported, and obstacles for its application in haptic displays are pointed out, such as the lack of extended surface contact, restriction (usually) to one point of contact and the impossibility of performing exploratory procedures known to be effective in natural haptics. It is stated that the haptic information obtainable in the haptic displays developed so far is not sufficient and accurate enough, and that conditions favouring mechanism such as Perceptual Filling-In should be seriously looked for.

1. Introduction

Visual displays can mirror the real world to a very high degree. So far, haptic displays lag far behind visual displays in efficiency of displaying representations of the real world. The success of visual displays depends both on the ability of vision to handle large amounts of complex information and the technical possibilities to imitate this information. However, the visual imitation is not perfect but utilises also the fact that vision can successfully handle also optical information deviating from the information presented in the real world. This simplifies the technical task considerably. One example of this is that a series of still pictures separated by black intervals (film) is perceived as a continuous, constantly changing event. This is based on the so-called phi-phenomenon (motion perceived from still pictures under certain conditions), and the perception is further improved by the perceptual fusion of high-frequency flicker. Another example is TV that is possible because of the fact that the eye has not sufficient spatio-temporal resolution to be able to perceive the rapidly moving dots but integrates instead the scene perceptually.

The aim of this paper is to discuss the possibilities of utilising related options for haptic displays, especially for 3D form perception. One possibility might be to utilise a perceptual mechanism that is important for vision and natural haptics and potentially useful also for display haptics. The mechanism is called *Perceptual Filling-In (PFI)*. The emphasis here will be on the problems of 3D form perception in haptic displays and the possible contribution of PFI. For comparison, some related visual phenomena will also be shortly presented.

2. PFI in vision

PFI handles situations where stimulation is incomplete or totally missing. Well-known examples of this mechanism in vision are the PFI of stimulation corresponding to the blind spot in the eye, as well as some kinds of scotoma; where the non-existing visual information on the retina corresponds perceptually to a surface of the same kind as the surrounding areas. Other examples are cases where whole figures and objects are perceived from incomplete artefacts when gaps in the stimulation are filled in perceptually. The Gestalt psychologists suggested a law of closure to account for perception in such cases. Subjective contours (also called illusory or cognitive contours) are phenomena of a related kind.

2.1. Visual point stimuli

Especially analogous to the stimuli presented by present-day haptic displays are visual point stimuli. It is well established since Johansson's motion perception experiments [11, 12] that two points in motion are perceived under many conditions as the endpoints of a rod. These results have been further elaborated concerning patterns consisting of a few dots in motion [2, 3]. Biological motion patterns [13] consisting of 12 moving dots are perceived as human beings with straight invisible lines of constant length connecting the dots. A point line pattern can also be perceptually connected by curved lines, for instance as a bending line [6, 19], and it has been demonstrated that the number of points in such a line can be considerably reduced without destroying the perception of an object bending smoothly [14].

3. Compensation with Visual Information

The problems with 3D form perception for haptic displays may not be identified as problems as long as haptic and visual information are available together. Vision provides an overview and thereby "fills in" the gaps in haptic information. It also suggests interesting parts of the scene to be explored, which makes haptic exploration more effective. This means that haptic PFI is less needed in this case.

The dominant role of vision for the judgement of 3D form of real objects with both visual and haptic information available has been experimentally demonstrated [16]. When vision was available together with optional haptics, the observers typically used only vision for judgements of geometric properties, such as size and form. Haptics was used mainly for material properties, such as texture and hardness. A similar result was obtained in a study concerning virtual objects [1].

4. Perception of Form by Haptics Alone

During natural conditions also haptics alone has a high capacity. In his studies of haptic perception of real objects, Gibson [4, 5, pp. 124-126) found that the observers can be quite successful under these conditions.

When observers have to rely on haptics alone when using haptic displays, as, for instance, blind people have, the situation is quite different. When natural and virtual perception of 3D form of small objects of simple geometric forms were compared, the virtual cases (explored with a PHANToM) were found to be both less accurate and requiring longer exploration times [7]. Even if performance was improved when objects were larger (up to 100 mm) [7], and when practice was allowed [10], the performance never reached the level obtained when real objects were involved. Effective presentation of virtual objects with a complex form is still a difficult problem [8].

4.1. The Importance of Exploration

The hand as a haptic sense organ may be described as a touch unit consisting of five fingers as suggested already by Katz [15, p. 59]. Considered in this way, the stimulus properties available when grasping an object is at each moment obtained from up to five small surfaces spatially separated by (sometimes) large gaps and from the kinaesthetic information from muscles, tendons and joints during the grasp. The haptic perception is usually further strengthened by exploratory movements, and total perception is based on integration over time. According to Gibson [4, 5], observers when exploring tactually curved their fingers around the face of the object, used all their fingers and fitted them into the cavities and used oppositions of thumb and the other fingers. In haptic perception of real objects an essential role was also played by finger directions and finger spans, the "bone space"[5, p. 125].

Lederman & Klatzky [17] presented more detailed studies of the exploratory procedures in haptics. Concerning perception of form/shape, they identified two main exploratory procedures: *enclosure*, which is performed by more than one finger and often both hands, and *contour following*, which may be executed by one or more fingers. These exploratory procedures may be performed in sequence. The efficiency of these procedures, also for quite complex object forms, is remarkable concerning both accuracy and speed.

5. PFI in Haptic Displays

The importance of PFI for visual perception has been demonstrated. Stimulation from two or more points may give perception of an object filling the space between these points. The present discussion concerns the possibilities of a similar mechanism in haptics, especially for the perception of 3D form of virtual objects. That such forms can be perceived is a critical feature for the usefulness of haptic displays when haptics is the only form of information available. If form perception under this condition is not sufficiently accurate and fast, the use of such a display without visual assistance may be questioned. It is therefore important to try all potential options to increase accuracy and speed in these cases.

5.1. 2D Form

That PFI can work also in virtual haptics is demonstrated by the relative success of displays consisting of a matrix of tactile point stimuli, such as the Optacon. The raised points of this kind of display are typically perceived as lines and areas in 2D. It should be observed, however, that in these cases a larger skin surface is in contact with the display, and some displays allow also the use of more than one finger.

5.2. 3D Form

The perception of 3D form by haptics is more complicated than, for instance, the perception of 2D form and of texture. A uniform texture (the microstructure or high frequency properties) can be explored rather similarly in natural and display haptics, by lateral movements over the surface, and the resulting perceived properties of the surface may be quite similar in the two cases [9]. In contrast, the exploratory procedures available when the task is to judge global form (the macrostructure or low spatial frequency properties) are quite different in natural and display contexts.

5.3. Differences in Exploratory procedures between Natural and Display Haptics

In natural haptics the exploratory procedures pick up information from both extended skin surfaces and from the kinaesthetic sensory system. When a real object is explored for judgment of form, the result is that an object is perceived that fills the space between the contact points. The goal for haptic displays should be to construct them such that sufficient information can be picked up to make perception of a virtual object between the contact points possible.

Important features of most haptic displays are that the contact between observer and virtual object is restricted to a minimal point of a virtual object and is mainly based on kinaesthetic information. 3D form may be perceived in this situation, but not with the same accuracy and speed as in real haptics [7]. That the elimination of spatially distributed information at the skin is an important factor was demonstrated by experiments where a similar restriction was applied to real object exploration [18]. The results in these experiments were that several haptic functions were substantially impaired.

Information about 3D form of a virtual object can in these cases be obtained only over time. Such exploration, for instance with a one-point stylus, is not common in natural haptics. Exploring with a thimble is more similar to natural exploration, but in natural haptics it is not the only available exploratory procedure.

5.4. Can Multi-Finger Displays Solve the Problems?

For PFI to function in simultaneous stimulation there must be at least two points of contact. For perception of 3D form there ought to be at least three. As with visual point stimuli it can be expected that stimulation changing over time increases the efficiency. With a one-point display it is not possible to enclose the virtual object in order to get information about its form. An important exploratory procedure is thus not available.

Haptic exploration of a real object is an effective but complex activity, which may be difficult to mirror for virtual objects. The object is moved around by fingers of one hand or both hands, which provides a richness of both cutaneous and kinaesthetic information far from the poverty of information obtained when only one small point at a time is in contact with the object.

There are efforts to provide the observer with more contact points. Using two PHANToMs, for instance, is possible, and a six-degrees-of-freedom PHANToM has been constructed (http://www.sensable.com), as well as multi-finger displays, for instance the CyberGlove and the CyberForce (http://www.virtex.com). Such devices increase the number of contact points, but to what extent

they improve the perceptual potentials of virtual 3D form perception does not seem to have been studied. A six-degrees-of-freedom stylus gives an opportunity to get more than one contact point. However, to what extent is information from minimal points along a stylus useful for judging the form of a virtual object?

It remains also to be studied if multi-finger displays offer stimulation sufficiently similar to that obtained in natural haptics to make effective 3D form perception possible. The availability of information from several minimal points may not be sufficient. The exact form of the kinaesthetic information is probably also critical. It is still an open question if such information is provided via the present multi-finger displays with force feedback in a few directions.

6. Conclusion

Natural haptics alone is quite accurate and fast in perceiving 3D form, but haptic displays developed so far are not as successful. They do not mirror very closely the haptic information obtained naturally, which means that the information they provide is not sufficient and adequate enough. The finding of conditions favouring haptic PFI ought to be seriously considered. It works in vision and natural haptics. If such conditions can be found, the performance of users may be improved and the technical development of new devices simplified.[1]

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Touching trajectories: the relation between speed and curvature in exploring shape.

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Abstract

Studies in motor psychophysics have documented that the tangential velocity of movement decreases with increasing curvature of the path being followed. Views on the origin of this relation range from higher order motion planning processes such as trajectory selection according to a principle of minimisation of mean squared rate of change of acceleration (jerk) to lower level motor constraints, for instance sinusoidal constraint on joint motion. We have examined finger-scanning movements in which eight subjects traced repeatedly round various raised outline shapes. We were interested to see whether velocity would be related to curvature from the outset, suggesting low level sensorimotor constraints, or whether the relation would emerge with experience, as a result of increased trajectory planning. We found evidence of a relation between speed and curvature from the outset, in support of lower level, rather than trajectory planning, constraints.

1. Introduction.

A fundamental law in motor psychophysics is the one third power relation between movement speed (or more precisely, tangential velocity) and radius of curvature of the path followed:

speed =
radius_of_curvature*exp(1/3).

The smaller the radius of curvature (the greater the curvature) the lower the speed.

Although a relation between speed and curvature has been acknowledged for over a century (Jack, 1895) there has been considerable growth in interest since Lacquaniti et al (1983) provided a thorough quantification of the law in drawing movements. The law holds for writing as well as drawing movements. It holds for movements in the plane or in 3d (Schall and Sternad, 2001) and for drawing motions directed by 3-d isometric force control (Massey et al, 1992). The one-third power law has been demonstrated in children as well adults although the exponent changes with age

(Viviani and Schneider, 1991). It has been found for mechanically constrained or free form movements, with or without visible trace of the path traced out (Viviani, BaudBovy & Redolfi, 1997) and for eye movements (de Sperati and Viviani, 1997). When participants were guided around an elliptical track by a robot, which followed a different relation between speed and curvature, subsequent free reproduction of the track without any guide conformed to the one third power law (Viviani et al 1997).

The one-third power law has been attributed to motion planning processes with trajectory selected according to a principle of minimisation of jerk, the third derivative of position, in order to obtain maximally smooth movements (Flash and Hogan, 1985; see also Wann, Nimmo-Smith & Wing, 1988; Viviani and Flash 1995). An alternative interpretation is that the relation reflects a fundamental constraint on motor control. For example, in handwriting it has been attributed to the combination of oscillatory tendencies related to x- and y-directions which may reflect joint rather than hand space constraints (Schall and Sternad, 2001).

In the above studies the movements analysed were made to spatial targets which the participant had opportunity to plan. We ask whether the one-third power law applies to tactile exploration where a continuous curve target path (circle and ellipses) has to be discovered. When finger scanning movements are used to trace an outline shape without visual guidance, it is reasonable to expect that the demands of tactile and proprioceptive information pick-up will result in relatively slow movements. But, will the slowing be related to curvature? If the one-third power law arises from planning processes, the relation between speed and curvature would only be expected to appear as information about the path becomes available from the haptic input. However, if the relation arises from low level sensorimotor constraints, these would be expected to scale down to lower speeds used in first exploring the shape. The results that we report in this paper show differences in speed at the major and minor axes of the ellipses

consistent with the power law thus supporting sensorimotor rather than motion planning constraints.

2. Method.

2.1 Subjects.

Eight subjects (4 male, 4 female, age range 19 to 22 years, right-handed for writing), students of The University of Birmingham, participated on a voluntary basis.

2.2 Apparatus.

Motion of a reflective marker placed on the nail bed of the index finger of the right hand was tracked at 100 Hz with a 3-camera infrared motion tracking system (Qualisys ProReflex). The system calibration yielded 0.2 mm resolution over a working area of 40 x 40 cm. Outline shapes were constructed from (4 mm diameter) plastic coated electrical cable glued to a stiff backing board. They comprised a circle (radius 12 cm), a wide ellipse (angular eccentricity 45° and linear eccentricity 24 cm) and a narrow ellipse (25° and 24 cm).

2.3 Task and procedure.

The subject was seated at a table with the outline shape placed on it so that the semiaxes (of the ellipse) were aligned to the subject's coronal (left-right) and sagittal (anterior-posterior) planes and corresponded to the x and y axes of the motion tracking system. Instructions were given to use the right index finger to trace each shape at a comfortable speed for 30 s in an anti-clockwise direction with the pad of the index finger on top of the wire. The subject was instructed not to rest the finger tip on the surface, nor to use the wire as a guide "fence", nor was any other part of the hand or arm allowed to touch the shape or surface of the table. Three successive trials were run with each shape before proceeding to the next shape. The ellipses were presented, first with long, then with short, axis parallel to the coronal plane. All trials were first run with the subject's eyes closed and subsequently repeated, one trial per condition, with the subject allowed full vision.

2.4 Data processing.

Tangential velocity (speed) at x- and y-extremes was determined from the finger tip trajectory after low-pass filtering (Butterworth 2-order 10 Hz) the x and y coordinate streams.

2.5 Design.

A repeated measures design was used with fixed order of outline shapes but with the order varied across subjects so that each shape appeared in first position approximately the same number of times.

3. Results.

Illustrative time and spatial finger tip trajectories for one subject tracing the wide ellipse oriented in the coronal plane without (above) and with (below) vision are shown in Figure 1. The time waveforms show the greater speed achieved in the presence of vision. The increased speed is associated with the development of a series of local speed maxima and these can be seen to be aligned with extremes in y-displacement associated with low curvature at each end of the minor axis of the ellipse. Emergence of similar maxima may be seen in the absence of vision, although, in this case, only after a couple of passes around the ellipse. In this example, the speed maxima are much more poorly defined than in the vision condition although there is a suggestion they align with the y extremes.
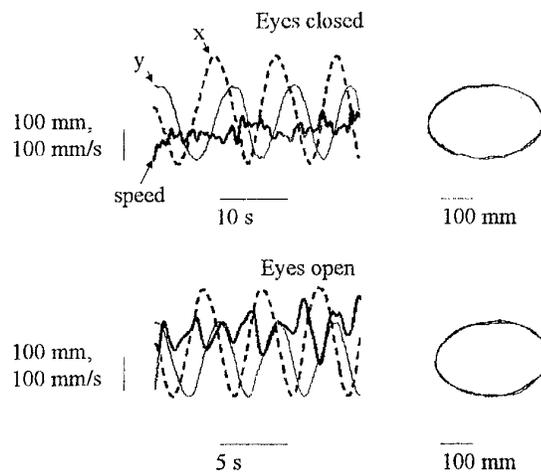
Figure 1: Time (left) and spatial(right) trajectories for two single trials in which the subject traced the wide ellipse by touch alone (above) or with vision (below). Displacements (x dashed, y thin continuous lines), speed (thick line) are plotted on the same vertical scale but note the difference in the time scale reflecting the doubling in speed with vision.

The number of cycles completed in each 30 s trial shown in Figure 2 provides an indication

of the average speed of finger scanning. It can be seen that, for each outline shape and ellipse orientation, the speed progressively increases across the 3 trials without vision, although remaining slower than with vision. This was confirmed by reliable main effects of trial ($F3,21=53.49$, $p<.01$) and stimulus ($F4,28=5.65$, $p<.01$) in repeated measures ANOVA. The interaction between trial and stimulus was also reliable ($F12,84=4.92$, $p<.01$).
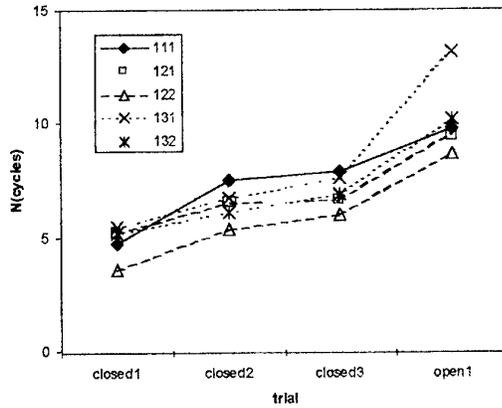
Figure 2. Average (N=8 subjects) of the number of cycles completed in each 30 s trial as a function of trial (trials 1-3 eyes closed, 4 eyes open). Five stimulus types are represnted in the five sets of lines - circle (coded 111), wide (12.) or narrow (13.) ellipse with the ellipses oriented with major axis parallel to the coronal (..1) or saggital (..2) plane.
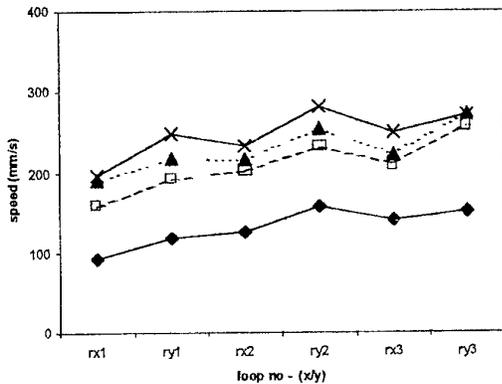
Figure 3. Speed as a function of 3 successive loops (measures taken at x and y extremes in alternation) around the circle. The four curves relate to no vision trials 1-3 (lower speeds) and vision trial 4 (highest speed).

The measured speed at x and y displacement extremes in tracing around the circle for the first three complete loops is

shown in Figure 3. An increase in speed over haptic trials is clear although the trials with vision remain faster. There is also an increase in speed evident over the 3 successive loops around the circle.

The speed at major and minor axes of the wide and narrow ellipses is shown in Figure 4. An increase in speed over haptic no vision trials is clear although the trials with vision remain faster. There is also a slight increase in speed evident over the 3 successive loops. It can also be seen that the speed is greater for the lower curvature minor axis of the ellipse which, depending on whether the ellipse is oriented with coronal (LR) or saggital (AP) planes, corresponds to the y (in LR) or x (in AP) displacement extremes.
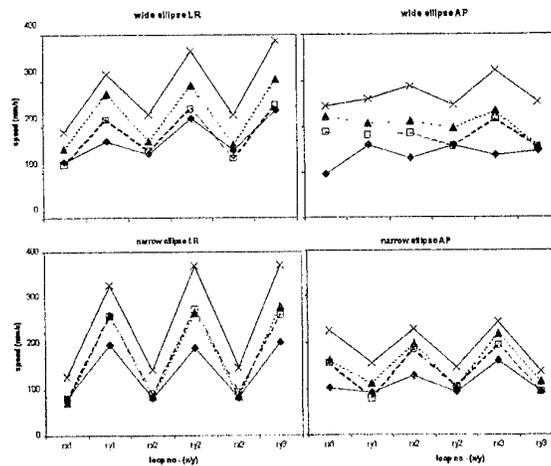
Figure 4. Speed as a function of 3 successive loops (measures taken at x and y extremes in alternation) around the ellipse. In each of the four plots the curves relate to no vision trials 1-3 (lower speeds) and vision trial 4 (highest speed). The separate plots relate to ellipse shape (top row - wide; bottom row - narrow) and orientation: (left column coronal LR; right column saggital (AP).

Separate repeated measures ANOVAs for each stimulus generally revealed significant main effects (9 out of 12 cases) of trials, loops and axis ($F3,21$, $F2,21$ and $F1,7$, ranging 8.57-38.88, $p<.01$, 3.89-16.86, $p<.05$ and 32.80-135.03, $p<.01$ respectively). Interactions terms involving loop number x axis and trial x axis ($F2,14$ and $F3,21$ ranges 6.34-32.51, $p<.01$ and 5.71-17.82, $p<.01$ respectively) were significant in 7 out of 8 cases due to there being less difference between speed at high and low curvatures at x,y extremes in the initial trial and initial loop. However, none of the three-way trial x loop x axis interactions was significant.

4. Conclusion.

Numerous studies have shown a power law relation exists between curvature and tangential velocity (speed). For the first time we have examined haptic exploratory movements in which subjects used the index finger to trace out a raised outline. We considered two alternative predictions. Under the motion planning hypothesis we predicted that in the early stages speed would be constant. Only with knowledge of shape gained from haptic exploration would the relation between speed and curvature emerge. Under motor constraints we expected that the relation between speed and curvature would hold from the outset, even at the lower speeds of initial exploration.

The results showed large increases in the speed of scanning with the index finger tip with growing experience of moving around circular and elliptical outline shapes. However, a relation between speed and curvature was observed from the very beginning, although the difference in speed at high and low curvatures was somewhat less in initial loop around the ellipses and on the initial trial. We therefore suggest that the one third power law reflects low level sensorimotor processes involved in movement execution and not higher level motion path planning processes. However, this conclusion must be tempered by the following observations:

1) in this preliminary analysis we have not documented the continuous relation between speed and curvature, but simply focussed on curvature extremes.

2) in this study, the regularity of the geometric shapes (circles and ellipses) may have led to rapid recognition of the particular form being traced. This means that subjects may have been able to form a mental image of the general shape class, sufficient to support motion planning very soon after contact. In further experiments we are evaluating haptic scanning of irregular raised outline paths of non-closed form.

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Psychological Theory in Haptic Interface Design:
Initial Steps Towards an
Interacting Cognitive Subsystems (ICS) Approach

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Abstract

Haptic tasks call upon diverse processing resources within the human cognitive architecture. In order to develop appropriate interfaces it may, in consequence, be advantageous to adopt a holistic, psychologically based approach to its study. A candidate theory through which this might be achieved is Barnard's Interacting Cognitive Subsystems (ICS). ICS is a comprehensive theory of cognition and affect. It abstracts across the details of individual types of processing in order to permit a generic understanding of the systemic principles operating across the human cognitive architecture.

ICS is briefly described, followed by an example scenario, in order to illustrate how it might be applied to the understanding of haptic tasks. In addition, the structure of mental representations within individual types of processing is outlined. The importance of system-wide cognitive processes is considered before finally, an outline is given of the aims and objectives of the author's future work.

1. Introduction

Effective haptic interaction frequently requires complex cognitive activity on behalf of the user. For example, touch-based perceptions may be affected by various factors. These include stored high-level knowledge [1], the particular object properties sensed [2], availability of cues for object identification [3], perceptual bias by other modalities [4, 5, 6] and cross-modal attention [7, 8]. The sense of touch is, therefore, dependent upon diverse cognitive resources and, as a result, it may be useful to adopt a holistic, psychologically based approach to its study.

The present paper outlines initial steps towards the achievement of a holistic, haptic psychological schema, based upon Barnard's Interacting Cognitive Subsystems

(ICS) [9]. ICS is a comprehensive theory of cognition and affect. It adopts a systemic approach in which information flows within a highly parallel and modular architecture of distributed cognitive resources. As behaviour arises out of the coordinated operation of its constituent parts, a major advantage of ICS is that cognition and affect can be considered within an overall psychological context, therefore making it ideally suited to inform reasoning about complex haptic interaction.

A brief outline of ICS will now be provided followed by a description of some of its implications for haptic processing. For a detailed description of the ICS architecture interested readers should refer to previous publications in which it has been outlined fully [10, 11, 12, 13].

2. ICS

ICS postulates nine subsystems, each of which differs in terms of types of information dealt with, level of representational abstraction and form of processing code (Figure 3). Although individual subsystems are associated with different types of subjective experience, they each share the same basic internal processing architecture, including a local memory (*Image Record*) and a number of parallel processes through which information is *transformed* from one form of subsystem code to another (Figure 1). This permits subsystems to operate together as a cohesive system. Behaviour results, therefore, from the flow of information through processing configurations within the overall cognitive architecture.

The transformations permissible have been derived systematically according to evidence available from experimental psychology and subjective plausibility (Figure 2). ICS has been applied within many theoretical areas including the understanding of depression [10, 11], mental number generation [14] and the analysis of cognitive processing in complex user tasks [15].

3. ICS and the haptic sense

ICS may be used to predict various mental and behavioural effects for users engaging in haptic tasks, with many implications for effective interface design. Most importantly, the model makes it possible to reason about the flow of information through the human cognitive architecture between sensation of a stimulus and production of a response. For example, if a user is presented with an apparently simple haptic task (such as to obtain as much information as possible about an unknown felt object) a characteristic flow of information processing may be predicted.
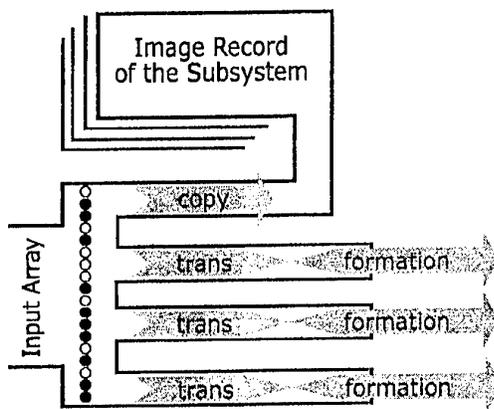
Figure 1.   The internal architecture of an individual subsystem

3.1 Sensation and premotor action plans

Information will arrive within ICS via the bodily receptor organs at the BS (*Body State*) subsystem. Representations within BS are based upon information about the type of stimulation experienced (e.g. cutaneous pressure, temperature, muscle tension etc.), its location, intensity and so on. The resultant subjective experience takes the form of bodily sensations including pressure, pain and positions of parts of the body. Three parallel transformations from BS code to other types of subsystem code will then occur, two of which are central to the understanding of haptic experiences.

A transformation from BS to the LIM (*Limb*) subsystem produces representations based upon information about bodily forces, target positions and timing of skeletal musculatures. Subjectively speaking the experience is of 'mental' physical movement. Through the combined action of the BS and LIM subsystems it therefore becomes possible for a comparison to be made between actual bodily states and planned bodily states. Once executed as physical actions upon the world, the

results can then be assessed through subsequent sensation, thereby forming a loop through which accurate bodily adjustments and readjustments may be achieved.
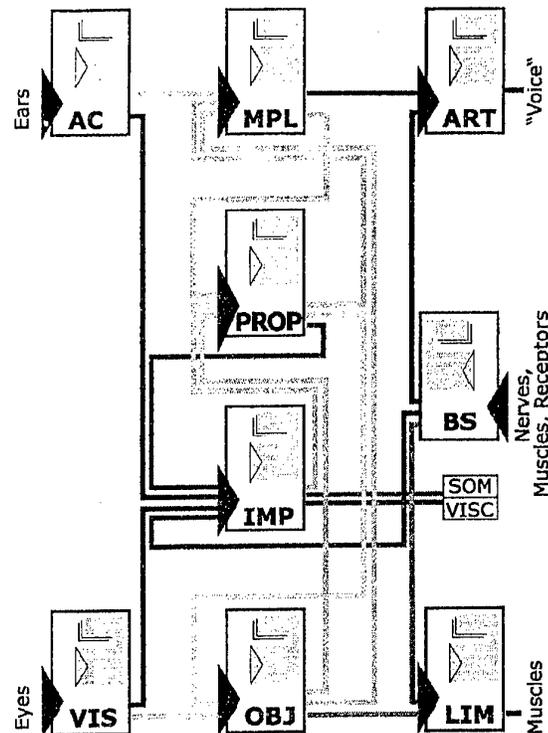
Figure 2.   Schematic representation of ICS including the full range of permissible transformation processes (grey lines)

3.2 Sensation and high-level cognition

A parallel transformation from BS to the IMP (*Implicational*) subsystem results in schematic representations of sensory experience. For example, abstract ideational properties, such as surface 'hardness' or 'smoothness', may be subjectively experienced. It is, therefore, possible for haptic information to access the level of meaning in a relatively direct manner within ICS. The result may be an ability to use touch to categorise sensation within different types of schematic concepts. In order for the user to take advantage of haptic experiences in other ways, however, further processing is necessary in terms of transformations to other subsystems.

For example, a transformation from IMP to the PROP (*Propositional*) subsystem results in representations based upon semantic fact, the subjective experience being of

PERIPHERAL SUBSYSTEMS

a) Sensory
(1) Acoustic (AC):
Sound frequency (pitch), timbre, intensity etc.
Subjectively, what we 'hear in the world'.
(2) Visual (VIS):
Light wavelength (hue), brightness over visual space etc.
Subjectively, what we 'see in the world' as patterns of shapes and colours.
(3) Body State (BS):
Type of stimulation (e.g., cutaneous pressure, temperature, olfactory, muscle tension), its location, intensity etc.
Subjectively, bodily sensations of pressure, pain, positions of parts of the body, as well as tastes and smells etc.

b) Effector
(4) Articulatory (ART):
Force, target positions and timing of articulatory musculatures (e.g., place of articulation).
Subjectively, our experience of subvocal speech output.
(5) Limb (LIM):
Force, target positions and timing of skeletal musculatures.
Subjectively, 'mental' physical movement.

CENTRAL SUBSYSTEMS

c) Structural
(6) Morphonolexical (MPL):
An abstract structural description of entities and relationships in sound space. Dominated by speech forms, where it conveys a surface structure description of the identity of words, their status, order and the form of boundaries between them.
Subjectively, what we 'hear in the head', our mental 'voice'.
(7) Object (OBJ):
An abstract structural description of entities and relationships in visual space, conveying the attributes and identity of structurally integrated visual objects, their relative positions and dynamic characteristics.
Subjectively, our 'visual imagery.'

d) Meaning
(8) Propositional (PROP):
A description of entities and relationships in semantic space conveying the attributes and identities of underlying referents and the nature of relationships among them.
Subjectively, specific semantic relationships ('knowing that').
(9) Implicational (IMPLIC):
An abstract description of human existential space, abstracted over both sensory and propositional input, and conveying ideational and affective content: schematic models of experience.
Subjectively, 'senses' of knowing (e.g., 'familiarity' or 'causal relatedness' of ideas), or of affect (e.g., apprehension, desire).

Figure 3. The functions of the nine ICS subsystems (adapted from Barnard and May, 1995 [13])

meaningful statements about the sensory experience such as 'This is a hard, smooth surface'. Two further parallel transformations then occur. A link direct from PROP back to IMP results in reciprocal loops of processing between the two subsystems. As a result, meaningful thought becomes possible. Indeed, the transformation processes between PROP and IMP form the processing basis for many types of high-level cognitive tasks and their combined action is, therefore, termed the *Central Engine of Cognition*. Furthermore, representations of tasks themselves will be processed within IMP and PROP, thereby allowing representations (achieved through transformations from the senses) to be related to the active aims and goals of the perceiver. In the present instance the task may result in representations at PROP such as 'learn new things using touch' and, at IMP, categorizations of information as 'old' or 'new'. The two subsystems will, therefore, complement each other in decision making such that new information is processed and old information is not.

3.3 Visuo-spatial and auditory Imagery

In parallel with the initial transformation from PROP to IMP a second process also occurs to the OBJ (*Object*) subsystem. Here visuo-spatial representations become active, the result being mental imagery based upon PROP output. Whilst this may permit the activation of a mind's eye image of the felt experience, it is rendered indirect by the need to pass first through IMP and PROP after the initial BS representation. Information sensed via touch may, therefore, permit the achievement of effective visuo-spatial imagery but only *after* processing at the level of meaning.

In addition, a third transformation from PROP to the MPL (*Morphonolexical*) subsystem produces representations characterized in terms of auditory imagery and, in particular, that relating to speech. The subjective experience for the user will be of an 'inner voice' - an internal verbal dialogue based upon the output received from PROP. As conduction of the haptic task progresses this will serve as a subvocal commentary upon the state of the interaction. Via a transformation back to PROP representations processed at MPL may, in turn, influence the level of meaning. The user might, therefore, engage in an internal discussion with him/herself through the reciprocal action of MPL and PROP.

3.4 Stored information

Haptic processing is also dependent upon stored representations at each of the various subsystems involved. If incoming information matches or activates representations within the image record of a given subsystem, the data held within memory may be used to

elaborate that derived from the immediate sensation, the result being relatively fast and detailed representations. If, however, stored representations are either unavailable or irrelevant, processing will be constrained to work upon the sensory input alone. In such circumstances haptic information will require increased processing time due to inherent restrictions on the degree of parallel processing its dedicated sense receptors are able to accomplish. In consequence it may be necessary to take advantage of a further transformation process from OBJ to LIM, the result of which being an influence of visuo-spatial imagery upon planned bodily movements. Once physically performed, the results of bodily actions can then be sensed, providing a loop between cognition and the sensory environment.

3.5 High-level cognition and premotor plans

A parallel transformation process from OBJ back to PROP ensures that visuo-spatially-based planned movements are not implemented without first taking into account the aims and objectives of the user. Representations at OBJ can, therefore, be transformed to factual statements at PROP and processed within the Central Engine of Cognition. Through comparison with representations of the currently active task, PROP can then feed-forward once more to OBJ which, in turn, influences planned movements at LIM. Actual physical behaviour is, as a result, strongly influenced by higher level meaning representations and, in consequence, the effects upon the sensory environment then become available once more to sensation, thereby allowing the whole process to begin again.

4. Implications

The above description of a touch-based scenario within an ICS framework suggests various implications for the development of effective haptic theory. The hypothesized processes operating within the BS and LIM subsystems validate the aim of many haptic researchers to understand low-level bodily sensations and pre-motor action plans. Importantly, however, ICS also highlights the need to consider more general cognitive processes, including high-level cognition and visuo-spatial mental imagery. Through its holistic approach the theory provides a means by which such analysis might be achieved. As described in section 3 this involves consideration of the processes operating between subsystems across the overall architecture. In addition, however, ICS also postulates generic principles upon which representations are structured within *individual* subsystems. In effect, therefore, although the types of data contained within each of the subsystems may differ, the rules by which their information is organized will be the same.

5. The structure of mental representations

Representations within individual subsystems have a hierarchical structure made up of various constituent items [16]. For example, an OBJ representation of a car dashboard may consist of the visual objects 'instrument display', 'steering wheel', and 'center consol'. Each item, in turn, consists of a group of further items one level down the representational structure. In the present OBJ example, therefore, the instrument display may consist of 'warning lights', 'speedometer' and 'revcounter'. Indeed, the hierarchical structure of the scene may extend through many representational levels down to the lowest possible discriminable unit. This is determined by the point at which further structural decomposition becomes impossible due to a lack of constituent items at the next level down the structure.

Within a representational structure the item that is the current focus of attention is referred to as the *psychological subject*. Through shifts in attention it is possible to change the subject to any item within a structure. There are, however, important constraints on the manner in which this may be achieved. For example, other items at the same level of structural decomposition as a psychological subject form its context. They provide information that is useful in discriminating the subject from other constituent items and are collectively referred to as its *predicate*. It is possible to make a direct *transition* of attention from a psychological subject to any of its predicate items so that a new subject is formed and the old subject becomes part of its predicate.

In addition, a subject and its predicate form the structure of the next item *above* in the representational hierarchy. Conversely, the items at the level *below* a psychological subject form its structural group. A single transition is required to move subject up or down a level in the representational hierarchy. Shifts of two or more levels, however, require changes through successive levels. If, therefore, in the OBJ representation of a dashboard, the psychological subject is shifted from the speedometer to the 'hazard warning light button' on the center consol, the transition 'path' must first move up a level so that the instrument display becomes the subject. The predicate of the instrument display will then include the center consol and so a further transition will be possible with the center consol as the new subject and the instrument display now part of its predicate. Finally, as it is now a constituent item within the group of items forming the center consol, the psychological subject can be shifted down the structure again to the hazard warning light button. Importantly, with each transition there is an associated cognitive cost. Complex transition paths therefore lead to high processing demands.

6. System-wide processing

The OBJ subsystem example is useful here because it permits illustration of the manner in which system-wide cognitive resources may be involved in haptic interaction. Say, for example, that the user must investigate our imaginary dashboard using a haptic device, with no other sensory input. In addition to the processing occurring within the BS and LIM subsystems, cognitive activity can also be predicted to occur within other forms of representation, including OBJ. Via transformations through the level of meaning (IMP and PROP), visuo-spatial imagery will be formed within OBJ with the representational structure described above. This may influence further haptic exploration as the user attempts to move his/her hand in line with this 'mind's eye image'.

The OBJ subsystem example has been developed here purely for illustrative purposes. It is, however, essential to understand that such structural principles form the basis of processing within all nine subsystems of ICS. The difference between types of representation is the kind of data dealt with and not the manner in which that information is processed. In principle, representational structures can be hypothesized for all of the subsystems involved in a given haptic scenario and it is, therefore, important for designers of haptic interfaces to consider system-wide cognitive processes.

7. Summary

The present paper deals with a limited range of haptic issues. ICS is not, however, restricted to a narrow array of applied contexts. Indeed, because the model underspecifies the details of individual types of mental processing, it is possible to use it to understand the complex cognitive processing occurring within various different instances, thereby enabling an ICS equipped interface designer to reason about most haptic situations.

In addition, it is possible to use ICS to make theoretical predictions about the effects of various changes to the interactive situation. For example, differences in task, changes in stimuli, the effects of other modalities, user expertise and knowledge, the availability of meaningful information, even the user's affective state, are all factors that can be reasoned about within its architecture. We are currently engaged in further work that attempts a comprehensive outline of ICS within the context of haptic interaction, together with empirical validation of the predictions of the theory and its practical implications.

Acknowledgements

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Image to Haptic Data Conversion: A First Step to Improving Blind People's Accessibility to Printed Graphs

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Abstract

This paper introduces a system which converts scanned line graphs into a data format which is interpretable by a haptic device. A virtual line graph can then be rendered and explored through touch by using the haptic device. This system provides an alternative method for blind or visually impaired people to access printed graphs. This method has a simpler production process than the conventional raised paper. Moreover, exploring graphs through a haptic device can provide assistance and guidance to less confident users. At the current stage, simple line graphs can be converted and rendered on two haptic devices: SensAble PHANToM and Logitech WingMan force feedback mouse. Evaluation of the system is being carried out and further improvements have been planned.

1. Introduction

Automatic conversion of printed information into electronic data formats has been studied for many years and as a result, scanners and Optical Character Recognition (OCR) software have been developed. Converting visual images into computer recognisable data provides people with the manipulation flexibility and the ability to preserve and reprint invaluable documents [1]. Computerising Braille is one of the examples to preserve aging Braille printout. It is a process to recognise Braille cells on an image captured by a camera. The electronic copy of the Braille document will be stored on a computer after processing. Although it is a good idea to preserve old Braille documents via optical media, it faces some technical difficulties, such as severely degraded paper quality, stains and marks left on the document and problems with double-sided Braille. All these make the recognition difficult and hard to achieve very accurate results [2].

Commercially available products have been developed to help blind people to access printed documents using scanners, OCR software and screen readers [3]. The scanned document is processed by the OCR software, and subsequently the device reads out the recognised text to blind people. This provides blind people with an easy access to printed documents without the need to convert them into Braille first. However, problems of recognising document layout and interpreting pictures and images cannot be resolved easily by OCR software. How many words are needed to describe a complex graph if a picture is worth a thousand words? In order to address this problem, we have been investigating the possibility of image to haptic data conversion so that graph features can be extracted and rendered on a haptic device.

Research work has been done on presenting graphical information to blind people using force feedback devices. Blind people will use these devices to feel the data representation through the sense of touch [4, 5 & 6]. Our previous work has shown that blind people are able to use a PHANToM to comprehend the contents of line graphs [7]. Therefore, it is desirable to develop a system which can interpret graphs and render them on a haptic device so that blind people can explore the data on the haptic representation. In this paper, we introduce our haptic line graph modelling methods and the attempt to make image to haptic data conversion possible.

2. System

The system consists of three main components: a flatbed scanner, an IBM compatible PC and a force feedback device which can either be a SensAble PHANToM or a Logitech WingMan force feedback mouse (Figure 1). The control flow of the system is illustrated on a schematic diagram (Figure 2). The scanner acts as a data input device through which printed graphs will be acquired and stored as digital images. Image processing techniques are then applied to extract useful features for the haptic rendering process. After the features have been extracted, the haptic rendering will take place and the user can then explore the haptic representation of the graph through the force feedback device.

The standard TWAIN interface is used to acquire the image of a printed graph from an optical scanner.

Considerations have been made to improve the accessibility of blind people. TWAIN will call up the user interface provided by the scanner manufacturer for setting some parameters of the scanner such as the scanning area, colour depth and degree of exposure. This will become a problem to blind people as it is impossible for them to know the interface arrangement and especially when different manufacturers provide different user interface for their scanners. Therefore, an alternative scanning control is provided. Blind people can use a short-cut key to scan a printed graph based on the default settings which would meet most needs of the application.

(a)   (b)

Figure 1. (a) SensAble PHANToM, (b) WingMan force feedback mouse.
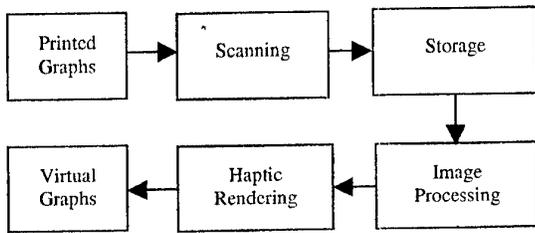
Figure 2. Visual to haptic data conversion process.

The image to haptic conversion process is mainly about transforming raster data to vector representations. The scanned image will be in the digital form consisting of pixel information. The features that need to be extracted from the image depend on the requirements of the haptic rendering process. Therefore, we need to know about the haptic modelling techniques that are used to create the haptic graphs.

2.1. Haptic Modelling

The haptic modelling of line graphs varies and depends on the haptic device being used due to the hardware limitations and software API support. In the PHANToM case, the haptic line graphs are constructed by using the GHOST SDK. Users feel the line graphs through the end-effector of the PHANToM. The lines are modelled as channels which have a V-shape cross-section designed to retain the PHANToM pointer effectively (Figure 3). The reason for constructing the line model as a concave object is due to the findings in our previous study [8]. We found that users have difficulties to keep the pointer on round objects securely. Therefore, polygons are used to construct the V-shaped channels and the inner surface is defined as

touchable by the PHANToM so that the pointer can penetrate from the outside and become retained in the inside. By moving the pointer along the channels, users can trace the path of the lines.
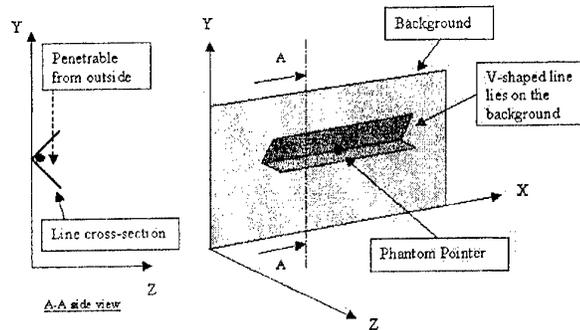
Figure 3. Haptic line graph modelling technique on the SensAble PHANToM.

In the WingMan force feedback mouse case, the Immersion TouchSense Developer Toolkit is used to create the force effect. Lines are modelled by using the spring effect and enhanced by a friction model. A constraint type of force feedback is produced by the combination of these two effects. In operation, when the mouse cursor gets close to the line, it will be snapped to the line like entering into a magnetic field (Figure 4). Strong force is applied to the direction which is normal to the gradient of the line so that the cursor is retained on the line and can only move easily along the path. Sharp corners are the source of problems in this modelling technique as the cursor can easily shoot off the line path if the user moves too fast. A remedy to this problem is now under investigation. A specific force feedback at corners is being developed so that the transition from one section of the line to another can be smoother.
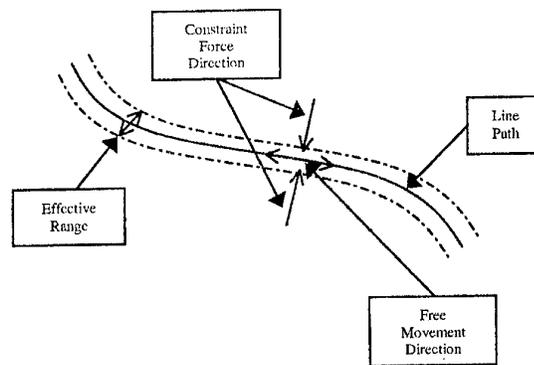
Figure 4. Haptic line graph modelling technique on the WingMan force feedback mouse.

Despite the different haptic modelling techniques, the data input required by both haptic devices is the same. The essential data required to represent a line includes the start, end and intermediate points which are the turning points on the line. In order to cope with multiple lines on one

graph, a simple structure is designed to allocate the data. The information stored in this data structure is the number of lines, number of points on each line and the co-ordinates of each point. To link up the optical system to the haptic devices, image data need to be converted into the specified data format. In other words, pixels of lines have to be detected and extracted from the scanned image and then transformed into the data format required to generate the virtual graph.

2.2. Data Conversion

Data conversion relies on image processing as useful information has to be extracted and formatted for the use in the haptic rendering. This is not an easy process and could be complicated by several factors, such as the quality of the printed documents, the complexity of the graph content, and the type of graph being processed. In the present development, only simple line graphs are used for the purpose of the initial concept proving study. Further development can be made to extend the system capability to cope with more complex contents and wider range of graphs.

The printed graph is acquired from the scanner and stored as a bitmap file. The scanned image contains a large amount of information which is actually irrelevant to the haptic rendering process. As a result, it needs to be filtered out before the feature extraction taking place. The redundant information includes the colour on each pixel, noise on the graph, and text labels. The colour information and the noise can be reduced in the initial processing while the text labels will be ignored in the feature extraction in the later stage. Colour to greyscale conversion is used to reduce the amount of information and thresholding is used to further eliminate the unnecessary data.

At this point, the image is ready for the feature extraction process. A custom neighbourhood seeking technique is used to interrogate the interesting pixel points on the image in order to determine whether they are parts of a line or something else. It is based on convolution techniques and checks the surrounding eight pixels for possible neighbours. If the point is a part of a line then the algorithm will start tracing the line and recording feature points. The related pixels are then allocated together to indicate the start, end and intermediate points on the line. They are grouped together according to the line to which they belong and also to their position on the line. Therefore, they are in the same format as required by the haptic rendering process.

Complications occur when lines on the graph start intersecting which will confuse the algorithm as it is generally difficult to know whether the points belong to the original line or another one. Some assumptions are needed to deal with this kind of situation, i.e. assuming lines would not change direction at the intersection and continue on the same gradient. More investigations are required to explore different conditions and obtain satisfactory solutions.

3. Future Work

In the current development, the system only deals with simple line graphs however the concept of using image to haptic data conversion to provide access to printed graphs to blind people is demonstrated. It is possible to tackle more complex line graphs such as multiple intersecting lines and lines with different patterns. Moreover, converting other types of graphs, such as bar charts, pie charts and other types of data visualisation techniques, will be investigated and supported in the system. Besides expanding the capability of the system, an orientation adjustment method is under investigation so that the right orientation of the scanned graph can be automatically detected. This will improve blind people's accessibility in the system as it is difficult for them to tell the orientation of a printed document without any form of assistance. Furthermore, evaluation of the system is being carried out. The main investigations are focused on two different aspects: accessibility and usability of the system, and the effectiveness of the feature extraction techniques developed in the system.

4. Acknowledgments

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Perception of Gradient in Haptic Graphs: a Comparison of Virtual and Physical Stimuli

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Abstract

We report an experiment in which people were asked to make a judgement about the gradient of a simple line graph. As part of the MultiVis project on data visualisation for blind people our aim was to discover how accurately linear graphs can be rendered using relatively simple technology: raised paper, and a haptic force-feedback mouse. Results show that both media allowed very accurate performance.

Introduction

This work is part of the MultiVis project (multivisualisation for the blind). The main objective of this project is to make statistical information, such as graphs and tables, more accessible to blind people. Using virtual reality technologies, it is hoped this will be achieved by using alternative forms of displaying information to the blind and the visually impaired.

Blind and visually impaired people interact with the world using auditory and tactile sensory modalities. For this reason, the project explores the use of 3D sound and virtual reality haptic presentation to render information. The focus of this study was the haptic domain, and in particular its utility for presenting information related to virtual reality line graph displays.

The Study

The aim of this study was to examine how accurate people are at processing varying gradients of simple line graphs presented as tactual lines on raised paper or as virtual haptic lines via a force-feedback mouse.

A comparison between physical and virtual reality media will allow assessment of the haptic force-feedback device. In particular, we were interested to establish whether the force-feedback mouse would provide an accurate means for presenting simple linear graphs when compared to physical raised lines (on a relief map). If it is accurate, the virtual reality device has many advantages over the physical map, particularly in the fact that the display can be changed very simply (e.g., by re-rendering information) whereas separate physical displays (relief maps) need to be constructed for each new presentation.

From the psychological perspective, there has been little research on the processing of tactile line orientation [eg 1, 3]. The patterns of results obtained from these studies generally focus on particular phenomena such as the "haptic oblique effect". This shows poorer performance in oblique linear orientations than in vertical and horizontal ones [1]. These experiments have been conducted using physical media that can be fully explored by touch. Whether haptic perception of virtual line orientations follows the same pattern as with physical media is an important question in terms of data visualisation for the blind [4, 5]. It is by no means clear that the two media will be equivalent in this regard. Virtual reality force-feedback devices are limited to a single point of contact, and do not support the direct skin contact available for physical stimuli. If virtual reality force-feedback media are to be used to render line graphs for blind people, it is important to establish whether these media are sufficiently sensitive to do so. Since line orientations in a line graph are a primary source of information, we began our investigations by asking whether people can process the gradient of a given line with such media. To investigate this question, an experiment was set up which used simple linear graphs and a forced-choice paradigm.

Experiment

20 participants were recruited for this experiment. All participants were sighted, as well as right-handed. None had any known

sensory or motor disabilities which might have affected their haptic perception.

A set of virtual, haptic stimuli was presented using Logitech's WingMan force-feedback mouse. The virtual stimuli for use with this mouse were generated using the Immersion Studio Application (version 3.4.2) software.

Another set of stimuli was presented on raised paper (swell paper). This allows the photocopying of stimuli onto special paper, which is then put through a HotSpot machine raising the darkened areas through a heating process, and producing a relief map.

For the virtual, haptic stimuli a set of 68 virtual lines was generated. These consisted of four replications each of a set of angled, virtual lines taking a horizontal orientation ($0°$) as reference point. This formed the basis for producing virtual lines at stepwise angular increases of $3°$ each, both sloping up and down from the horizontal, up to $24°$ either side of the horizontal. This generated a set of virtual, angled lines at the following angles (taken from the horizontal): $3°$, $6°$, $9°$, $12°$, $15°$, $18°$, $21°$, $24°$ (all sloping up), $-3°$, $-6°$, $-9°$, $-12°$, $-15°$, $-18°$, $-21°$, $-24°$ (all sloping down) and $0°$ (horizontal). Furthermore, four virtual haptic practice lines were generated consisting of $2 \times 30°$ (upwards) and $2 \times -30°$ (downwards) angled lines.

Generating the virtual lines themselves was accomplished using the *Enclosure Effect* within the *Position Based Effect* which is supplied with the Immersion Studio software. This Enclosure Effect gives the impression of a haptic line which is determined by four walls as boundaries. In this way, participants haptically perceive a line as an engraved groove. Pilot studies had shown that an "engraved" effect was easier for subjects to use than a "raised" effect. The latter, though approximating more closely to a raised-paper line, tended to allow subjects to lose the region of interest by "falling off" the line [5]. Stiffness and saturation for all stimuli was set to 10,000 units for left/right and top/bottom walls. Thickness of these was set to 25 units. A stiffness mask was activated for each stimulus pertaining to 'In_Top', 'In_Bottom', 'In_Left' and 'In_Right'. The centre width of each line (ie enclosure) was set to 500 units for width and 50 units for height. For each virtual line boundary coordinates were variable as were the centre settings for both the x and y coordinates. All lines were presented to participants in the centre of the haptic display field of the force-feedback mouse. The strength of the force-feedback was set to maximum strength throughout.

The haptic 'viewing' field in which the force-feedback mouse operates was 4cm x 3.5cm in size.

For the raised paper lines the same set of 68 angled lines and four practice lines as for the virtual stimuli was created. Lines for these stimuli measured 9.7cm in length and .5cm in width. Raised line stimuli were presented to participants in a styropor foam frame. This allowed participants to feel the stimuli themselves, as well as the boundaries set by the frame. The overall frame size measured 37.5cm x 25.5cm. The haptic 'viewing' field measured 13.5cm x 9.8cm.

Design and Procedure

There were two conditions in this experiment: raised lines and virtual lines. The presentation of the two conditions was blocked and the order of presentation for these counterbalanced. Participants were randomly allocated to the presentation order of the two conditions and were blindfolded throughout the experiment. They were presented with the linear graphs, and asked to say whether the gradient was positive or negative (sloping upwards or downwards from left to right). They were instructed to guess if they were unsure unsure of the direction of a gradient.

For each virtual line the mouse's cursor was positioned on the line's centre. The mouse itself was positioned straight on its fixed pad and placed in front of participants. In the virtual lines condition participants were firstly familiarised with the mouse and its force-feedback by letting them explore two demonstration files supplied with the WingMan utilities, FEELitObjects.

For the raised paper lines, the styropor frame was fixed in front of participants.

Once a given line was set up for presentation, participants moved their own hand into position to feel it. In order to reflect real world users' variability in exploring objects tactually, participants were allowed to explore the lines in any manner they wished, employing any strategy they wanted. They were also allowed to explore each line without time limit.

Participants were given four practice stimuli for each condition.

Results

The percentage of correct responses for both the raised lines (swell paper) and virtual lines (force-feedback mouse) can be seen in Figure 1.

Figure 1. Participants' responses to raised and virtual lines.
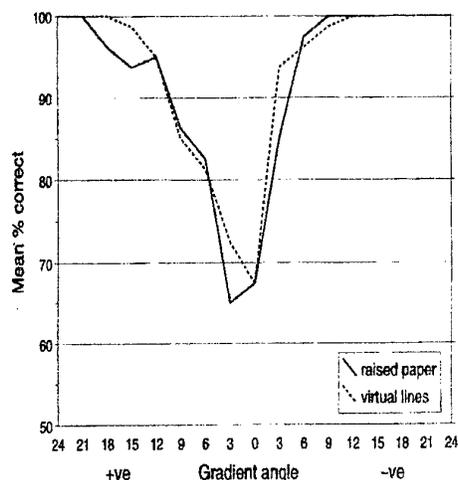
Statistical analysis was conducted on data from –9 to +9 degrees, as inspection showed ceiling effects beyond this range. Within this range, there was a very large effect of angle, reflecting a drop in performance as the angle became shallower (F6, 114) = 10.5; p < 0.05). There was no significant interaction (F(6, 114) < 1) reflecting the fact that decreasing angles affected both presentation media equally.

In the case of zero degrees, participants did not behave at random, but exhibited a bias towards responding "downwards". This bias was significant across the groups (single sample t-test, t(19) = 4.3; p < 0.05) and equivalent for each.

These results show that both media allowed highly accurate performance, and that the pattern of errors appears to be equivalent across each.

Discussion and Conclusion

First, we note that subjects were very accurate at this task. Within roughly 6 degrees of the horizontal they perform at ceiling levels. Even within 3 degrees of the horizontal, performance is very good. Second, we note that the pattern of accuracy and errors appears to be very similar across the two media. This is perhaps surprising, because the physical raised-paper appears to off richer information. Interacting with a physical object, subjects can use both tactile and haptic cues, whereas the force feedback mouse allows only a point-haptic interaction.

The pattern of results observed in this study supports the use of virtual reality haptic media in the rendering of line graphs for blind people. Although employing blindfolded participants, there is no reason to suggest the pattern of results should be different for blind people. The basic psychological processes required to make gradient decisions on differently sloping simple line graphs should be the same for seeing and blind people.

Furthermore, the degree of accuracy in making gradient decisions in both media is encouraging in regards to the use of this form of information rendering for statistical data such as line graphs for the blind.

An experiment is currently in progress to expand the present study to the use of the PHANToM force-feedback device. This experiment investigates whether the orientation of the presentation plane (ie horizontal vs vertical) has an effect on perception of line gradient, since each plane presents a different context of gravitational cues [2].

We conclude that the haptic mouse allows very accurate rendering of simple line graphs.

Acknowledgements

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Micro-Actuation Principles for High-resolution Graphic Tactile Displays

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Abstract

One of the possible actuation principles which were found to be the most promising candidates for high-resolution tactile displays is presented. The actuators are based on SMA wire, which includes a clamping mechanism, to overcome high energy consumption and its consequences. A module consisting of 16 taxels in one row, with a distance of 2.54mm separating the taxels, was designed and produced with μEDM technology. Special setting and resetting procedures have been developed with the purpose of overcoming friction problems that were noticed during the first tests. The design and the procedures are presented.

1. Introduction

Tactile displays are already available on the market, but only for Braille text (mostly in one row). The conventional actuators used in such commercial products (piezoelectric bending elements) are not suitable for high-resolution graphic tactile displays because of their dimensions and high price.

Fast development of micro-manufacturing technologies, as well as the micro-actuators produced with them, has opened new possibilities for the production of actuators which are suitable for meeting the requirements of a high-resolution graphic tactile display.

After evaluation of the available actuation principles, some of the most promising candidates were chosen for further testing and development. The evaluation criteria employed allow full compatibility with standard Braille text and provide good representation of the graphic items. The main criteria employed for evaluating both the actuation principles and the actuators designed according to these principles were as follows:

Table 1. Requirements

• Possibility of miniaturisation (the actuator has to allow packaging of at least 10 actuators per inch, i.e. the outer dimension of a single actuator must not exceed 2.54mm).
• Amplitude of vertical movement has to be 0.6 – 0.8mm.
• Actuator should be able to bear a vertical force of at least 100mN (an optimum load would be 150mN).
• Possibility of integrated production with minimal additional assembling.
• Possibility of independent manipulation without mutual influence of neighbouring actuators.
• The response speed has to allow setting and resetting of the display within a reasonable amount of time (on the order of seconds).
• Good long-term stability.
• Low cost.

2. Principles

There are several basic principles that can be used to form a convexity on a surface. They can be divided into main groups as given below:

Table 2.1. Principles
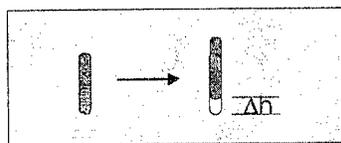
- Linear movement
- Rotation

Table 2.2. Principles

- Change of the length

- Change of volume

- Change of shape

The ways to create a matrix of convexities on a flat surface

Linear movement

Electromagnetic forces

Electrostatic forces

Pizo-electric forces

Rotational movement

Electromagnetic forces

Electrostatic forces

Pizo-electric forces

Change of the length

SMA wire

Electrostrictive or magnetostrictive forces

Thermal extension

Change of the volume

Liquid evaporation (steam mashine)

Electrolysis of the water

Engineering responding gels

Change of the shape

SMA springs

SMA thin plates

Piezo-electric bending elements

Bimetal (thermo) bending elements

Electroactive polymers

Carbon nanotubes

Change of fluid pressure

Micro-pumps

Different actuation principles

Micro valves using external fluid pump

Different actuation principles

Electro Rheological Fluids (ERF)

Magneto Rheological Fluids (MRF)

After the evaluation of possible solutions (see tables 2 and 3), the following principles showed that they are suitable for achieving the requested criteria:

- Actuator based on SMA wire which uses a clamping system to prevent high energy consumption and its consequences.

- A valve matrix based on a fluid that can change its viscosity under the influence of an electric field (electro-rheological fluids or liquid crystals); this matrix uses an external fluid pump to provide a continuous fluid flow and the required pressure.

- A matrix of mechanically multiplexed micro-valves based on sequential driving (time multiplex) row by row. The advantage of that system is that it reduces number of actuators necessary (for the matrix consisting m x n valves, the number of the actuators is m + n).

The actuator based on SMA wire will be presented in this paper, while the other two principles are still in the phase of investigation.

2. The actuator based on SMA wire

Different actuator designs using SMAs (Shape Memory Alloys) intended for tactile displays have already been presented (see references [1], [2]).

Table 3. Principles and solutions
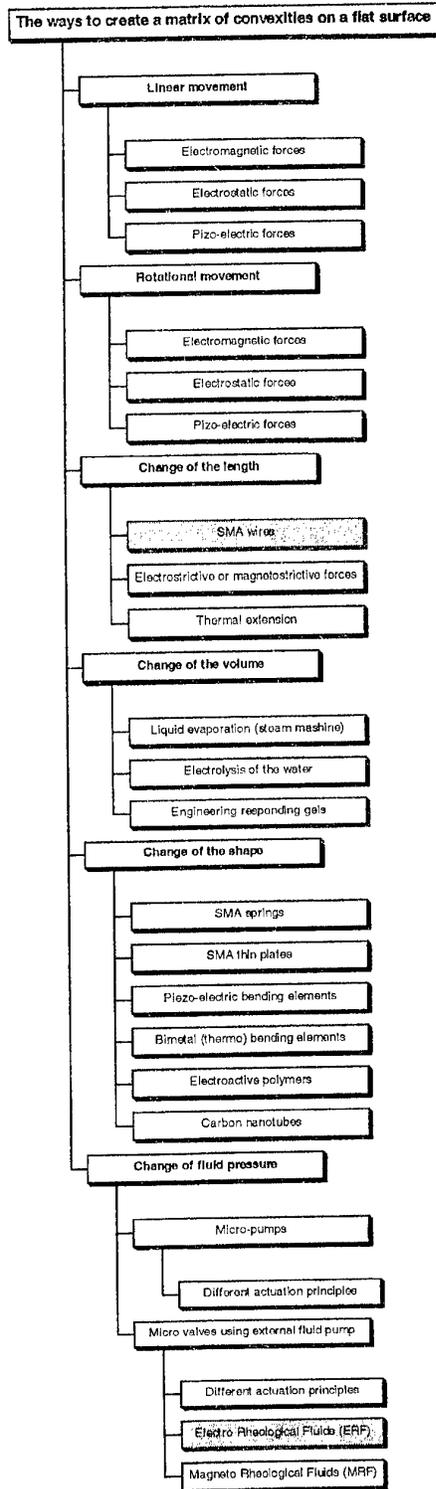
The advantages of the SMA actuation principle are simplicity, compactness, and safety of the mechanism, a high power/weight ratio, and clean and silent operation. The SMAs are mostly used as springs, though also in the form of plates and wires of various diameters. In the case of SMA wires, the ratio of the force that can be delivered to the wire's cross-section is especially high. There is no other actuation principle which can deliver 350mN of force with a cross-section of only 50μm (the parameters of the wire used in the presented actuator).

The main disadvantage of the Shape Memory Alloys' actuating principle is low efficiency (about 5%), and consequently high thermal dissipation. For the presented actuator, thermal dissipation on the wire is approximately 0.06W (when active) per actuator. A larger matrix of those actuators (an ideal graphic tactile display is usually defined as a matrix consisting of 320 x 240 taxels) would have a thermal dissipation on the order of kilowatts. Despite the high energy consumption of the display as a whole, more important problems are the high density of the thermal energy and, as a consequence, the high mutual influence of neighbouring actuators. It would be practically impossible to keep one actuator inactive when it is surrounded by a number of active ones for longer than several seconds.

If we consider that one "reading" of some graphic (or several rows of textual) tactile information can take tenths of a second or more, it can be concluded that, instead of actuators that require energy in the active state, the actuators working in "bi-stable" mode are more appropriate. These actuators require energy only when switching to one of two possible states. No energy is required in any of two end positions.

One of the ways of achieving that effect is to use an appropriate clamping mechanism which holds the actuator in position until the change is necessary.

The actuator using SMA wire as an active element and a micro-machined clamping mechanism was designed and produced at the Institute for Micro Technique and Precision Engineering. The functioning principle is presented in Fig. 1.,

An SMA wire works in the following manner: At temperatures below the transition temperature, the wire can be easily extended using a weak force (bias force). If the wire is heated above the transition temperature (the easiest way to heat it is to apply an appropriate electrical current directly to the ends of the wire) it contracts till it reaches the previously programmed length. During the contraction, the wire can deliver a force that is 5-10 times stronger than the force necessary for extension.

SMA alloy wire (trade name FLEXINOL, produced by DYNALLOY, Inc.) with a diameter of 50μm and transition temperature of 70°C is used as an active element. This wire can provide a force of about 350mN
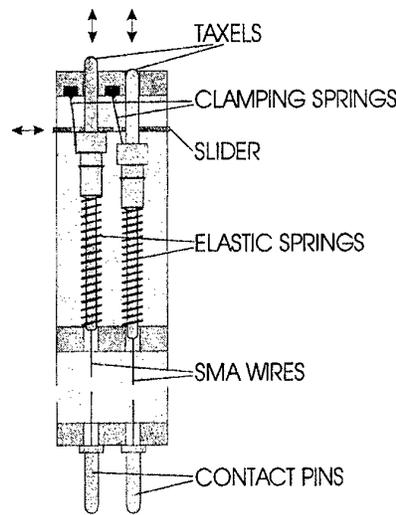
Figure 1. Principle of SMA actuators and their clamping mechanism

during contraction. If extension of the wire does not exceed 3% of its active length, it could provide hundreds of thousands of actuations (data given by the producer) without losing its initial properties. Long-term stability tests have not been done yet.

The active length of the wire used was 30mm (not whole lengths as presented in Fig. 1), while maximal displacement was limited to 0.8mm. This results in a wire extension of 2.66%, which is below the critical limit.

Elastic springs are used to provide the necessary bias force, and they are chosen so that they can bear a vertical load of 150mN in the upper position (the force required for standard Braille actuators).

The upper end of the wire is fixed to the taxel, and its lower end is fixed to the contact pin by means of mechanical clamping.

The main part that holds all of the parts serves as a common electrical contact (all of the parts are made of metal), while contact pins (isolated from the main part) fixed to the lower end of each wire provide an electrical contact for each single actuator, as well as the releasing (resetting) actuator.

In the starting (reset) state, the actuators are in the upper position (on the left in Fig. 1). In this position, clamping springs are stressed, providing a very weak force that presses the corresponding taxel from the left to the right side. The force is so weak that it is unable to move the taxel. If an appropriate electrical current (the current of 90mA was found to be the best compromise regarding fast response and high consumption) is applied between the main part and one or more contact pin(s),

corresponding SMA wires are heated, and they contract until the predefined length is reached. The actuators are adjusted so that the corresponding clamping spring is released shortly (about 200μm) before the taxel reaches the lowest position. The electrical current is than disconnected, and the elastic spring tends to extend the SMA wire.

However, the taxel is clamped in the lower position under the influence of the clamping spring, which is now located next to the right taxel in Fig. 1. No energy is required to keep the taxel in this position and its upper position.

When the taxels have to be reset, a slider, also presented in Fig. 1, is pulled from right to left. The clamping springs are pulled to the taxel at the same time so that elastic spring can extend the SMA wire to the upper position.

According to the described principle, a module was designed and produced; it consists of 16 taxels in one row, separated by 2.54mm, as well as one releasing actuator which also uses SMA wire (two parallel 150μm wires instead of one 50μm wire are used for each taxel) and resets all 16 taxels at once.

The main part, which holds all of the other parts, the slider, the rotating part that serves as a lever mechanism for the slider (see Fig. 4), and the clamping springs, was produced using μEDM technology [3]. The taxels and contact pins were milled.

REM pictures of some of the important details are presented in Fig. 2, Fig. 3 and Fig. 4.

Figure 3. REM picture that shows the design and position of the slider, which serves to pull the clamping springs, thereby releasing the taxels
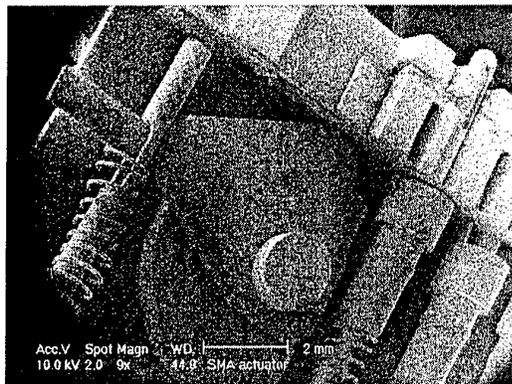
Figure 4. REM picture that shows the design of the lever mechanism, which serves to transfer the vertical movement produced by the SMA wire and the elastic spring accompanying it to the horizontal movement of the slider

The main problem that appeared in the first tests of the system was the friction between the slider and both the main part and the taxels that were in the upper position during resetting. To overcome this problem, a resetting procedure was developed. The time diagrams of the setting and resetting procedures are presented in Fig. 5.

The time diagrams show the control voltages applied to the drivers that provide the required electrical current to the SMA wires. LOW logical levels are active states (the current flows through the wire). The "line enable" signal is used because the module is intended to be part of a matrix. The "line enable" signal actually addresses the selected module (multiplex driving will be used).

To set the selected taxels, no special procedure is necessary. The time necessary to move one taxel from the

Figure 2. REM picture showing three of the taxels, as well as the position of the clamping springs

upper to the lowest position was determined to be 0.5-0.7s (if a current of 90mA is applied). To be sure that all of the selected taxels have reached their lowest position, the current must flow through the SMA wire (Tset in Fig. 5) for a longer amount of time. The period of $T_{set}=1s$ was found to be the most appropriate.

SET PROCEDURE:
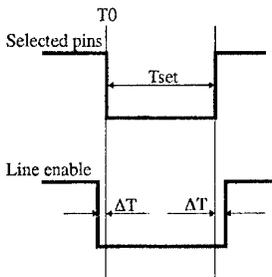
RESET PROCEDURE:
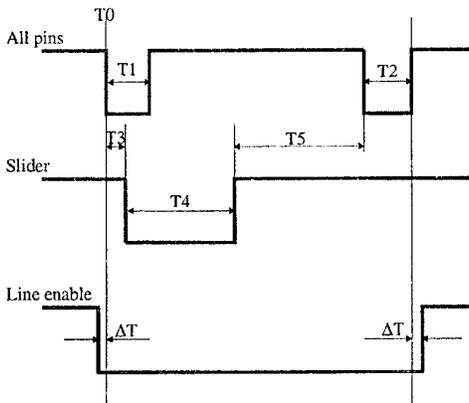
Figure 5. Time diagrams of the control voltages during setting and resetting of the taxels

Concerning resetting, several consequent steps are necessary. The steps and the corresponding time periods (see Fig. 5) are as follows:

Step 1: All of the taxels are activated (the current starts to flow through the corresponding SMA wires). This releases the slider, which is no longer clamped between the taxels and the main part, and it can now slide freely without friction. It also helps that the clamping springs are not pressed by the taxels from below, so that only their elastic forces are present when the slider is being pulled.

T1=0.5s

Step 2: Shortly after the taxels are activated, the slider is activated, and it starts to pull the clamping springs.

T3=0.2s

Step 3: After the period of T1-T3=0.3s, the taxels are deactivated, but the slider continues to pull till the taxels have reached upper position.

T4=1.5s

Step 4: The slider is now deactivated, but some time is necessary till the corresponding SMA wire cools down and relaxes.

T5=1.5s

Step 5: As the bias spring is not strong enough to push the slider to the start position (the slider is again clamped between the taxels and the main part), a short pulse must be applied to all of the taxels. The slider is released for the short period, which is enough for it to reach its start position.

T2=0.2s

The whole resetting time is:

$$T_{reset}=T3+T4+T5+T2=3.4s$$

If a higher current were applied, both the setting and resetting times would be shorter, but this could influence the long-term stability of the system as a whole.

3. Conclusion

To a design of micro-actuators based on SMA wire which uses an appropriate clamping mechanism was presented. The actuators were initially intended for graphic tactile displays for the blind, but they could be used wherever tactile feedback is desired (in minimally invasive surgery, by fighter jet pilots, etc.).

Further evaluation as well as the necessary improvements of the presented actuators will be done. Improvement of the surface quality, either by using a different manufacturing technology or polishing the surfaces, could solve the friction problems and allow simpler (faster) resetting. The next step would be adapting the presented design for production with microinjection moulding, which would reduce the price for serial production. Some ways of realizing easier (automated) assembly and adjustment of the system have already been discussed by the working group. And finally, though not less important, is finding a possibility to integrate a feedback mechanism with the purpose of providing some degree of interactivity.

The work concerning the other mentioned principles is also ongoing.
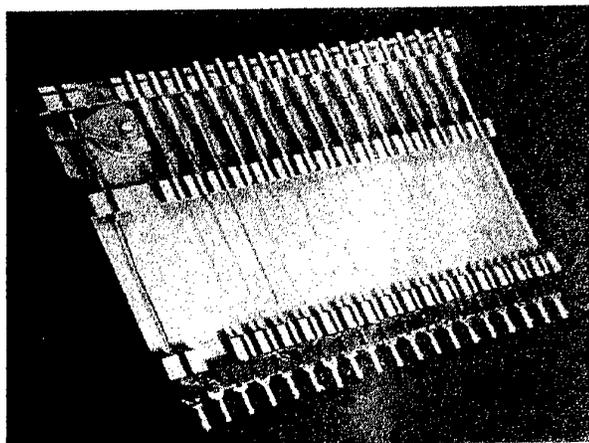
Figure 6. Assembled module consisting of 16 actuators in one row
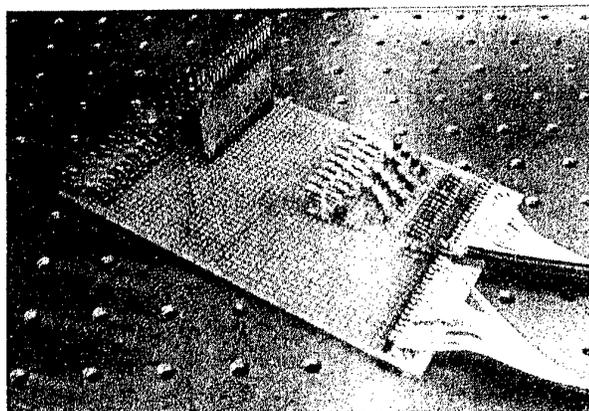
Figure 7. Experimental set up

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Vibro-Tactile Information Presentation in Automobiles

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Abstract

This paper describes the potential of using vibro-tactile displays for automobile drivers. Technological developments in the field of driver support systems and tactile displays, combined with the ever increasing need to enlarge the capacity of the driver's information channel, form the reason to review the possibilities of in-car tactile displays and to identify some promising applications. In the second part of the paper, we describe a feasibility study in which we tested an in-car tactile display in a driving simulator. The results show that the tactile navigation display resulted in better performance compared to a visual display, and that it reduces the driver's workload. This study gives a first indication that employing the tactile modality may be a major step to accomplish safety improvements.

1. Motivation

In-car systems can have a negative effect on safety when they enlarge the workload or distract the driver [1]. The interaction of the driver with the in-car system may result in an overload situation in which the driver no longer processes all the information relevant for the driving task, which may result in errors and late detection of other road users [2]. Based on the assumptions of the multiple resource model [3] which predicts no performance degradation when independent resources are used, and the fact that most information in driving is visual, safety may be improved by presenting information via audition and touch instead of vision.

1.1. Vibro-tactile perception and displays

Vibro-tactile displays in general consist of arrays of vibrating elements coupled to the skin. Appropriate stimulation of specific receptors in the skin by means of applying localised vibration typically leads to a 'tickling' sensation at that specific location. Human vibro-tactile perception is sensitive to location, duration, frequency, amplitude and several other (derived) aspects of vibro-tactile stimulation. Obviously, the Braille reading skills of visually impaired people have proven our general ability to process complex spatio-temporal patterns presented to our skin.

1.2. The tactile modality in man-machine-interfaces

State of the art man-machine-interfaces (MMIs) almost routinely use the visual and auditive channel only. Using the haptic and tactile channel in MMIs is rather uncommon, despite good reasons to do so. Advantages of the tactile channel are, amongst others, that it is always ready to receive information, that it draws attention, that it is private, and that it can be used in a natural and intuitive way. The latter is of course dependent on the kind of information that is presented. Examples include displaying object properties such as roughness [4], and variants of a 'tap-on-the-shoulder' to present navigation information. Another good reason to incorporate the vibro-tactile channel in MMIs is that adding the tactile modality may enlarge the total effective information processing capacity of the user. It may thus free the overloaded auditory and /or visual modalities.

Recent developments resulted in small, cheap, robust, and readily available tactile display elements (e.g., those used in mobile phones and pagers). These simple elements can be combined into sophisticated displays. This will eventually result in the introduction of relative simple tactile displays which have a much larger information transfer capacity than the 1-bit 'your phone is ringing' message. Recent applications of these vibro-tactile displays hint at more intuitive ways of using the skin as an information channel [5]. For instance, it has been shown [6] that stimulating a single point on the torso immediately leads to a perception of external direction. Such an intuitive perception of external direction can be very useful in applications requiring a sense of spatial awareness, such as when

navigating a car through an environment, operating in space [7] or when flying super-agile aircraft [8, 9].

1.3. Classes of information in car driving

After recognising the potential of applying tactile interfaces in an automobile, dimensions that need to be studied are the types of information and the coding possibilities that are suitable. We discern the following classes of information:

a) **Spatial information**. Spatial information may be one of the most promising areas of applying tactile displays [9]. First of all, the visual system is restricted in field-of-view. This means that it normally extracts spatial information from the 180° forward view only. Not perceiving relevant objects in space (e.g., cars in dead angles, crossing pedestrians) is a major cause of accidents. Secondly, presenting 3D information on a 2D visual display may result in errors and a high visual workload. Presenting such information to the skin is likely to reduce those problems.

b) **warning signals**. Since the tactile channel is always ready to receive information and has the characteristic of drawing the observer's attention, it is well suited for warnings. Furthermore, a visual warning on the dashboard may be on for a long time before the driver actually notices it, and auditive warning signals can be lost in tyre, radio, or conversation noise.

c) **communication**. Tactile displays allow silent and private communication. This is relevant since almost all of the communication of the car is meant for the driver only. Why bother the passengers with this information, especially when they are working or communicating with others?

d) **coded information**. This category encompasses all types of (abstractly) coded information available to the driver (e.g., speed, engine rpm, and fuel supply). Optimal ways of coding must be determined for each parameter. Information of this type could be presented when the driver asks for it, or when specific conditions or limits are reached.

e) **general**. Tactile / haptic information can also be used to guide the driver to different locations on the dashboard or the middle console, can give information on the settings of switches and buttons, can indicate preference points, etc., without the need of the visual modality.

2. Integrating tactile displays in the driver's workplace

For optimal safety, the workplace allows the driver to have both eyes on the road, both hands on the steering wheel, and both feet on or near the pedals. This safety strategy goes beyond keeping the driver's attention focussed on the road. A consequence is the increasing use of controls on the steering wheel, for example to control the radio, phone, or climate control system. However, using these controls as display is largely unexplored. Besides the primary and secondary controls, tactile displays can be incorporated in, for example, the pedals, the seat and the safetybelt.

2.1. Integrating tactile information with (existing) haptic information

Not all information in driving is visual. For example, forces in the steering wheel provide the driver with indispensable information on vehicle behaviour, road conditions, etc. Therefore, although presenting additional haptic information in controls may be an attractive option to present information [10], the interference with naturally available haptic information is a potential disadvantage. For example, presenting additional forces on the steering wheel to display course deviations sensed by a heading control system might interfere with the natural information. Using the tactile modality - such as a small vibration presented to the hands holding the steering wheel (not on the steering wheel itself) - may not have these consequences.

2.2. Joystick control: completely integrating haptic and tactile information

The introduction on a large scale of joystick control in automobiles may not be far away. Nowadays, joystick control is already applied in vehicles for the handicapped driver. The major advantage of the use of a joystick instead of a steering wheel is that the latter is a major source of injuries in case of accidents. Apart from the design issue of providing the correct force feedback information in joystick control, it also opens opportunities to integrate haptic and tactile information. Since the driver has his or her hands at a fixed position on the joystick (irrespective of the manoeuvre) the fingers and palm are interesting locations to present tactile information. An accompanying advantage is that the fingers are not only suited as display, but can also act. This opens up the possibility to design a fast, intuitive stimulus-response system.

3. Examples of applications: SAFE: Safety,

Assistance, Fun, and Efficiency

Below, we will give some examples of tactile display applications in the car. We divide the applications in four categories - safety, assistance, fun, and efficiency - and provide some examples of each category.

Safety. Tactile information can help to make driving safer by enabling the 'hands on controls' strategy, by releasing the visual workload, and by presenting information in a natural and intuitive way. An example of the latter is displaying cars from behind, cyclist in the dead angles of mirrors, and crossing pedestrians in the periphery. The feasibility study described in Section 4 provides a first proof-of-concept of an in-car tactile navigation display, consisting of actuators in the seat.

Assistance. A simple and straightforward form of assistance is applying a tactile signal on the appropriate control. For example, a small tactile vibration on the handbrake-release-button can indicate the moment that there is enough torque on the wheels to pull up a slope. This probably allows even the most inexperienced driver to pull up smoothly. Van Winsum [11] used a tactile stimulus on the accelerator pedal to indicate when a speed limit was exceeded, and compared this way of displaying with an auditive message. The tactile display resulted in a decreased workload and faster responses.

Fun. The fun of tactile information probably lies in the fact that it enables silent and private communication with the machine, which is to a large extent just between the driver and the machine and of no concern to other passengers. An example is a tactile signal on the door handle when the lights are left on. The latter is much more fun than an annoying auditive signal that everybody in the parking lot can hear.

Efficiency. Optimising fuel consumption is an important issue in the automobile industry. Tactile displays can support a more efficient gearshift regime by the direct coupling of display and actuator. Indicating the moment to shift gears can be realised by a signal on the appropriate hand (e.g., via the steering wheel). The optimum will be the situation in which the fingers are already on the gearshift controls as in joystick control or when the gearshift controls are integrated in the steering wheel.

4. Feasibility study: in-car navigation displays

Research has shown that badly designed in-car displays can negatively effect safety. For example, a safety evaluation [12] of in-car displays that provide real time traffic information showed a 50% increase of the number of critical traffic situations (as judged by a driving instructor) of two badly designed interfaces as compared to two well designed interfaces. Earlier work at TNO Human Factors has shown that a tactile display that presents driving behaviour feedback results in a lower workload than an auditive display [11], and that tactile displays can be used effectively for presenting spatial information, such as the direction of waypoints [6]. The present study aims to investigate the feasibility of an in-car tactile navigation display. Special emphasis will be on workload. The hypothesis is that presenting information to the tactile sense will decrease the visual burden of car driving.

4.1. Design of the visual and tactile navigation symbols: the icons and vibrocons

In-car navigation displays present relatively simple visual symbols: Information is usually only presented when a course change is required: no message means go straight on. The information consists of two parts. The first part is the direction of the oncoming (course) change (e.g., left, right) and the second is the remaining distance to this change. The latter may be dependent on the road category or driving speed. We adopted this simple symbology in the present experiment.

Visual and tactile symbols were made for three distances: 250, 150, and 50 m. Distance was indicated alphanumerically for the icon, and by timing for the vibrocon. The icons (arrow plus distance) were presented on a separate LCD display left of the steering wheel with a resolution of 64 by 64 pix. In an analogue way, we developed the tactile coding principles. Based on a pilot study, the following were the most appropriate ways to code the direction and distance, respectively:

Direction of the course change:
  $ location: a tap on the left or right side of the body,
  $ motion: simulate motion to the left or right by activating several actuators in a specific spatio-temporal pattern.

Distance to the next waypoint:
  $ rhythm: by presenting the course change patterns at closer intervals, a smaller distance to the waypoint is indicated,
  $ intensity: a higher intensity of the course change pattern indicates a smaller distance.

In the present experiment, we used rhythm to code distance. The timing parameters of the vibrocons are depicted in Table 1. Direction was coded as follows: a left turn was indicated by activating four tactors under the left leg (vibrocon left), turn right by four tactors under the right leg (vibrocon right), and go straight by the consecutive activation of the tactors

from back to front under both legs with a burst duration of 60 ms and an inter stimulus interval of 0 ms (vibrocon straight). Table 1 reads as follows: the vibrocon 'left at 50 m' consists of activating the tactors under the left leg five times for 60 ms with inter stimulus intervals of 52, 40, 32, and 20 ms.

Table 1. Timing parameters of the vibrocons.

distance	burst duration	inter stimulus interval	number of bursts
250 m	60 ms	264, 264 ms	3
150 m	60 ms	264, 212, 160, 108, 52 ms	6
50 m	60 ms	52, 40, 32, 20 ms	5

4.2. Method

4.2.1. Subjects, task, instruction, and performance measures.

Six male and two female drivers participated. Their age was between 23 and 51 years. All were experienced drivers, had normal vision, and had experience with driving simulators. They drove 12 experimental routes in a driving simulator, preceded by a familiarisation run. During this run, the drivers could get used to the simulator, the driving environment, the icons and vibrocons, and the instructions. The instructions were: a) to employ a normal driving style, including the priority rules and speed limits applicable, b) to follow the messages of the navigation system, c) to use the direction sign on the steering wheel (i.e., left / right) directly after receiving the navigation message, and d) to react directly on the stimuli of the Peripheral Detection Task (PDT, see below) by pressing a finger switch.

During the complete route, a PDT was presented. The PDT is based on the narrowing of the visual view as function of workload [13, 14, 15]. The PDT is able to measure the workload during driving and to measure workload peaks of short duration. [11]. The PDT presented red squares in the left periphery of the visual field (between 11-23°, 2-4° above the horizon) for 1s. The stimuli were presented with a random interval between 3-5 s. The participant's task was to react as fast as possible to the stimulus by pressing a finger switch, attached to the index finger of the right hand.

The 12 runs were divided over three conditions based on the modality in which the navigation information was presented: visual only, tactile only, and visual plus tactile. The runs were blocked accordingly. After each block, the participant filled in the BSMI, a standardised subjective mental effort rating [16]. The BSMI has an interval scale.

Three other perfomance measures were calculated for each route: the mean reaction time to the PDT, percentage detected PDT stimuli, and the reaction to the navigation information, expressed in the remaining distance to the next waypoint at the moment of indicating direction. The order of the conditions was balanced over the subjects, the different routes were balanced over the conditions.

4.2.2. Apparatus.

The experiment was run in the TNO LoCo simulator. This driving simulator has a $180 \times 30°$ field of view, rear-view mirrors, haptic feedback in the controls, automatic gear change, and interactive traffic. The database chosen for the present experiment was an urbanised area, measuring 3×3 km. Included were town roads, traffic signs, interactive traffic lights, interactive traffic, intersections with different priority situations, and roundabouts. Primary data (including position, heading, steering wheel angle, etc.) were stored with 60 Hz sampling frequency. The tactile actuators were Special Instrument MiniVib 4 vibrators. These are small boxes (18×22 mm) and present a 250 Hz vibration. The vibrators were mounted in the seat (four for each thigh, in a straight line from rear to front) with a centre-to-centre distance of 4 cm). Based on the distance to the next waypoint (250, 150, 50 m), the navigation symbol (icon, vibrocon, or both) was presented. Each icon was presented till the next icon appeared or the wapoint was reached.

4.3. Results and discussion

The results of each performance measure were analysed by a within subjects analyses of variance with modality (3) as independent variable. Significant effects ($p < .05$) were present for the BSMI (mental effort) rating, and the distance to the waypoint at which the subject reacted to the navigation message. The means are presented in Figure 1 and 2, respectively.
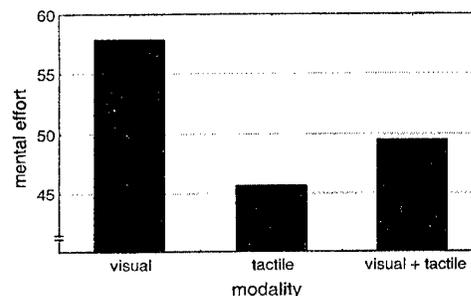

Figure 1. The effect of modality on the mental effort.
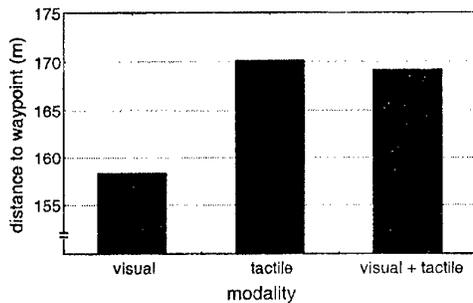
Figure 2. Effect of modality on the remaining distance to the oncomming waypoint when the driver reacts to the navigation message.

Figure 3. Effects of modality on the performance in the peripheral detection task.

The analysis of the mental effort shows that the rating in the visual only condition is about 25% higher than in the tactile only condition. The rating in the visual + tactile condition is in between. The same order of conditions is also present on the remaining distance to the waypoint at which the driver reacts to the navigation message (here a higher score indicates better performance). The means indicate that drivers react faster to the tactile messages than to the visual messages, while the score for the tactile + visual condition is close to the tactile only score. Since the first navigation message is presented 250 m before the waypoint, it means that the mean distance to react to the message is 80 m in the tactile condition and 92 m in the visual condition, an increase of 15%.

Both effects show the superiority of the tactile modality over the visual modality for presenting navigation messages: Drivers react faster to the message, and with less mental effort. The fact that adding the visual modality to the tactile messages reduces performance may be due to the fact that some drivers check the tactile message by looking at the visual display, especially during the first runs with the tactile displays. Afterwards they stated that it takes some time to learn to 'trust' the unusual tactile messages. This extra check reduces performance and increases the mental effort.

The MANOVA on the performance in the PDT did not result in a highly significant of condition ($p < 0.10$). The means for the percentage detected stimuli and the reaction time are given in Figure 3. Both PDT measures showed better performance in the tactile-only condition.

The PDT data objectively confirm the result of the mental effort rating scale: the tactile navigation display results in a decreased workload as compared to a visual navigation display.
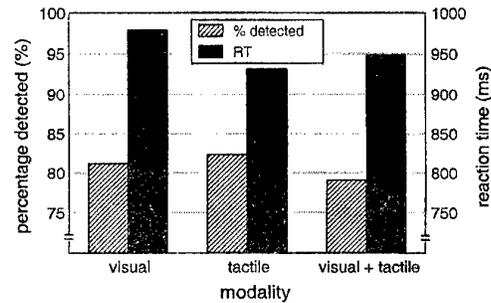
4.3. Conclusions

The results of the feasibility study show the superiority of the tactile navigation display over the visual display in the current set-up: faster reaction, lower mental effort and lower workload. These are the first indications that using the tactile modality in automobiles may improve the quality and safety of the man-machine-interface. However, we recommend performing field experiments with an instrumented vehicle and expert opinions to measure the effects on vehicle control and traffic behaviour

. However, it may be expected that the results in real driving may be even more pronounced. There are several reasons for this. For example, in the present set-up, the PDT stimuli were presented on the same side (left) as the visual navigation messages. With the visual display located on the opposite side, effects of a narrowing field of view will be stronger for the visual-only condition. Another important aspect is that in the driving simulator the navigation display and the outer scene are presented at the same distance. On the road, the driver must adjust to the light levels and focal distance when switching between the navigation display and the outer scene. Furthermore, some of the participants indicated that it takes more (training) time for them to learn to 'trust' the tactile messages than one three-minute training run.

5. General Conclusions

Using vibro-tactile displays in cars appears to be a useful concept, as the list of potential applications and initial proof-of-concept study shows. Its major promise is to improve the safety, efficiency, and fun of car driving. The technological feasibility is certainly high; the required displays can be constructed from cheap and robust elements that are now on the market. Former research showed the superiority of a tactile display over an auditive display for

warning the driver when exceeding a speed limit. The present experimental data show that a tactile navigation display results in faster reactions to the navigation messages and lower workload and mental effort than a visual display. Vibro-tactile displays seem to offer a valuable answer to the demand of the automotive industry to improve the man-machine interfaces in cars.

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A New Approach to Operating Machines with High Functionality

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Abstract

This paper presents the necessity and the concept of a new approach to control-units for technical devices with high functionality.

Due to the increasing contact of humans with technical devices in everyday life and the growing complexity of these devices, the man-machine communication gains in importance. The state of the art man-machine interfaces to operate complex technical devices are conventional push-buttons and touch-screens. Because both lack in either flexibility and clarity, or in haptic feedback, investigations about new solutions are necessary.

The approach presented is characterized by a flat control-panel, where buttons can arise in variable configurations. The buttons are programmable in size and haptic properties. The panel will comprise of single segments, each of them consisting of an actuator and a position sensor, which are currently in development.

The requirements, possibilities, and difficulties of this approach are discussed.

1. Introduction

The communication between man and machine nowadays gains in importance. On the one hand people are more often in contact with technical systems in everyday life. Transportation, communication, professional and leisure-time activities are almost unthinkable without using technical devices. On the other hand these devices keep on increasing their number of features. The success of modern microelectronics enables the implementation of additional functionality with almost no additional costs [1]. In summary there is a trend towards technical devices becoming more powerful and complex.

2. Problem

Unfortunately the increase of functionality does not imply only advantages for the user, especially with regard to the man-machine interface. The additional features have to be selected and controlled by the user, what often changes the usability of the device for the worse. People suffer from "feature shock", meaning they are unable to use the functionality due to the difficulty in operating the machine. This is a serious problem, as the features of devices from competing companies grow closer together, and therefore the man-machine interface becomes decisive for sales [2].

2.1 Conventional solution

There are two common ways to handle the high functionality of technical devices. One possibility is to provide a huge control panel with a lot of buttons and switches. Besides the drawback of a confusing appearance of such a panel, the available space for the control unit limits this solution. In order to be used by human fingers, every single control element, like a push-button, must not fall below a certain size.

Another more promising way to handle the large amount of features is with the use of touch-screens. The touch sensitive displays offer the opportunity of a menu-driven handling, similar to what is used in computer software. The menu structure is based upon the idea of not offering all selectable functions at once, but to divide them into different levels. Therefore a lot of functions can be offered by displaying only a manageable number of control elements. Today touch-screens are already often used for pda's, ticket-machines, cash-dispensers etc.

The major disadvantage of touch-screens is the missing haptic-feedback, that ordinary push-buttons provide in contrast to the virtual push-buttons of touch-screens. This results in an unexpected perception during the operation. People are used to feel the contact between the finger and the control element, the force exerted by the button to the finger, the movement during the depressing, and the haptic "click" when the electric contact is closed. These sensations form the basis for using control elements in an intuitive and automatic way without the need of attention [3]. As the user only pushes on a rigid screen made of glass while using a touch-screen, the operation does not happen intuitively. Figure 1 depicts the differences of the information flow between using a conventional push-button and a touch-screen.
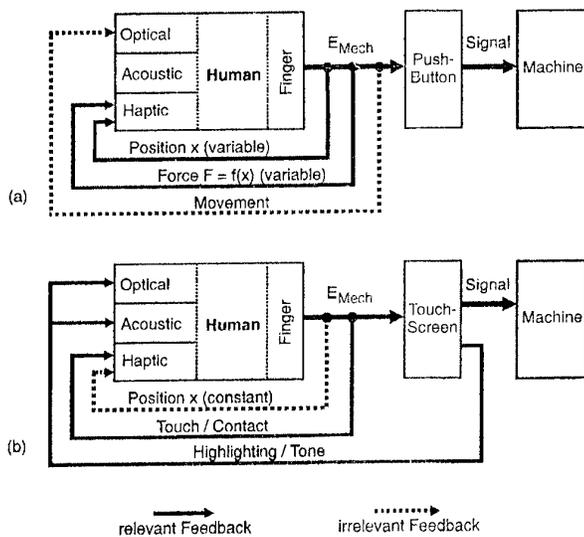
Figure 1. Comparison of the sensory feedback while using (a) a conventional push-button and (b) a touch-screen. The position and exerted force (mechanical impedance) of the push-button change during depressing, which is sensed by the haptic channel. The rigid touch-screen provides only a haptic sensation of the contact between finger and screen. An additional feedback to another sensory organ has to be generated artificially to confirm the operation of the virtual button on the screen.

Even if people are able to learn new patterns of behaviour for controlling machines by a lot of training, it is questionable if the human should be forced to do so, especially if elderly people have to use these machines (e.g. ticket-machine) too. We think that new technology should adapt to the human, not vice versa. This view is also stated by other authors [4].

3. New approach

As haptic feedback is expected by the user and helpful for intuitive machine operation, it appears reasonable to investigate the haptic aspect in man-machine communication. The claim for haptic feedback during the operation of machines in order to prevent uncertainty and enable fast and comfortable controlling is mentioned by several authors [5][6][7]. Therefore we are working on a new approach to operate the enormous functionality of modern technical devices without neglect of the haptic requirements. The solution seems to be a combination of both the flexibility of touch-screens and the haptic stimuli of ordinary push-buttons.

We envisage a flexible control-panel that is able to offer different numbers of buttons, which are – in contrast to the virtual buttons on touch-screens – indeed to be pressed down by the user similar to conventional push-buttons. Depending on the current situation or level of the menu-structure, the control panel is able to generate the

required number of buttons with programmable shape and size.

3.1 Concept and applications

The concept of a flexible control-panel with haptic feedback can be realized as follows: Imagine a flat area consisting of many single segments, which can arise independently from each other as illustrated in figure 2. In this way different numbers of buttons with variable forms and sizes can be generated. With a specific controlling the buttons can put up a resistance when pressed down by the user. Thus a menu-driven handling with adequate haptic feedback is possible.
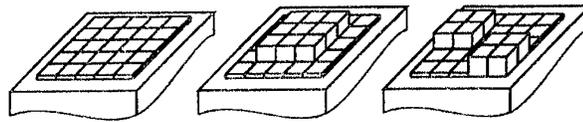
Figure 2. Sketch of a control-panel with buttons variable in number and size. The panel comprises of single segments.

The range of control-panels designed in this way is very wide. In many cases they could substitute touch-screens. But even new applications can be imagined. A universal remote control for TV-set, video-recorder, satellite-receiver and so on could be designed, that offers for every device just the accessory control-elements. Such a remote control differs from other universal controls on the market in its clear arrangement of the buttons.

Moreover the force exerted by the buttons of the described control-panel is variable, as the conditions of the segments are programmable. So for instance an user specific adaptation is conceivable. Depending on the user's desire, more or less force is needed to press the buttons down. Another possibility is to adapt the characteristic of a button to its function. For example the more important or serious the launch of a function is, the more force is needed to push the referring button down. Additionally some more information can be transferred to the user with a special behaviour like vibrations of the buttons. An event like a malfunction can be indicated in this way.

4. State of the project and further tasks

In order to demonstrate the advantages and performance of the concept presented, a control-panel for testing purposes should be developed.

Currently the design of the segments, which will finally form the control-panel, is in progress. As the position and the exerted force of the segments have to be controlled, every single segment is a system consisting of an actuator and a sensor.

In order to ensure a wide range of different programmable combinations of buttons with various shapes, the

dimensions of the segments should be relatively small. For the demonstration system the mechanical design should not exceed a maximum size of 1x1 cm² per segment. Besides the limited space, the actuator needs to show some more important performance characteristics. A minimum pressure of 20 mN/mm² is required to create a unique haptic impression during the depressing. So a button of the size of 1 cm² can exert a force of 2 N, which is an average value of conventional push-buttons.

Several authors discuss the force output resolution for force feedback devices. According to SRINIVASAN [8] a resolution of 0,01 N is necessary to make full use of human haptic capabilities, whereas SHIMOGA [9] recommends 0,05 N, respectively 0,02 N/cm².

The stroke of the actuator has to be at least 5 mm. This is not so much necessary for the haptic impression, as to ensure a visible difference between an inactive and an active, which means extended, segment.

The choice of possible actuators is strongly limited by these constraints. On closer examination only an electro-dynamic actuator seems to fulfil the demands. Moreover such an actuator has the advantage of a linear relation between the active current and the exerted force. This enables a system without force sensors, as the force can be calculated if the current is known.

As the realised control-panel should provide buttons with an appropriate haptic feedback, the exerted force must not be constant during the depressing. There is the need for a rising resistance until the button switches, afterwards a decrease. This characteristic behaviour is called "haptic click" and supports an intuitive operation [5]. In order to provide such behaviour, the position of the segments need to be measured by a sensor.

Similar to the design of the actuator, the sensor design has to be adapted to the human haptic capabilities. Although the threshold to detect static height differences by skin deformation at the human fingertip is 10 µm [10], ROSENBERG advises a position resolution of 25 µm [11] for a high quality force feedback system. Further the size of the sensor should not exceed the dimensions of the actuator. With respect to cost efficiency, an optical sensor, which evaluates reflecting light of an infrared light-emitting diode, will be used for the first conception.

After completing the design of the actuator and the sensor, a prototype of a single segment has to be fabricated. An evaluation referring to the mechanical and electrical behaviour will show whether a redesign is necessary. If the resolution of the exerted force and of the measured position matches the expectations, the next step is to compose an array consisting of several segments. The mechanical design of this array requires much development effort, as a modular concept is preferred to enable a simple assembly and serviceable operation.

Beside the mechanic and electronic development of the actuator-sensor-system, investigations about the controlling have to be done. Depending on the desired appear-

ance of the new created control-panel, the array has to be configured in such a way, that the correct number of buttons arises with the expected size and location. Therefore the stroke and exerted force of every single segment has to be controlled independently from other segments.

A major challenge is to provide a uniform movement of all segments forming one of those buttons, even if not all segments are touched and therefore depressed by the user's finger. Otherwise the button would not visually appear as a self-contained unit. This would confuse the user.

Finally the prototype of the new approach to control-units has to be evaluated by thorough investigations. Both the technical performance and the usability for everyday applications have to be checked.

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Cursor Displacement and Velocity Profiles for Targets in Various Locations

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Abstract

In order to create an algorithm, which predicts the endpoint of a cursor movement, an experiment was performed to reveal characteristics of cursor movements. In the experiment subjects had to click on a button in the center of the screen after which they moved the cursor onto a target which subsequently appeared. After the target was reached it disappeared. Targets were radially located at angles of $n * 45$ degrees $(0 \leq n \leq 7)$, and at distances of 150, 250 or 350 pixels (34 pixels/cm). Each of nine subjects executed this experiment three times, using either a mechanical mouse, an optical trackball or a mechanical force feedback trackball. The variables included in the analyses were curvature, variability around the mean path and the distance whereon peak velocity occurred. The results show that there is no need to compensate for a curvature other than zero in the algorithm. As the devices differ in their amount of variability and the location of the peak velocity one algorithm for each device is preferable. Within one device it could be considered to have a less accurate prediction or to make a special-case algorithm for direction and distance. To increase the accuracy even more one could choose to make an algorithm for each person separately.

1. Introduction

Technical development and cognitive ergonomical research on human-computer interaction have resulted in more userfriendly interfaces. More and qualitatively better colors and sounds are being used in a more efficient and attractive way.

Another phenomenon starting to integrate in human-computer interaction is the use of the sense of touch. This can be done by tactual or force feedback devices. For instance, playing games with a force feedback joystick is already very common. Other areas wherein tactual feedback is developing rapidly are medical training (e.g. the PHANToM) and blind computer users (e.g. the Virtual Reality mouse).

In every-day computer use the use of tactual feedback is not yet very common. However, tactual feedback can be very helpful in this area as well. Keyson [4] showed that target acquisition with force feedback was 10-15% faster than without. Unfortunately, force feedback in this area clearly needs restriction, because getting force feedback every time the cursor crosses an object does not make any sense, in fact this will be very disturbing. We think that the advantages of force feedback in this area are best used when it helps the user toward an object he/she wants to reach while not being disturbed by other objects. Therefore the computer needs to know what the users' target is in advance.

For this purpose we want to create an algorithm that can predict the users' intended target using the initial part of a cursor movement. Tactual feedback can then be released to help the user moving toward the target and away from non-targets. In order to create such an algorithm we need knowledge about the characteristics of cursor movements toward a target. Characteristics

can be the curvature of paths, the variability of paths around the mean path and the velocity profiles. When we know these path's statistics it is possible to use the initially observed direction and velocity of a cursor movement to predict the location of the users' intended target. The amount of variability can be used to estimate the maximum target resolution at which an algorithm can predict the user's target with a certain pre-specified probability. However, these characteristics could be influenced by factors like direction, distance, device and user.

In this paper we describe an experiment in which we explore cursor movements from a fixed starting point to targets located at three different distances and in eight different directions. When the factors mentioned do not influence the characteristics it is possible to create a general prediction-algorithm which is valid for all cases. When the factors do influence the characteristics, it might be useful to create special-case algorithms or to give in to the accuracy of the prediction.

2. The experiment

This experiment aimed to analyse cursor trajectories created by computer users in eight different directions, three different distances and three different devices. The data sampled were the co-ordinates and time. From these data we calculated mean paths curvatures, the variability around the mean paths and velocity profiles.

In the analyses the following aspects were involved:

- Per device we tested whether the mean path curvatures in each direction and on each distance differed from zero. A non-zero curvature would mean that the trajectories are not straight, but curved in a certain way. When this is the case it could be useful to compensate for it in the general prediction-algorithm. Also, when this is the case for some of the mean paths, for example in one direction, it could be useful to alter the general algorithm for this occasion.

- We investigated the influence of the different factors on the variability around the mean path. The amount of variability defines the accuracy with which the prediction can be made. More variability means a less accurate prediction. For example when 90% of the paths vary within 20 pixels around the mean path, an accuracy of 90% can be reached when objects are located 40 pixels away from each other. That is two times the variation around each mean path. By decreasing the resolution of the objects the accuracy of the prediction will increase.

- We calculated at what fraction of the target distance velocity was maximum. In the general algorithm this fraction sets the multiplication factor to assess the target distance. As well as the other variables, this fraction could be influenced by direction, distance, devices or user and therefore needs special-case multiplication factors.

2.1. Material and techniques

The experiment was done with three devices; a mechanical mouse, an optical trackball and a mechanical force feedback trackball. The mechanical mouse we used was a Logitec mouse. We call this a mechanical mouse because the movement of the cursor is related to the mechanical movement of the ball within the mouse. The optical trackball was the Logitec Marble Mouse. The force feedback trackball is a trackball with two motors, which can roll the ball in either x- or y-direction [2]. Without activating the motors this trackball acts as a normal trackball except that it is rather big (diameter 55mm) and that the friction is greater as a result of the contact wheels of the motors.
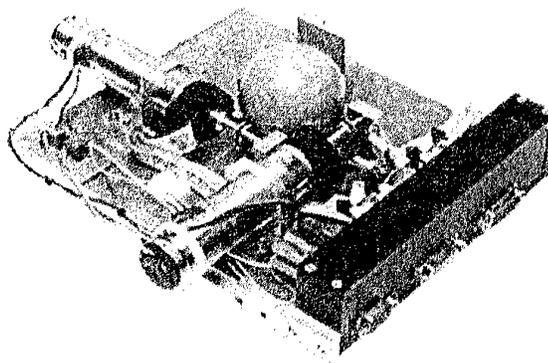
Figure 1. The mechanical force feedback trackball (opened)

We used a PC (Pentium II) and a 17-inch Dell-monitor with 1248*768 pixels for the sessions with the mechanical mouse and the optical trackball. For the session with the force feedback trackball we used a 386-PC and a 17-inch Philips Monitor. On the screen an interface was created with Visual Basic 5.0. The target consisted of a black circle 30 pixels in diameter, radially located at angles of $n * 45$ degrees ($0 \leq n \leq 7$), and at distances of 150, 250 or 350 pixels (34 pixels/cm).

During each trial x- and y-co-ordinates (in pixels) and the system time were sampled. This was done at 50 Hz.

2.2. Subjects

Subjects were nine colleagues, five men and four women. The mean age was 29.6 with a standard deviation of 4.5. All subjects were experienced mouse users, but had no experience with trackballs.

2.3. Procedure

In the experiment subjects had to click on a button in the center of the screen. A target appeared in one of eight directions and at one of three distances to which the subjects moved the cursor. After the target was reached it disappeared. The next trial started when the button was clicked.

2.4. Design

The experiment was divided into three sessions. In each session another device was used, the order of which was random.
Each session consisted of a practice and an experimental part. The practice was included to get the subject accustomed to the device and the task. In the practice part each target was presented two times in a random order. In the experimental part each target was presented ten times, also randomly. A session lasted for about 15 minutes.

2.5. Variables

Before calculating the curvature and the variability we performed a resampling on the data, because the original sampling was time controlled. This means that velocity of the movement influences the spacing between the samples. To calculate the curvature of a trajectory, however, we want equal spatial distances between the samples, because then every part of the trajectory contributes equally to the calculation of the curvature. Therefore, for each trajectory new samples were calculated, by interpolation, for every one-percent of the total travelled distance (distance of the trajectory itself).

To assess the *curvature*, the paths were first rotated until start and end positions were on the positive x-axis. Then the distance between each calculated co-ordinate and the x-axis was taken. This distance is equal to the accompanying y-co-ordinate, both with respect to value, sign and unit. Curvature was then defined as the mean value of this distance along the path [1]. E.g., an average distance of +3 means a positive curve of three pixels.

The *variability* of the paths is represented by the standard deviation of all sample points around the mean path of the ten trajectories performed per subject per direction and per device. The standard deviation is calculated over each ten-percent section of the whole path.

3. Results

Figure 2 shows the mean paths and the variability around it for each device and each of the three different distances. Standard deviation bars were computed and plotted at every one-tenth path length. From this figure a number of statistics can be derived for both curvature and variability.

3.1. Curvature

The mean paths shown in figure 2 look rather straight, but this can not be simply assumed to be the case (as Murata [5] did). We tested the calculated curvature against zero for every direction separately. It was also tested separately per device in order to observe possible systematic effects of the mechanics of each device.

Curvature is significantly different from zero on almost every direction for almost every device. Paths made with the mechanical force feedback trackball are three to four times more curved than paths with the other two devices. For the mechanical mouse and the optical trackball curvatures range from -2 till $+6$. The optical trackball shows curvature from -8 to $+11$. However, including a curvature variable into the prediction algorithm will only be effective when the curvature is more than the amount of variability. Looking at Figure 2, this will not be the case.

3.2. Variability

An overall mean variability of 12.63 pixels was calculated. A repeated measures ANOVA on variability, with device, distance and direction as within-subjects factors, showed that there is a significant influence from device ($F_{2,7}=25.526$, $p<.01$), distance ($F_{2,7}=27.866$, $p<.001$) and direction ($F_{7,2}=60.770$, $p<.05$) as well as an interaction effect between device and distance ($F_{4,5}=7.434$, $p<.05$). Also a significant subjects effect was found ($F_{1,8}=296.05$, $p<.001$). Post hoc tests showed that the variability of the paths depends on the first three factors in the following way:
(1) direction: for each device the variability in opposite directions equal each other. Also, movements with

each device are significantly less variable in horizontal direction than movements in the oblique directions.

Vertical movements are somewhat more variable than horizontal movements, but this effect is not significant. (2) distance: the nearest target results in the least variability (10,6 pixels), except for the mechanical force feedback trackball which yields a more complex pattern.

(3) control device: the overall variability is highest with the optical trackball (16.3 pixels) and lowest with the mechanical mouse (9.7 pixels). These results are comparable with results found in an earlier experiment by Keuning and Houtsma [3].
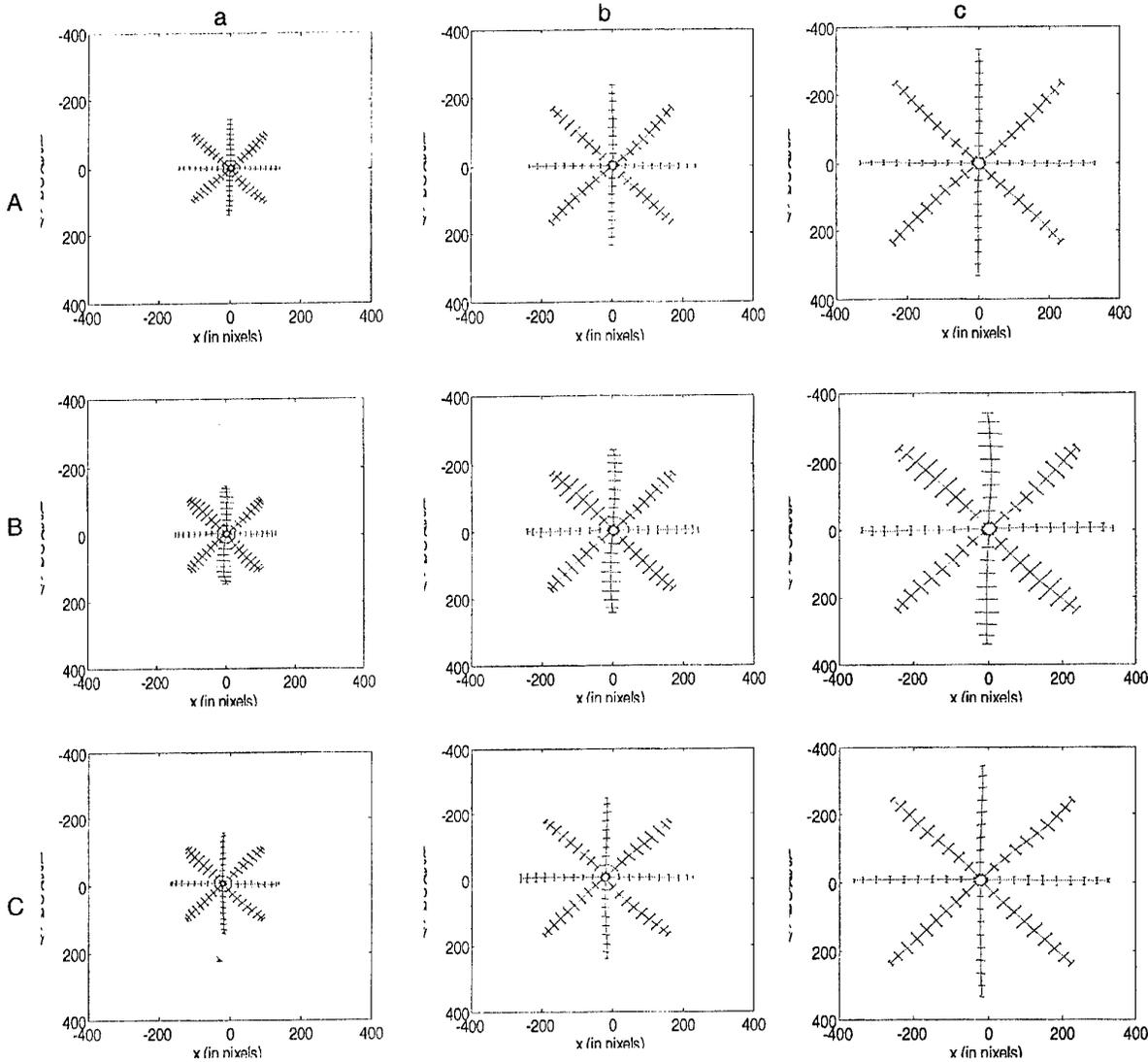

Figure 2: Mean paths and variability for A. mechanical mouse, B. optical trackball, C. mechanical force feedback trackball, separately for each distance a. 150 pixels, b. 250 pixels, c. 350 pixels.

3.3. Velocity peak

Averaged over all directions, distances, control devices and subjects the peak velocity was reached at 53% of the total distance. A repeated measures ANOVA on the location of peak velocity showed that there is a significant influence of device ($F_{2,7}=5.658$, p<.05), and distance ($F_{2,7}=103.017$, p<.001). The mean velocity profiles per device and distance can been seen in figure 3. Also an effect of subjects was found ($F_{1,8}=869.12$, p<.01). Post hoc tests showed that the influence is as follows:

(1) distance: the further away the nearer the peak (49% for the farthest target and 58% for the nearest) .

(2) device: the higher the friction of the device the further away the peak is. With the optical trackball having the lowest friction, the peak is at 49% and the mechanical force feedback trackball, having the highest friction, the peak is at 59%).

Direction did not (significantly) affect the relative distance of the peak velocity.

Figure 3. Velocity profiles of the mechanical mouse (dashed line), the optical trackball (solid line) and the mechanical force feedback trackball (dotted line).

3.4. Target resolution

Assuming variability for the nearest targets of 10.6 pixels at 50% of the distance, a prediction accuracy of 69% is reached within 7,5 degrees. The farthest targets, having a mean variability of 14.6 pixels, result in a 69% accuracy within 4,5 degrees. Taking the shortest distance as the worst case, targets must be at least 15 degrees (2 times 7,5) away from each other.

4. Discussion and conclusions

Since curvatures are not greater than the amount of variability it is not necessary to compensate for it in the general prediction-algorithm. This means that the direction of the users' target can be assessed from the direction of the initial movement of the cursor.

The accuracy of this prediction will depend on the object resolution and on the relative distance whereon the prediction is done. In earlier research it was concluded that the variability climbs to a maximum at 80% of the distance and then falls down rapidly (see [3]).

To increase the accuracy of the prediction of the direction one could decrease the distance between objects or change the distance at which a direction prediction is made. Also, multiple predictions can be made along the path.

The distance of the target can be assessed by multiplying the distance of the peak velocity by a factor two. An algorithm per device, however, would be preferable. The multiplication factors would then be 100/49, 100/53 and 100/59. A further specialisation is possible if the factor changes when the distance of the peak changes.

For each variable the best algorithm would be a subject specific one. It depends on purpose and costs whether this is rewarding.

The most important conclusion to be drawn is that creating a useful prediction algorithm seems to be possible. A prediction of the target distance is possible when the cursor is about halfway. A prediction of the correct direction appears possible in an even earlier stage.

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Interaction Techniques for Object Selection/Manipulation in Non-Immersive Virtual Environments with Force Feedback

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Abstract

The interaction techniques (ITs) that are used for object selection/manipulation are very important for easier and faster user interaction with objects in virtual environment (VE). Although research in this area is very intensive, few works are interested in possibility to combine these techniques with force feedback. In this paper we present short review of ITs for immersive VE. We discuss the possibilities to apply these ITs in non-immersive virtual environment with force feedback. We also show advantages and disadvantages of force feedback in VE and we try to adapt the methods to provide with better interaction.

Keywords: 3D interaction techniques, 3D user interface, virtual environment, selection and manipulation techniques, haptics, force feedback, PHANToM

1 Introduction

To perform selection and manipulation in virtual reality is not easy, because we are restricted to our arms reach. It means that we are able to select and manipulate objects that are within notably limited area in the neighbourhood to the user. Hence to realize these operations it is necessary to use interaction techniques that would allow us to accomplish given type of interaction better and faster.

In the last five years, the research of interaction techniques for object selection and manipulation for immersive VE was very progressive. But we have not found any work which tried to combine these techniques with force feedback and use it in VE applications. Adding force feedback enables users to feel the object shape and its other properties such as hardness, lubricity or weight of the object.

In this paper we deal with selection/manipulation techniques enhanced with force feedback. We especially study their properties i.e. advantages and disadvantages which occur in the presence of haptics. With respect to the features they show, we adapt them to achieve the improvement of their properties.

For realization of force feedback we have used PHANToM 1.0 device. This device provides single 3DOF force feedback applied at space point in limited space.

2 Previous work

The research of interaction techniques and their modifications was focused to immersive virtual reality (VR), and later also to augmented VR. Several studies [2, 5] compared individual techniques one to another. These studies allow the user to choose appropriate technique for given type of interaction. Unfortunately, only a few of them dealt with haptic interaction in VE.

That was the reason why we chose to evaluate the interaction techniques with haptics as described bellow.

3 Interaction techniques

VE Interaction techniques extend user's workspace for object manipulation within virtual scene and they enable to select the object situated out of our physical reach. Important requirement for these methods is that they must be easy to use and learn.

The taxonomy of interaction techniques for manipulation was published by Poupyrev et al [5]. Using this taxonomy we study the usage of haptics within *egocentric* ITs, especially techniques based on *virtual hand* and *virtual pointer* metaphor.

3.1 The taxonomy of manipulation techniques

The taxonomy [5] (Figure 1) divides current manipulation techniques for VE according to their basic interaction metaphors.

E MANIPULATION TECHNIQUES

```
├─ Exocentric metaphor
│        ├ Worl In Miniature
│        └ Automatic scaling
│
└─ Egocentric metaphor
         ├─ Virtual Hand metaphor
         │       ├ "Classical" virtual hand
         │       ├ Go–Go
         │       └ Indirect Go–Go
         └─ Virtual Pointer metaphor
                 ├ Ray–casting
                 ├ Flashlight
                 ├ Aperture
                 └ Image plane
```
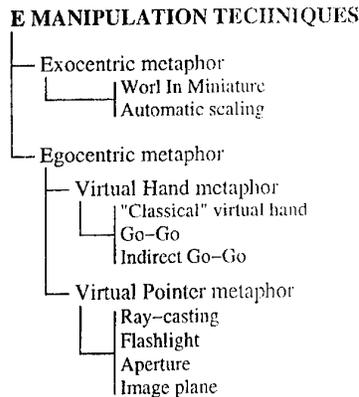
Figure 1: Classification of VE manipulation techniques depending on their underlying metaphor. Reproduced from [5].

The techniques are divided into *exocentric* and *egocentric* group. Exocentric techniques are also known as God's eye viewpoint, where user interacts with a scene from outside. An example is World In Miniature (WIM) technique [6].

On the contrary, with egocentric techniques the user is situated and interacts inside VE space shared by user and objects. These techniques are subdivided according to the metaphor they employ - either virtual hand metaphor (the user selects or manipulates the object using a virtual representation of a hand) or virtual pointer metaphor (where user interacts by pointing).

3.2 Egocentric techniques for selection and manipulation

In this section we describe the techniques that we used, other techniques are mentioned only briefly.

3.2.1 Virtual hand metaphor

With methods based on virtual hand metaphor it is possible to select the object in the case of intersection between the object and a cursor (in our experiment, the cursor follows the position of end point of PHANToM's arm). These methods are subdivided to

classical virtual hand technique and techniques that extend arm length in some manner.

The virtual hand technique uses direct linear mapping of physical cursor motion to motion of his virtual representation, mostly in 1:1 correspondence. It means, that selection and manipulation is realized in the same way as in the real world.

On the contrary, techniques extending arm length use either non-linear mapping or arm length is modified by some signal. The Go-Go and Fast Go-Go interaction techniques use non-linear mapping. The Go-Go technique [4] defines a local region around the user to distance D (Figure 2). While the physical cursor
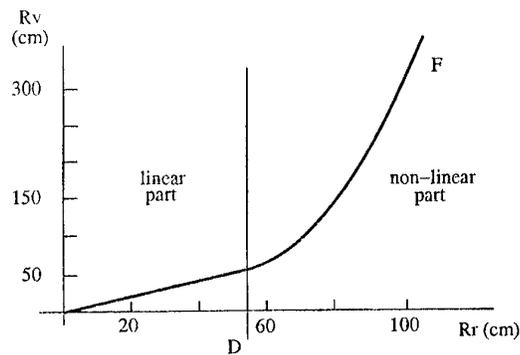
Figure 2: Example of mapping function F, for Go-Go technique. Reproduced from [4].

stays in this region, it uses linear mapping. When the cursor leaves this region, virtual representation of the cursor begins to move faster due to non-linear mapping. This way we extend range of manipulation at the expense of manipulation preciseness. Modification of this method is the Fast Go-Go technique [1] which has no local region and applies more rapidly growing mapping function. Next there belongs the Stretch Go-Go technique that extends arm length according to which region around the user the cursor is located in. On the contrary, the Indirect stretch Go-Go technique realizes the change of length using two signals.

3.2.2 Virtual pointer metaphor

With the virtual pointer metaphor, selection and manipulation is realized by a ray (ray-casting technique) [1, 3]. The ray is defined by its position and orientation. Object selection and grabbing is confirmed by the user using some signal. This technique has specific disadvantages, especially selection of very small or distant objects is complicated.

This disadvantage is solved using technique called flashlight [1] [8]. The user can select objects that are located within spotlight's cone. To select among more objects contained in the cone, it is possible to use an aperture technique [9] (Figure 3). It is modification of flashlight technique where the selection of objects within the cone is done using a collision plane (represented by aperture circle here).
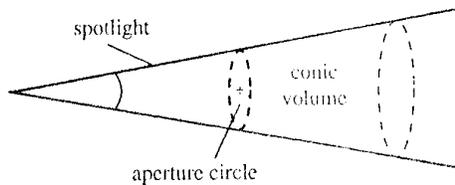
Figure 3: Aperture technique (Forsberg, et al. 1996).

3.2.3 Manipulation with egocentric techniques

To manipulate object only some methods based on virtual hand metaphor are appropriate. Especially the classical virtual technique, the Go-Go and Fast Go-Go technique [1, 4]. With the Stretch Go-Go and Indirect stretch Go-Go, the manipulation is not so easy.

From methods based on virtual pointer metaphor, the ray-casting technique [1, 3] is used to change object location. During manipulation, the object is being relocated using the ray. The change of position can be done relatively easily, but object rotation is rather difficult because we can rotate object easily only around a ray axis. Also during manipulation it is suitable to use fishing reel technique [2] [1] that allows to pull and push objects along the ray. It is realized using two buttons. The rotation around another axis can be enabled using additional signals.

4 The experiments

In our experiments we tested the properties of interaction techniques with haptics in immersive VE. Our goal was to find out if these methods allow users to interact better and faster with the virtual scene. We also wanted to discover what problems they bring along and how we can handle them.

The experiments used the virtual environment with several simple objects, such as cube and sphere, and

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[1] This method is also known as spotlight or also cone-casting technique
[2] This technique is also known as ray-casting with reeling.

PHANToM stylus was represented by a virtual stylus (Figure 4). Position and orientation was derived from the real stylus location. Using scene geometry and collision detection application computes appropriate force and applies force feedback to user's finger in PHANToM. All computations were done on dual PC system with RT Linux.

Thus, with the virtual hand metaphor, we can touch and feel the objects within the scene and select them at end-point of the virtual stylus. The object selection is confirmed when the user touches object and presses the stylus button at the same time.
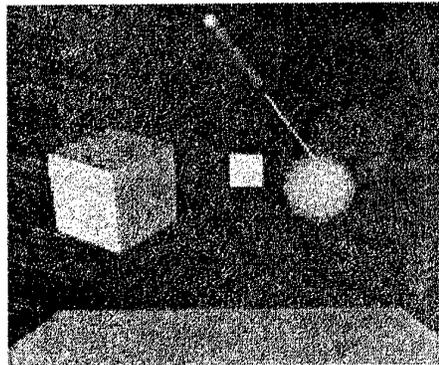
Figure 4: Example of the scene and the virtual representation of PHANToM stylus.

With virtual pointer metaphor, the location of ray was determined by the position of the real stylus and direction was derived from its orientation. Thus the ray is casted from the virtual stylus and is visualized by a short segment. In this case, the user performs object selection by intersecting some object with the ray. When feeling haptic contact, user may confirm selection by pressing the stylus button.

4.1 Properties of selection techniques with force feedback

The selection task can naturally exploit contact information provided with *force feedback*. It helps to detect a contact with object in a faster and more convincing way. Here we show various approaches of force feedback application, together with assets and problems they bring along.

4.1.1 Classical virtual hand technique

This is a typical technique which is used for selection of objects most often. Here force impact is

realized in the moment, when it comes to collision between cursor and object. Repulsive force is applied by PHANToM device to simulate natural haptic feeling.

The advantage of this approach is, that it allows the user to explore the scene in a given scale factor (depending on adopted linear mapping). Subsequently, the user is able to create a partial visualization of a real shape of the individual objects. Unfortunately, with this method we are restricted only to space mapped to physical PHANToM space, accordingly. Moving in larger virtual space using suitable scaling we achieve faster motion of the cursor but we disallow precise manipulation in the whole scene.

4.1.2 Go-Go techniques

The disadvantage of the classical virtual hand technique is partly solved using Go-Go techniques [1, 4]. When the cursor is located in the local region this method has the same properties as previous one.

When the cursor enters outer region, a user can move deeper into the scene using non-linear mapping. The disadvantage is that, due to the non-linear mapping the distances get shorter, and object shapes appear *deformed* (Figure 5). Another problem associ-
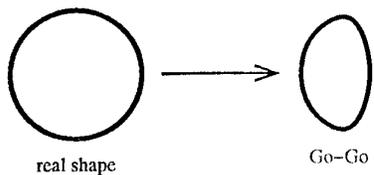
Figure 5: Shape deformation of sphere using Go-Go technique.

ated with this technique shows up, when cursor approaches the borders of the maximal reach. When it collides with a distant object close to the border, the interaction with it is very sensitive and unstable. Force feedback loop detects faster and deeper penetration of cursor in an object, resulting in enormous force grows, user's reaction and unpleasant vibrations. This undesirable property can be partly eliminated using appropriate force filter included to interaction loop (e.g. quadratic filter).

The next problem is occurrence of the so called *fast skidding* along an object surface when the cursor moves into the scene (Figure 6). This problem is notable especially in the case of faster motion. We tried to solve these problems by establishing the *lo-*
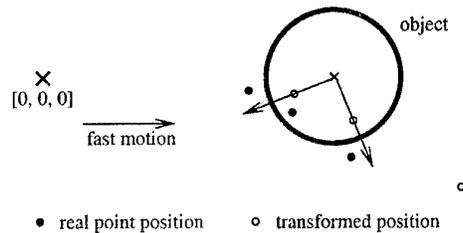
Figure 6: Fast skidding along the surface that is due to usage of the Go-Go technique.

cal region surrounding every object within the scene. When the cursor is located in such a local region, we apply linear mapping. Together with it we create a mild force barrier. This purposely created artificial force field holds the user close to the object and it helps him to not leave the object region unknowingly. Of course, it means that user would feel this force field and we experiment with its proper setting. With this approach, the user is able to recognize the real object shape, and the effect of the shape skidding is almost eliminated. Local region with force field also improves object manipulation (see section 4.2.2).

However, this solution has also some drawbacks. The problem appears when the cursor leaves the local region of an object and non-linear mapping is again switched on. To change mappings immediately could lead to the situation when the cursor is relocated to the inside of some other object. Subsequently repulsive force changes very rapidly. This problem may be solved using an algorithm that realizes smooth transition between both types of mappings.

4.1.3 Ray-casting technique

With ray-casting technique [1, 3] there are two obvious solutions how to apply the force feedback. The first way is same as with virtual hand metaphor where the ray repulsion from the object is used. Force is applied in point that is the centroid of the ray intersections with an object. Situation is shown in Figure 7a. Using this solution, the user is partly able to recognize a profile of the object shape.

The second way is to derive the force acting against a ray motion inside the object (Figure 7b). When entering object with ray the user perceives the feeling of steering some volume with liquid. This way he/she detects, when scanning the scene, the objects with which ray collides. But in the quiescent state of the ray we do not feel any force resistance even in the collision
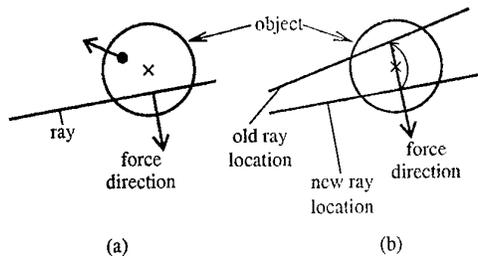
Figure 7: Applying the force when ray collides with an object. (a) Ray repulsion from the object, (b) Force acting against a ray motion inside the object.

situation. We have solved this drawback by application of a small force in direction opposite to the ray. Now we can easily detect the collision with an object even in the quiescent state. In both approaches rapid force changes may occur, which results in vibrations. It happens in the cases when ray collides with some distant object. Only a small angular change in ray's direction results in very fast penetration speed and unexpected force jumps. Here we also must use sophisticated filter, or rather an algorithm which reduces these vibrations.

4.1.4 Flashlight

With flashlight method [8] we can use both previously mentioned forms of force feedback, i.e. ray repulsion and force acting against a ray motion inside the object. When using ray repulsion feedback it may be difficult to approach some objects from some locations. To allow easy movement in densely populated space we have to either apply only a small repulsive force, or to narrow cone apex angle.

The second approach provides better and a more comfortable solution. Using the cone we may select objects easily and with supplementary force feedback both in static and dynamic form, the interaction is easier. As in previous case, the force have to be applied carefully to prevent "enemy behaviour" of interaction loop.

4.1.5 Aperture

When using aperture circle for selection inside cone space the second method, i.e. force acting against a ray motion is the preferable solution. Using this approach a user need not to strain when passing through the objects in front of object under interest. In addition, we have used two levels of the force feedback.

The smaller force is used to indicate to the user that some objects are located within the cone. The second, greater force signals the collision of some object with the aperture circle (Figure 8). Again, the size of these forces has to be chosen carefully so that a user recognizes it but is not restricted in interaction freedom.
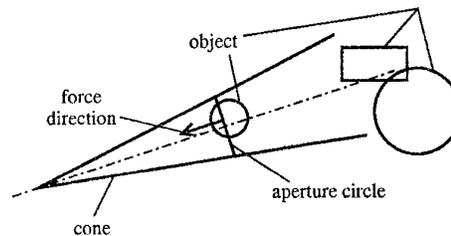
Figure 8: Usage of the force with aperture technique.

4.2 Properties of manipulation techniques with force feedback

4.2.1 Manipulation with virtual hand technique

The advantage is that this technique enhanced with haptics allows the user to relocate the object faster and with great precision. Of course the properties of 3D environments are exploited to support precise positioning. On the contrary, force feedback may extend the time of manipulation when we want to relocate object in the dense space. This situation could be solved by switching force feedback off. Unfortunately we lose haptic contact with the scene. The more preferable solution is to apply smaller forces appropriate for this situation.

4.2.2 Go-Go techniques

Manipulation using Go-Go techniques [1, 4] with haptics meets the same problems as simple virtual hand technique. Due to non-linear mapping especially in farther part of the workspace it is more difficult to achieve the precise location of the object (mostly, this problem occurs when we move one object close to another). Here we can again establish the *local region*, defined in the section 4.1.2, around all objects, and to perform more precise location of the object.

4.2.3 Ray-casting technique

Manipulation with this technique displays the similar properties as previous techniques, but in addition,

another problems appear as in the case of selection. The main problem is, that a small change of the ray orientation results in a big change of distant object position. Again we can partly solve this problem using appropriate force filter which reduces vibrations.

The next question is, how to grab an object by ray. The first solution is to transfer the scene so that the ray intersecting the selected object is in its center. The second possibility is to move the object in the plane orthogonal to ray, and to pull the object to ray. This choice brings along the problem of the unexpected penetration of selected object into another one, after grabbing it. To avoid unexpected force jumps, we use dynamically growing repulsive force which, starting from zero, subsequently resolves colliding situation. And finally, the third solution we can use, is to allow grabbing the object at any place.

Only the third solution seems to be optimal, because it allows us to choose any rotation axis and to manipulate with objects quite freely.

5 Conclusions and future work

In this paper we show that well known interaction techniques for immersive VE can be naturally combined with haptics. Force feedback may improve the user's interaction in virtual worlds. Techniques enriched with haptics support faster interaction with the objects. On the other hand their usage also brings many problems. We mentioned some partial solutions of these problems, but many others still remain opened.

In the future we want to find more general solutions of problems related to combination of two interaction spaces. The first one is the visual space of immersive VE with non-linear coordinate system and the second one is the haptic space with a different and, as we found, even dynamically changing coordinate system. There are also many other techniques that we want to adapt for haptic VE (such as the WIM technique [6], Voodoo Dolls [7], etc.). We also plan to continue in the search for novel interaction techniques for VE that would allow us to interact better with VE. Long distance goal focuses on the ways of interaction that would be appropriate for visually impaired people.

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The effects of a change in gravity on the dynamics of prehension.

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Abstract

Investigating cyclic vertical arm movements with a hand-held load in an airplane undergoing parabolic flight profiles allowed us to study how humans modulated their grip force (GF) when the gravitational and the inertial components of the load force (LF) varied independently. Eight subjects participated in this study; four had already experienced parabolic flights (ES) and four were inexperienced (NES). They had to move continuously an instrumented object up and down in three different gravitational conditions (1 g, 1.8 g, 0 g). In 1 g, GF precisely anticipated the fluctuations of LF which was maximum at the bottom of the trajectory and minimum at the top of the trajectory. However, as the subjects incompletely released their grip when LF was minimum, the grip-load force relationship was not linearly proportional as frequently described in the literature. When the gravity changed (0 g and 1.8 g), the grip-load force coupling persisted for all the subjects from the first parabola. In 0 g, GF was accurately adjusted to the two peaks of LF occurring at the two extremities of the trajectory due to the absence of weight. While the level of GF modulation was immediately adapted to the new force field for the ES, the NES dramatically increased their grip when he was faced with altered gravity for the first time. A progressive release of the grip occurred and a continuous grip-load force relationship with regard to 1 g was established after the fifth parabola. A new gravitational field was rapidly integrated into internal CNS models which could then be reused as required by the occasion.

Controlling Reaching Movements with Unpredictable Object Motion

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Abstract

In the experiment we investigated the reaching behaviour of 10-year-old children and adults for virtual objects moving either on a predictable (linear) path or an unpredictable path (with random direction changes). 24 adults and 24 10-year-olds observed a spherical object which varied in the predictability of motion (linear vs. nonlinear) and the speed of object motion (17 cm/s vs. 24 cm/s). In an action condition the participants had to reach for the objects via a force-feedback device. We compared reaching movements for the linearly moving object with reaching movements for the nonlinearly moving object (but only those trials were evaluated where the normally unpredictable object moved linear). We analysed initial movement direction and maximum speed of the first sub-movement. In a judgement condition participants indicated the initial movement direction on a rating scale. Children and adults produced higher initial movement speeds and the initial movement direction was geared further towards the current position of the object for unpredictably moving objects. Our results show that predictable and unpredictable behavior is processed differently.

1. Introduction

We investigated the visuomotor control of children and adults reaching for an object that was displayed on a computer monitor and moved either predictably or unpredictably. In various interception tasks, reaching for linearly moving objects has been studied by researchers interested in human motor control (see Schmidt, 1988) and the development of perceptual-motor skills (see Keogh & Sugden, 1985; Dorfman, 1977; Williams, 1973).

Cognitive aspects of interception skills have rarely been investigated in detail in this field of research. Recent infant studies, mostly conducted by von Hofsten and his group (von Hofsten, 1980, 1982, 1983; von Hofsten, Vishton, Spelke, Rosander, & Feng, 1998), constitute an exception. This research has shown that young infants are capable of manually intercepting a (slowly) moving object as soon as they begin to reach for stationary objects (von Hofsten & Lindhagen, 1979) and that their rudimentary interception skills improve markedly between four and eight months of age. Infants' reaching movements have been shown to be predictive in that they are geared toward the future interception point rather than at the object's momentary position (von Hofsten 1980; Clifton, Muir, Ashmead, & Clarkson, 1993). Although infants show anticipation of a future interception point if the object moves linearly, reaching is interrupted if the object moves on a non-linear path (von Hofsten et al., 1998).

Reaching for linearly moving objects has also been investigated with older children and adults. Reaching skills seem to develop quite slowly with respect to accuracy and interception speed and are not fully developed until the teenage years. Reaching movements of adults have been shown to be highly adapted to object speed: Objects that move with high velocity are approached faster than objects moving more slowly even if participants are instructed to reach for the object as fast as possible (Smeets & Brenner, 1995).

But how does the reaching movement change if object motion is unpredictable like in the case of animate objects? More specifically, do adults as well as children adapt their movements to the escape behaviour of a target object and gear them toward the object's momentary position instead of toward an anticipated interception point? To investigate this, we conducted an experiment where participants (10-year-old children and adults) had to intercept a moving object displayed on a computer monitor that moved either linearly or showed an escape behaviour.

Participants controlled another virtual object to intercept the target object.

2. Experiment

2.1 Method

Twenty-eight adults and 26 10-year-old children took part in the experiment. Two adults and one child had to be excluded due to technical problems and three adults as well as two children had to be excluded from the analysis because they did not follow the instructions (i.e., they did not try to catch the ball as fast as possible). The data of 23 adults (11 female, 12 male) and 24 children (12 female, 12 male) was analysed. The average age of the adults was 23 years and 8 month (min: 19;1, max: 28;7) and of the children 10 years and 2 month (min: 9;1, max: 11;3).

Participants' task was to intercept a spherical object moving on a computer monitor. In order to intercept the object they had to move a second object that they controlled via a PHANToM™ haptic interface. The target object moved with constant speed (either 17 cm/s or 24 cm/s) starting from the left or right border of the monitor. In a linear condition, the target moved on a straight and horizontal path. In a non-linear condition, the target was programmed to show an escape behaviour, i.e., it changed its direction (with a new direction at a random angle between 75 deg and 105 deg to the left or right of the former direction) as soon as the distance from the participant's object fell below a randomly chosen minimal distance.

The two conditions were presented separately in two experimental blocks. Object speed and direction were varied from trial to trial. To familiarise participants with the respective target behaviour, eight practice trials were

Linear Condition

Non-Linear Condition

presented at the beginning of each block. In the linear condition, eight experimental trials were given; in the non-linear condition, a total of 40 experimental trials were given in eight of which the target moved on a linear path, like in the linear condition with no change of the direction. Only these eight trials were analysed and compared with the eight experimental trials of the linear condition. The participants' catching movements were measured with the PHANToM™ haptic interface.

This action task was followed by a judgement task where only the target speed varied. After the target had left its home-field (marked by a circle around the starting position), participants had to indicate the most suitable angle for the initial sub-movement of the interception response. Two practice trials were followed by four experimental trials for each the linear and non-linear condition separately.

Figure 1. Linear (upper panel) and nonlinear condition (lower panel). In the linear and non-linear condition the target objects are a blue and orange sphere, respectively. The object controlled by the participant was a purple sphere. Its starting position was the left and right lower corner for a homefield of the target on the left and right side, respectively. The circular line around the starting position of the target sphere indicated the home-field. The angle α indicates the initial direction of the reaching movement. The distance dmin was chosen randomly each trial; it indicates the distance at which the escape behaviour started.

2.2 Results

Data of participants' initial direction of movement (relative to the current object position, calculated for the first 100 ms following the movement initiation) and maximum speed of the first sub-movement of each trial were analysed. The initial movement direction provided information whether participants' movements were rather geared toward the target's current position or toward an anticipated interception point. In the judgement task, the estimated angles were analysed. ANOVAs were performed for the action and judgement conditions separately on the within-factors object speed and predictability of object motion (linear vs. non-linear condition) as well as on the between-factor age.

Figure 2. Initial direction in the judgement condition for children and adults (L = linear condition, N= nonlinear condition, 17 and 24 indicate the target speed of 17 cm/s and 24 cm/sec)

2.2.1 Judgement – Initial direction. In the linear condition estimated angles were larger than in the non-linear

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ADULTS

CHILDREN

ADULTS

CHILDREN

Figure 3. Average produced initial direction in the action condition for children and adults. (L = linear condition, N= nonlinear condition, 17 and 24 indicate the target speed of 17 cm/s and 24 cm/sec).
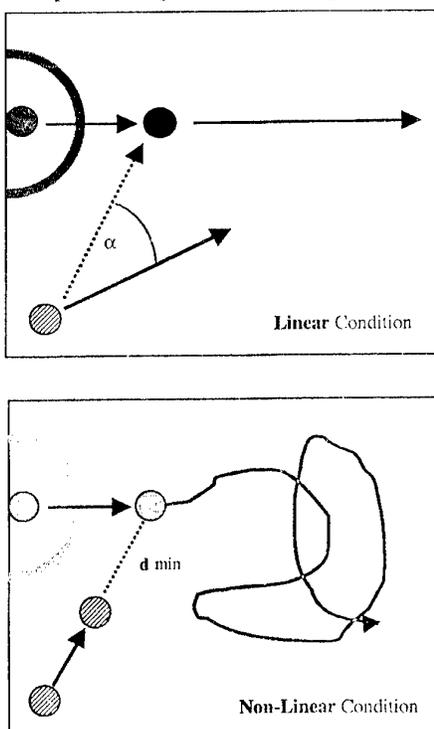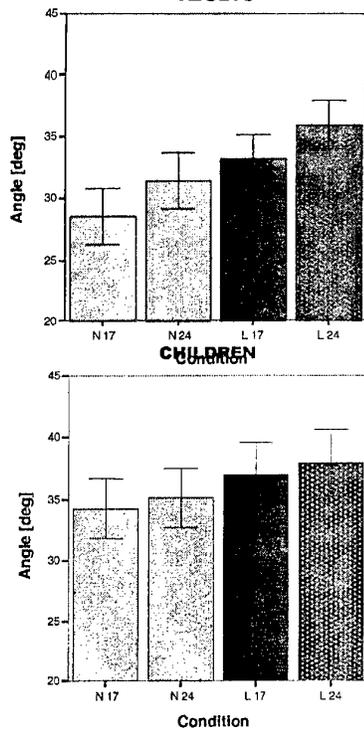
condition, $F(1, 46) = 9.11$, $p < .01$. Participants aimed further ahead in the linear condition. The estimated angles were also larger for the fast object, $F(1, 46) = 5.08$, $p < .05$. Overall, no age differences were found, $F(1, 45) = 1.71$, $p = .20$).

2.2.2 Action – Initial direction. The initial angle of the interception response varied with the predictability of the target's motion: The angle was larger in the linear condition than in the non-linear condition, $F(1, 45) = 9.15$, $p < .01$. This indicated that participants rather aimed for an anticipated interception point in the linear condition but approached the target object more directly in the non-linear condition. Overall the initial direction did not differ significantly for the high and low target speed, $F(1, 45) = 2.51$, $p > 0.1$. The two way interaction of the factors object speed and predictability of object motion, $F(1, 45) = 5.02$, $p < .05$, as well as the three way interaction with age, $F(1, 45) = 5.91$, $p < .05$, turned out to be significant, however. The initial angle tended to be smaller for the fast object, in contrast to the judgement condition. Children did not show this effect, however, in the non-linear condition.

2.2.3. Action – Maximum speed. The maximum speed of the first sub-movement varied with both object speed and the predictability of object motion. It was higher in the non-linear condition than in the linear condition, $F(1, 45) = 55.23$, $p < .001$, and higher for the fast object than for the slow object, $F(1, 45) = 107.95$, $p < .001$. Overall, adults produced higher movement speeds than children, $F(1, 45) = 5.70$, $p < .05$, but age did not interact with the object speed, $F < 1$ or the predictability of object motion, $F(1, 45) = 1.37$, $p = .25$.
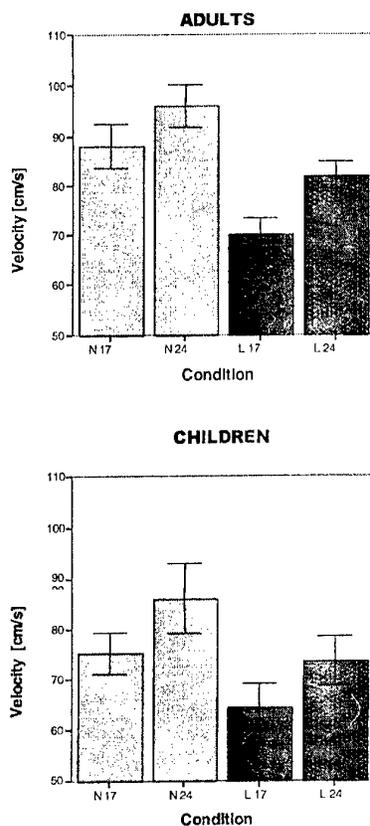
ADULTS

CHILDREN

Figure 4. Average produced maximum speed for the first sub-movement for children and adults. (L = linear condition, N= nonlinear condition, 17 and 24 indicate the target speed of 17 cm/s and 24 cm/sec).

3. Discussion

In general, we found different visuomotor control strategies for reaching toward targets moving predictably or unpredictably. The reaching movement differed with respect to both the initial movement direction and maximum speed of the first sub-movement. In the linear condition, participants aimed at an anticipated interception point while, in the non-linear condition, participants approached the object more directly. Participants reached faster for unpredictable than for predictable targets. Additionally adults and children reached faster for the fast object than for the slow object.

Taken together, these results show that participants' reaching movements were adapted to both target speed and predictability of the target motion. Participants used different strategies in the two conditions. In the linear condition, reaching for the target is a simple intercep-

tion task where the interception point can be anticipated and approached with a velocity tuned to the target speed. In the case of unpredictable objects the anticipation of an interception point is not possible and participants tried to reach for the target much faster and more directly toward the target.

Based on the present results, it appears possible to investigate (implicit) knowledge about the predictability of object motion. In future studies, children's knowledge about animate and inanimate objects could be investigated using our paradigm. Children making mistakes in judging whether an object belongs to the animate or inanimate category, nevertheless, may show different reaching behaviour when asked to catch these objects.

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Haptic Modelling – An Alternative Industrial Design Methodology?

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Abstract

Physical models continue to form an essential outcome from industrial design practice. Whist the professional may be removed from the "hands-on" model build by employing the services of a model-maker, many designers consider such physical interaction as an important part of their idea development process. Visual and tactile feedback from model generation is considered by many as an essential part of the experience of physical interaction with form and material. However, the advent of remote model building technologies via rapid prototyping and computer controlled machining, has given professionals an alternative method of working which offers other advantages to the design process. This has meant that the designer is increasingly removed from such physical interaction with the model.

The emergence of three dimensional digital modelling via haptic feedback devices may offer a route whereby professional designers can gain the benefits of a digital process yet continue to be involved with tactile design modelling. Acknowledging the need to utilise digital design techniques, this paper investigates the capabilities of haptic modelling for use within industrial design practice. The research is based on an industrial design case study for a communication device that was undertaken by the authors.

The paper discusses the attempts made to emulate workshop-based modelling activities with Sensable Technologies Phantom haptic feedback device using Freeform software. Whilst the initial response to the system was not entirely satisfactory, the research identified the potential to use the haptic feedback device to produce forms that would be virtually impossible to specify using traditional digital techniques. Having gained some experience in the capabilities of the hardware and software, creative opportunities emerged that were a direct result of the application of this technology.

1. Introduction

As a profession involved in the definition of product form, industrial designers make extensive use of three-dimensional (3D) models. These may vary in sophistication from relatively simple study models to full prototypes ([1] Knoblaugh 1958 p15, [2] Kojima 1991 p38). The type of model most associated with industrial design practice is the appearance model, which embodies the form of the production item but none of the functionality ([3] Powell 1990 p11).

Prior to the advent of remote model building technologies such as rapid prototyping and computer controlled machining, models would be produced by manual working and craft-based techniques. Some designers take design decisions as they manually manipulate the material, modifying it accordingly.

As professional practice makes increasing use of remote model building technologies, the opportunity for the designer to be directly involved in the shaping of material decreases. This has been shown to be the case with the full range of models, from study models to prototypes ([4] Sharbaugh in Carrabine 1999 p24). In contrast the digital technology that enables remote model building has also enabled increasing use of virtual evaluation whereby 3D computer aided design (CAD) and computer aided industrial design (CAID) systems are used to provide photo-realistic visualisation and real-time animation.

One could argue that the experienced practitioner might have sufficient levels of skill and judgement to bypass the direct interaction with form. Indeed, personal experience has shown that such practice often takes place when deadlines are tight or resources are limited.

However there is a strong groundswell of opinion that tactile product development is beneficial to the final products form and so a way should be found to combine the craft based techniques with digital product development.

Recognising this need the emerging technology of digital modelling using a haptic feedback device may have the potential to develop and encourage the physical manipulation of form on a virtual level. Haptic feedback devices give the operator the "feel" of the virtual object. If the operator moves a cursor onto an object as seen via the monitor, they actually feel its presence via an electro-mechanical system attached to the pointing device.

The authors, having backgrounds as both design practitioners and educators, have explored the nature of haptic modelling, considering its potential for integration into industrial design practice and design education. There follows a record of a programme of research that involved the industrial design of a highly conceptual communication device that was produced as an entry for the Nagoya International Design Competition in May 2000. The structure of the case study follows the three phases of professional practice as identified by Pipes [5], involving concept generation, design development, and specification. These are now explored in some detail.

2. Concept Generation

The brief for the communication device specified that its form should cross the boundaries between what we consider to be jewellery and a consumer product. The design was to have some of the functionality of a mobile telephone, without the transient feel of a polymer consumer product. Concept generation was undertaken using paper-based sketching, examples of which can be seen in Figure 1.

Whilst CAID was available throughout the project, the industrial designer felt that the application of this technology was inappropriate at the concept generation stage due to the lack of spontaneity afforded by its modelling methods. This is identified by Pipes [5] when he states that "Conventional CAD at an early stage can stifle creativity by its insistence that the designer provides the system with exact dimensional and geometric information right from the start".

A small brooch-like product emerged from the concept generation phase, its form based around an elliptical body with a large answer button. Other functionality was accessed via three smaller buttons positioned on one end. The speaker/microphone was located on the opposite edge.

The paper-based sketches provided the industrial designer with sufficient detail on form and size to progress to the second phase of design development. If

operating to a more traditional design methodology, this phase may involve some modelling in "soft" materials such as Styrofoam, or even the manipulation of more resistant materials. For the purpose of the case study, haptic modelling was to be introduced as an alternative.

Figure 1. Concept generation using paper-based techniques.

3. Design Development

Sensable Technologies based in Boston Massachusetts made the Phantom Desktop input device and Freeform software available. Twin Intel 450Mhz processors with 512MB of RAM were used to run the software, and Sensable Technologies UK consultant provided support. The Phantom Desktop device can be seen in Figure 2.
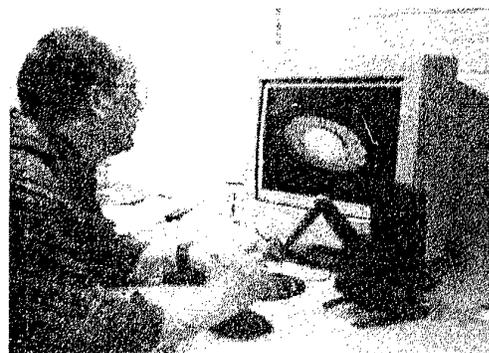
Figure 2. Phantom Desktop input device with Freeform 2 software.

As a precursor to the product being modelled, an exploratory use of the technology was undertaken. This involved an evaluation of the additive and subtractive (Boolean) modelling techniques, along with smoothing operations and manipulation of material density. The move from interacting with a physical object, to a virtual model, was initially found to be an unusual experience. However, as familiarity with the software and system developed, the modelling capabilities of the media emerged. Indeed it soon became apparent that the haptic

modelling system was capable of producing forms that could not be generated using CAID, although the value of these relatively abstract surfaces represent a separate issue. Figure 3 shows one of the models produced during the exploration of the media.

After a period of familiarisation, it became evident that the modelling system could be used on two levels. The first involved techniques closely associated with normal CAD modelling, whereby forms could be generated by non-haptic input e.g. creating standard shapes and modifying by stretching. The second technique was true haptic modelling which had the potential to produce forms via various shaping operations whilst receiving physical tactile feedback.

Following the evaluation of the haptic modeller, which only lasted some 2-3 hours (a credit to the usability of the system), the decision was taken to model the communication device using the using both of these methods. This was particularly appropriate for the communication device, as the basic outer form of the product was easily constructed from primitive shapes combined via Boolean operations. However to fulfil the design brief in removing the typical feel of a plastic injection moulded product the basic form was intended to be enhanced by surface finishes more normally associated with hand crafted products.

The basic outer form was first created in the modelling system by taking a sphere and distorting it to produce the required flat, curved form. Subtracting a suitable scaled cylinder created the central cutout for the 'answer' button. The speaker/microphone notches were to be modelled by haptic feedback techniques. The designer was attempting to create the effect one would achieve by taking a scoop of soft ice cream, leaving a cavity with smooth sides. When the operator performed a haptic scooping operation, the surfaces were excessively rippled, as there was no tight control of the motion. This was the first disappointment in the use of the modelling system, which will be discussed later in this paper. The notches were again produced using non-haptic techniques of subtracting forms generated by extruding curves.

At this point it was recognised that the form produced had been developed in the haptic system but had not used any of the benefits of the haptic feedback. The system was being used much like a traditional CAD system. As a parallel test the communication device was modelled using a surface modeller familiar to the operator in less than ½ an hour and was imported into the Freeform software via an STL file (a standard file transfer format which transfers the shape information via triangular facets). The imported surface can be seen in Figure 4. This raises questions about the suitability of haptic techniques for developing certain forms. Again this will be discussed later.
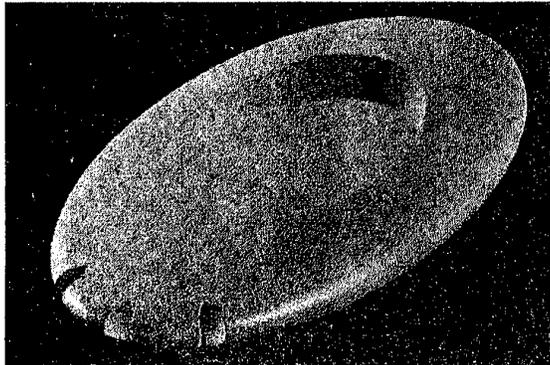
Figure 4. Imported CAID surface.

The surface finish to be applied to the model was not rigorously defined at the concept generation stage as it was intended to explore the possibilities of forming the virtual material using techniques closely related to craft-based interaction. The first finish to be explored was a hammered finish normally applied to soft metals such as copper. The desired result was achieved by using a rounded tool to repeatedly strike the surface. It was important for the operator to understand the parameters that could be varied to affect the material properties of the model. Using a soft material produced very smooth rounded and rather indistinct indentations whereas harder material settings produced shapes that resembled more closely cuts into the surface. The progression of the hammering can be seen in Figure 5.
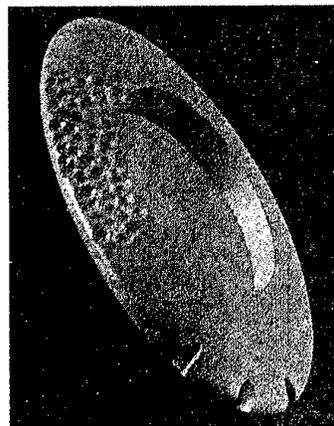
Figure 5. Haptic modelling of hammered effect.

The haptic system was easily able to take advantage of other digital design techniques seen in other CAD systems. For example the hammer finish was only applied to ¼ of the model and mirroring reproduced the other quarters. Careful attention was paid to over striking the centre lines to ensure that they did not exhibit any mirror effects.

When completely hammered, the surface looked quite effective but the edges of the hammer marks were considered too sharp so the whole model was smoothed-out to soften corners. The final finish can be seen in Figure 6.
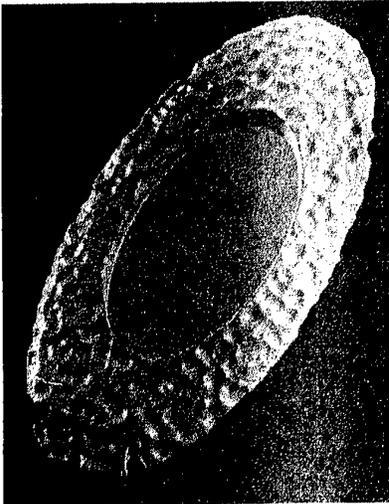
Figure 6. Final hammered effect.

The final design features, the 'answer' button and three function buttons, were once again added using traditional CAD design techniques based on standard primitive shapes and extruded/revolved curves. The completed model was saved as an STL file and exported to a CAID system for rendering. The rendered product can be seen in Figure 7, and as a photomontage with user in Figure 8.
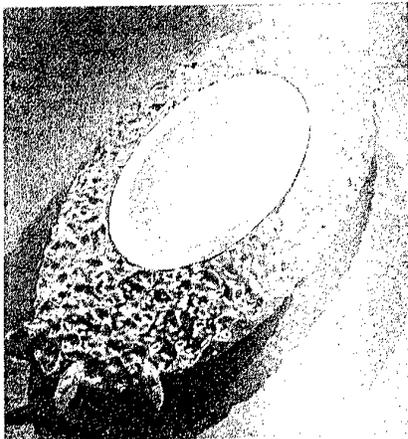
Figure 7. Rendered hammer finish.
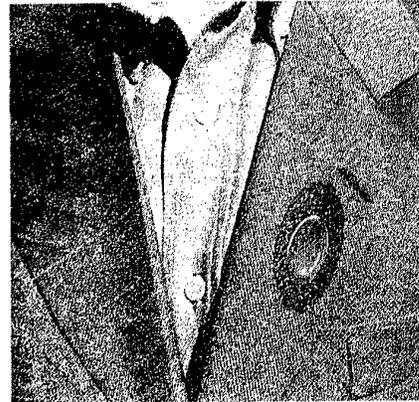
Figure 8. Photomontage of hammer finish product with user.

4. Specification

The specification of product form to design engineers and manufacturers who are conversant with digital design techniques is relatively straightforward, requiring the transmission of digital geometry in a mutually compatible format e.g. IGES or STL.

The proposition for the hammered product was for a low-volume, jewellery-like product. It would therefore be straightforward to output the surface geometry of the body to an STL file and utilise this information to produce the components in wax using a rapid prototyping system such as Sanders. Investment casting could then be used to manufacture the components as a direct copy of the model.

5. Conclusions

This design project has raised a number of issues, both positive and negative, relating to haptic modelling.

The ease of use of the software makes it very straightforward for even inexperienced computer operators to start modelling very quickly. The software does however require a high level of hand-eye coordination for the tools to be used effectively. This should not be considered as a problem since this skill is expected of designers as part of their repertoire and so they should feel quite at home with the input methods used. It does tend to alienate other groups from using the software. For example, experience with engineers attempting to use the system has shown that in general they lack the skill to operate it effectively although they appreciate the value of tactile feedback.

The apparent ease of use should not disguise the fact there is a technical element to the software that need to be understood. This is especially apparent when dealing

with aspects such as the variable hardness and 'density' of the material. Even in the relatively small modelling exercise undertaken for this project it was necessary to vary material properties to achieve the desired results. Although this is relatively easy to achieve in terms of the user interface the user needs to understand the knock on effects such modifications have on the model. For example reducing the 'density' of the model enables finer detail to be produced but the size of the storage space for the model increases dramatically (100 Mb files are common) and even using relatively powerful computers performance reduces dramatically. This can be very frustrating to a designer who does not want to be concerned with such 'technical' details.

At the beginning of the project, the expectations of the haptic modelling system were high. Assumptions were made that the modelling techniques would be very close to those of conventional foam and clay concept modelling. Unfortunately, the functionality of the software and hardware made it difficult to obtain the surface quality needed for both rendering and production. This was highlighted by the attempts made to produce a clean scoop when modelling the speaker/microphone detail. These shapes were easily reproduced by other techniques but these duplicated more traditional methods of modelling found in traditional CAD systems and so did not benefit from haptic feedback. The fact that the system can model in this manner is advantageous but it is disappointing that haptic modelling could not reproduce the same effects. It is almost an admission that haptic techniques are not yet able to model large smooth surfaces effectively.

Another related area that concerned many operators of the system was the reproduction of sharp edges. This is highlighted in Figure 8, which shows feathering on the edges of the button cutouts.

Figure 8. Edge feathering.

The method of representing the model in the Freeform software means that edges between surfaces can never be perfectly sharp. They are always feathered to some extent. This feathering can be reduced by increasing the accuracy of the model (with the consequences already

mentioned) but will always be present. This always concerns operators as they zoom in to the model closely. In practice the feathering is not a problem as when viewed at normal scale the feathering is not visible and has never shown up in derived rapid prototype models.

The responsiveness of the haptic modelling system to the generation of the hammered effect was impressive. The production of the hammered effect was very closely associated with traditional hands-on modelling, whereby the designer controlled the manipulation of material whilst responding to tactile feedback.

For industrial design practitioners, the findings of the case study indicate that haptic modelling as currently implemented in the Freeform software has its limitations. Whilst the stylistic trends within industrial design require smooth, crisp surfaces, the authors feel that haptic modelling has significant limitations. However, the principle of haptic feedback being used in the model process is unquestionable and when the product shapes being designed are appropriate then the Freeform software and haptic modelling are the only realistic modelling method. The only alternative method for reproducing the hammered finish would be to use greyscale pictures to generate a bump mapped surface but the results are unlikely to be as effective. One can only assume that future development in the hardware and software for haptic modelling will address the shortcomings identified in the case study. Further work will then be required to re-evaluate such capabilities.

In terms of the generation of random, almost craft effects, haptic modelling has much to offer. The authors feel that such a system may be of interest to practitioners in may areas of design such as jewellery. This would be particularly relevant if the virtual material could emulate the characteristics of precious metals that may be too expensive to use. Indeed it may be possible to use haptic modelling to practice on a virtual material before working on the real (and expensive) precious metal.

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New Metaphors for Interactive 3D Volume Segmentation

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Abstract

This paper describes on-going research at the Swiss Federal Institute of Technology to develop new paradigms for interactive segmentation of medical 3D volume data. In our segmentation system we are using a haptic device as a 3D mouse with force-feedback. The paper introduces the basic components of our framework and the ideas behind our multi-modal approach. On the one hand we are trying to increase the sense of immersion of the user by allowing him to interact in a natural way with the presented data, on the other hand we are using force-feedback as an additional channel to mediate information. The segmentation of linear structures in the human body serves as a case study for our system. We successfully used our approach to extract the skeleton of a radiological colon data set, which then served as the basis for a full segmentation of the object of interest.

1 Introduction

Over the last decades, computer imaging techniques have become an important tool in the practice of modern medicine. In medical imaging, large voxel data sets, containing information about the internal anatomy and/or physiology of a living patient, are obtained from a variety of tomographic imaging modalities, such as Computer Tomography (CT) or Magnetic Resonance Imaging (MRI). Before any high-level reasoning, for instance radiation treatment planning, can be applied to this data, it has to be broken down into its major structural components. The process in which the data sets are subdivided into their constituent parts is called segmentation. The algorithms used in this step can be classified with regard to their degree of automation:

- Manual segmentation:

  This approach is highly insensitive to noise, tolerant of incomplete information and in many cases sufficiently precise. Nevertheless, it is very time consuming and has to be done in a tedious pixel-by-pixel manner. Furthermore, it lacks reproducibility.

- Automatic segmentation:

  This term refers to computer algorithms which can segment an image without manual interaction. These methods can only be applied successfully within exactly defined bounds. This is mainly due to the difficulty of formalizing the a priori knowledge of the examined anatomical structures as well as incorporating this knowledge into the segmentation process. Unfortunately, none of the so far published algorithms is robust enough to provide general purpose, fully automatic data segmentation.

- Semi-automatic segmentation:

  In between the former two approaches lie semi-automated algorithms, which try to merge the advantages of both worlds. Rather than attempting to duplicate the complex and poorly understood human capability to recognize objects, they try to provide an interactive environment in which users control the segmentation process and exploit their expert knowledge.

The developed methods can be further classified according to the underlying interaction paradigms in either two or three dimensions. In a two-dimensional approach the segmentation is done in a slice-by-slice manner, making a subsequent reconstruction step necessary, in which the previously segmented contours are combined into a three-dimensional structure.

More seldom are systems that exploit the possibilities of interactive 3D segmentation [18, 17, 8, 19, 11].

This is often justified by the problems that arise due to adding another dimension to the user interaction:

- Editing, controlling and interacting in three dimensions often overwhelms the perceptual powers of a human operator.

- Todays desktop metaphors are based on two-dimensional interaction and can not easily be extended to three dimensions.

- The visual channel of the human sensory system is not designed for the perception of volumetric data.

These major drawbacks are valid in terms of interactive systems that are based on two-dimensional Window-Mouse-Icon-Pointer (WIMP) interfaces that solely rely on the visual sense of the human operator.

In the presented project these limitations are alleviated by enhancing the segmentation process with additional sensory feedback. Properly applied, the use of more than one sense to investigate complex data sets promises to improve the user's understanding of the data and their ability to interact with them [13, 9].

Possible approaches for multi-modal interaction stemming from virtual reality applications are the addition of auditory as well as haptic feedback. In this work we focus on providing additional perceptual information to the medical expert by using force-feedback technology.

2 Related Work

Though the need for understanding the influence of human-computer interaction on semi-automatic segmentation is recognized, only very few research has been done in this direction. The only work we know of investigates this problem for 2D segmentation [16].

Other related research mainly focuses on separate aspects. New 3D interaction paradigms, that can assist the end user in navigating in volume data sets have been evaluated in [8, 19, 11], but this work only focuses on visual interaction with the data. Nevertheless, the results show, that novel ways of interaction can enhance the navigation in the data. The application of force-feedback to improve the understanding of volume data sets in a medical setting has been done in the field of surgical planning [6] and navigation [4]. In both projects only the navigation is enhanced with force-feedback. The necessary segmentation of the medical volumes is still done with traditional methods.

The usage of haptic feedback to augment human performance in graphical user interfaces is investigated from a more general point of view in human-computer interaction research projects. In [1] it is shown that a mouse with force-feedback can aid a user in targeting tasks. The usage of a haptic device to lessen the information overload of graphical displays is studied in [15].

The addition of force-feedback to facilitate the understanding of multi-dimensional data was used in [5]. Complex relationships between different currencies are rendered visually as well as haptically.

Generally, using multi-modal interaction in volume visualization is not a widely studied subject and only a few research groups have begun to investigate the possibilities of such an approach. A good introduction to using haptics for volume visualization is given

in [2]. Also in [14] the benefits of haptic rendering of volume data have been recognized. Mainly, research is carried out in the field of visualization of geoscientific data [7, 3, 12, 20].

3   Segmentation Tool

To understand the effects of adding force-feedback to a segmentation program we followed two different approaches. Firstly, we investigated how exploration of 3D data could be improved by haptic rendering. Although the main goal of our research is to improve segmentation, these initial studies gave us an insight into the way humans interact with a multi-modal interface. Secondly, we examined a haptically assisted segmentation process. The reconstruction of tubular objects in the human body served as a case study for our system. The segmentation of these structures is of great medical interest and has several areas of application, for instance the reconstruction of the nervous and the vascular system or the bronchial tree. While haptic cues ease the three-dimensional interaction and orientation in the tubular structures, we present an optimal 2D cross-section for visually guided contour extraction.

3.1   Haptic Data Exploration

To give a user a more thorough understanding of the volume he is interacting with, we mapped the gray values of the medical data to different haptic representations. We have to mention, that instead of giving a user a "realistic" feel of body tissue we only tried to mediate information about 3D cursor localization and tissue densities. To this end we combined haptic volume rendering to encode tissue borders with viscosity or vibration effects to display density values. Due to the limited continuously exertable force of the haptic device and the JNDs of the haptic effects, we chose to discriminate only between three types of densities, i.e. bone, soft tissue and air.

A force field derived from image gradients gives us information about the border location between the tissue types by resisting the motion from an area with small density to an area with a larger one. After

thresholding, we approximated the gradient vector field of the resulting data set by central differences. Moreover, to ensure the stability of the computed forces, we smoothed the obtained gradient map with a 5x5x5 binomial filter. This force field was precomputed before the actual interaction, to ensure a fast enough haptic update. Because the gradient vectors are located at discrete voxel positions, we have to do a tri-linear interpolation during the interaction to obtain the continuous gradient force map $\vec{F}_{grad}$ needed for stable haptic interaction.

Apart from the gradient map we encoded the tissue density itself, using vibration and viscosity. The vibration effect is created by sending a sinusoidal force with frequency and amplitude depending on gray values to the device. One interesting observation regarding this approach are the unintended audio signals that were generated by the vibrating haptic device, which gave a user additional information about the densities. The viscosity was computed according to Stokes Law, which holds at low velocities in fields free from turbulence:

$$\vec{F}_{visc} = 6\pi r \vec{V} \eta,$$

where r is the radius of a sphere moving with velocity $\vec{V}$ through a medium with viscosity η. The viscosity parameter was again adjusted according to densities.

Linearly combining the gradient field with the viscosity rendering

$$\vec{F} = \alpha \vec{F}_{grad} + \beta \vec{F}_{visc},$$

allowed a user to do a haptically enhanced data exploration. Additionally to the force display, the medical volume is also volume rendered in stereo and sagittal, transversal and frontal slices of the data set are shown. Furthermore, the 3D mouse can be used to place a free oblique slice in the volume. During some limited experiments with this setup users reported, that tasks like tracing the tubular structure of the colon, were much easier accomplished by relying only on the haptics cues. This was mainly due to the complex task of integrating the 2D slices of the volume into a 3D representation, which required a lot of visual attention distracting from the actual task.

The described framework helped us to understand more about the psychophysics of haptic interaction in order to design a system using a force-feedback device in a segmentation process.

3.2 Multi-modal Segmentation

The initial step of our multi-modal approach is the haptically assisted extraction of the centerline of a tubular structure. We create forces that guide a user on a path close to this centerline. In the optimal case of good data quality, the user "falls through" the data set guided along the 3D ridge created by the force-feedback. While moving along the path, the user sets control points which are used to approximate the centerline with a spline.

The segmentation of tubular structures can be optimally facilitated, if all cross-sections of the object are orthogonal to the centerline. Therefore, we use the interactively generated spline to determine the appropriate orientation of slice planes through the data volume. In a subsequent step an active contour model [10] is used to extract the 2D cross-section of our structure of interest from these slices. The re-orientation of the cutting plane allows us to make a rough assumption about the shape of the cross-section, which should be approximately circular. Furthermore, as we always update the slice orientation, we can use the segmentation of the previous step as a fairly good initialization for the next cross-section. This can be done, because the deviation between subsequent cross-sections in a tubular structure is usually small.

To create the force field that is guiding the user, we adopt an approach similar to the one used by Bartz for enhanced navigation [4]. Instead of using the gray values directly, we first compute an Euclidean distance map of the data set S that resulted from the thresholding step: For each $(x, y, z) \in S$, the map value

$$DM(x,y,z) = \min_{(x_i,y_i,z_i)\in S} d[(x,y,z),(x_i,y_i,z_i)],$$

is determined, where d denotes the Euclidean distance from a voxel that is part of the tubular structure to a voxel of the surrounding tissue. In the next step the 3D distance map is negated and then processed similar to the gradient rendering approach. Additionally, to ensure stability, we apply a low pass filter to the computed forces over time.

In the case of sufficient data quality this approach works very well, nevertheless, more interesting is the case of poor image quality, because conventional segmentation algorithms do not suffice in this situation. Here a user can be assisted by the forces to bridge a gap in the linear structure. We have to mention that a decrease of data quality comes along with an increased user interaction time and effort. We intend to overcome this shortcoming with more advanced gap closing mechanisms.

4 System Overview

Our setup (Figure 1) consists of two main components: an SGI Octane and a haptic device. The Octane is equipped with two R10000 processors running at 195 MHz and 512 MB memory as well as an MXI graphics board with 4 MB texture memory, allowing us to render 128x128x128 volume data sets in real-time.

We are using a distributed architecture for our current prototype to ensure the necessary update rates for the visual and haptic display. The separated processes exchange data via a shared memory with semaphore functionality.

Only within the last few years suitable force-feedback devices became accessible for the development of multi-modal applications using touch interaction. In our project we are using SensAble Technologies' PHANToM as a sophisticated 3D force-feedback mouse. The lack of rotational forces is not a problem for our application, as we only need point force creation for our current approach. Nevertheless, in order to haptically encode the orientation of the cross-sections we are going to change to a haptic device, which also allows the creation of rotational feedback.
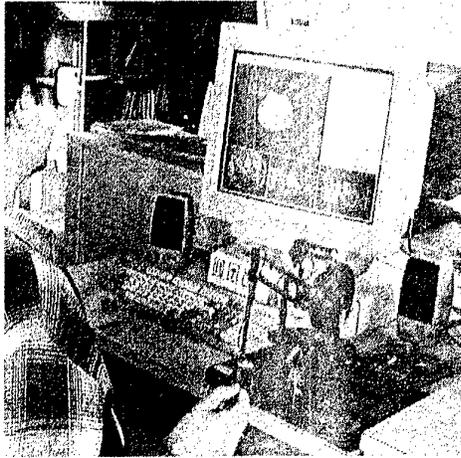
Figure 1: System setup

5 First Results and Future work

In this paper we presented a new paradigm for interactive segmentation which allows the handling of medical data in a natural way. Additionally, we described how multi-modal interaction can enhance the process of interactive segmentation. We used this approach to extract the skeleton of a linear structure which then served as the basis for a full segmentation of the whole object of interest. In order to reduce the interaction effort we have to evaluate more sophisticated algorithms for gap closing.

Moreover, we will study if providing force-feedback to both hands can improve the interaction. Another aspect in this direction is the usage of different haptic devices, for instance a glove with force-feedback could be used for the non-dominant hand to hold and manipulate the data. Additionally, we are going to investigate the possibility of including other perceptual cues. The most obvious addition would be the auditory sense.

Acknowledgement

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The Visualisation and Making of Sculpture and its Potential Implications for Computer Interfaces and Three-dimensional Modelling.

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Abstract

The deep tacit knowledge of material, tool and creative process, developed over many years of professional practice as a sculptor or applied artist is examined and outlines of an analysis of 'sensory feedback loops' present in a specific making process are described. The significance and role of the sense of touch within the development of 'making' skill is discussed in relation to 'embodiment' (or transparency) in processes involving both real and virtual, tools and materials. Conclusions are related to the human-computer interface and specifically concern the role of haptic and other sensory feedback in the visualisation and creation of three-dimensional virtual objects. A progressive staged model of this is described in relation to the Artist/Craftsperson('maker').

1. Introduction and background

The authors are involved in detailed research surrounding the potential role of haptic feedback in creative making processes. The background and approach of this research arises from the problem of reconciling the needs and aspirations of artists whose work is grounded in the making of material, i.e. non-virtual three-dimensional artworks, with the potential use of computer visualisation systems.

2. Methodology and analysis

Reflection on the author's glass sculptural work and the unique techniques and processes that have been developed over 25 years of professional practice, together with an examination of the visualisation models employed by sculptors, provided the basis of consideration of the qualitative analysis. This paper describes research which centres on an experimental view of the author's and others profound 'making' experience. Issues of intentionality and skill level within each task would also seem to be significant factors.

For the purpose of the analysis, the task can be broken down into three elements, Human, Tool, and Material. The process, chosen by the maker, and influenced by the material and available tools may be said to act as a mediator in the task; all sensory feedback is evaluated within its domain. In this basic scenario, that of unskilled beginner engaged in a non-specific process, both tool and material are 'other', neither are yet embodied. Perception is engaged by all the senses and is directed at both tool and material via process. Thus the task becomes subordinated to conscious and sub-conscious filtering and sensory feedback evaluation. In the case of a non-specific task, any or all of the senses, touch, hearing, vision, taste and smell may be engaged, however the processes themselves define which senses are engaged dependent on the particular task.

In figure 1, which refers specifically to a technique of carving glass, the senses of smell and taste are normally irrelevant. However, touch, sound and vision all convey useful information. (As a novice with any process, all available sensory feedback is monitored). The peculiar characteristics of the process however, place vision in a subordinate role to the other two senses, since due to the refraction and reflection of the water used as cutting lubricant, and the profusion of glass powder produced as a result of the process, little can be seen.

Prior experience of similar processes, materials or tools appears to speed up the development of embodiment and to make the development of skill specifics more rapid. Figure 2, examines the case of a later stage in skill development where a reasonable change in the constituent elements of the feedback loops.

This is an interim development towards full mastery. The tool has achieved embodiment and has become a natural extension of self. The amount of time and
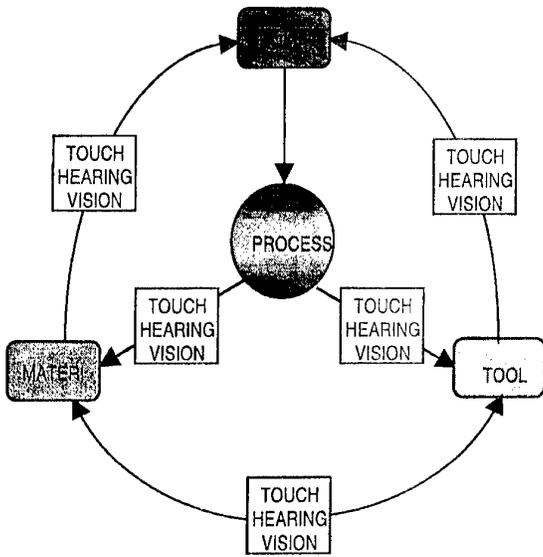
Figure 1. Sensory feedback pathways in glass carving by rotating diamond tool. (Novice).

Figure 2. Sensory feedback pathways in glass carving by rotating diamond tool. (Moderate skill).

habituation necessary to achieve this state is variable. Perception in this case appears to be solely directed towards the material. It is significant that the sense of touch has by now become dominant, indeed it is difficult to imagine an embodiment that could take place at all, in the context of making, without a highly developed form of this sense.

As basic skill develops to 'mastery', a state that takes many years to develop, a particularly interesting

Figure 3. Sensory feedback pathways in glass carving by rotating diamond tool. (Mastery).

phenomenon has been observed. Not only does the tool become embodied as described by Heidegger [1], but also embodiment grows to include the material being worked.

In figure 3, both tool and material have achieved embodiment. The amount of time and habituation necessary to achieve such a state of *'material embodiment'* is considerably longer than the previous case that embodied only the tool. It was seen that touch was integral in all parts of the maker's sensory loops, and is the only means of response to any information, no matter by what sensory input it arrives.

Full embodiment reduces response time to a level of 'transparency'. England [2] defines this as, " ...*a well learned ... motor behaviour which can be performed without conscious attention.*" (p.159.) He further states,

"*Movements faster than the visual processing time (e.g. 190 ms) may therefore be under kinaesthetic control.*" (p.161.) and cites the studies of Carlton, [3] and Glencross, [4] which seem to indicate that kinaesthetic response times may be swifter than visual triggering due to the differing physiological mechanisms involved.

The authors believe that this analysis of skill development indicates that if computer technology is to be applied to processes resulting in material objects,(e.g. sculpture or industrial products), haptic feedback is vital for the development of full embodiment, and that full embodiment is necessary to achieve maximal control and skill 'mastery'.

Performing a similar analysis of the current standard interface devices shows a picture where true embodiment is simply not possible, since tool and material both exist in computer space. This situation is somewhat analogous

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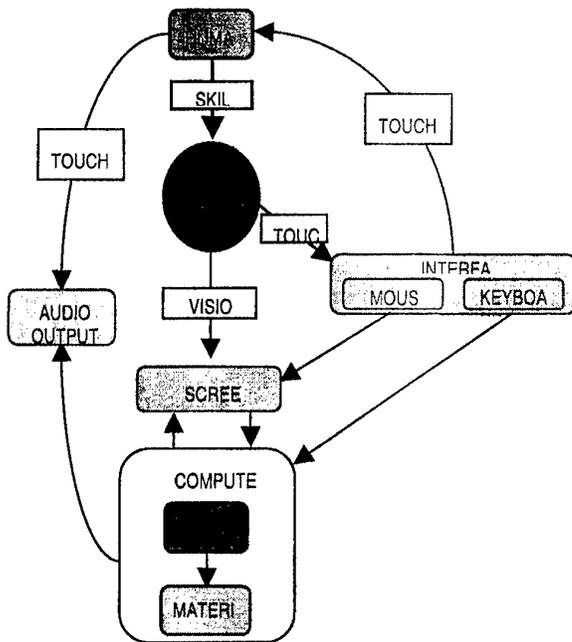
Figure 4. Sensory feedback pathways in **current standard human-computer** interface.

to attempting to re-arrange the furniture in one's house by standing in the garden poking a stick through the window.

In figure 4, touch feedback is restricted merely to the physical interface device, mouse or keyboard. No direct contact is available between the user and that which he / she seeks to manipulate. If the material being manipulated is solely abstract information, this might be acceptable, however computers are increasingly being expected to manipulate informational representations of objects, real or imagined, thus providing an alternative interim emphasis. New metaphors must be devised to elicit the ways we personally model computer technology if we are to develop new and more integrated ways of using their potential. Coyne, [5] identifies three basic metaphors implicated at the outset of computer development. The computer as "calculating device", the computer as a "drawing tool" and the computer as "an intelligence". He further identifies a variation on the drawing metaphor as: *"... to see the computer as a modelling tool. Drawing and calculation conspire to construct a powerful metaphor of the design model. A drawing is a two-dimensional model. Cartesian geometry is used to specify values for points, lines, and planes, which are in turn models, or perhaps metaphors of designed objects."*

There is however, a considerable experiential gulf between **drawing** a three dimensional model as Coyne's metaphor suggests and actually **making** one, putting ones hands either directly or via a hand held tool onto a piece

of material, and shaping it as one wills. The progressive model outlined in figures 1, 2 and 3, describes the evolutionary nature of material 'knowing'. This experience is somewhat reproducible by computer technology in the domain of two dimensional, drawing or photo-manipulative software. What the computer is currently unable to recreate is an authentic three-dimensional process.

3. Conclusions

Conclusions are based around the implicit hypothesis of positive tacit action in making objects. The novel process of analysis surrounding a personal practice is considered to be a rich source of qualitative information. This has now been extended to include other practitioners across a range of disciplines so that comparisons may be made.

- In process-based 'making' activities with tool and material, embodiment (transparency) develops with skill, first the tool becoming embodied, and much later the material also becoming embodied.

- This process of embodiment is fundamental in skill development and develops directly from the sense of touch. It is not primarily a cognitively learned process.

- Current computer interface technologies do not address this embodiment of tool and material adequately, rather there is substituted an embodiment of the technology itself.

- The perceptual experience of a physical three-dimensional object is markedly different to the perception of an iconic representation of that object and consequently the manipulation of each requires and develops substantially different skills.

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Haptical Rendering of Triangle Meshes with Fixed Direction Hulls

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Abstract

We present the system for the force-feedback visualization, which uses hard realtime operating system. Software architecture uses two cooperating tasks. The first one autonomosly resolves forces for haptic contact within the small set of triangles and it maintains stable high update rate in the range of several kHz. The second task runs in order of magnitude slower. It selects triangle sets contained in limited subspace from the virtual scene with the help of Fixed Direction Hulls.

Keyword: PHANToM, haptics, RT-Linux, virtual environment, fixed direction hull, force feedback

1 Introduction

To get the sense of touch we add haptical rendering to the graphical visualization. For haptical visualization we use force–feedback device PHANToM. For the best experience graphical and haptical systems have to run fast and fluently. Processing complicated analytic surfaces like NURBS[1] is still highly computation intensive task. As we use OpenGL for graphical visualization it is natural to use uniform representation based on triangle sets and meshes. Hence we triangulate all complex models including analytic surfaces before we visualize them.

In this article we present our approach for haptical visualization of large triangle sets on PHANToM device using hard realtime operating system RT–Linux[1].

With this system we try to avoid the computation of complicated surfaces in the realtime as they could be precomputed into triangle meshes without the notable loss of quality.

We have decided when we have already triangulated objects for 3D rendering, it would be good to use the similar representation (preferably the same one) also

for haptical rendering. Simple geometrical objects like spheres, toroids and various other shapes, which could be described by algebraic equations, are more precisely haptically rendered using the analytic approach. However in the real life scenes it is hard to find such objects and we usually work with huge triangle meshes from 3D modelling tools. Moreover these triangle sets commonly contain problematic areas and its not even specified what it means to be inside or outside of an object.

Some researchers have already presented their algorithms for haptical rendering of triangles, but these are usually not prepared to work reliable with update frequencies in the range of a few kHz.

In this article we also mention some preprocessing steps we use to minimalize problems with more or less incorrect triangle models. These are usually being generated by various 3D modelling tools.

2 Previous Work

To achieve hard surface with haptical rendering we need high update rates (at least 1kHz) and fast methods for evaluation of reacting forces. Contact points necessary to compute forces are usually found with the help of collision detection systems. That means we have to use very efficient and fast algorithms here.

A good overview of traditionally used methods including oriented bounded boxes (OBB) and axis aligned bounding boxes (AABB) and bounding volume hierarchies (BVH) can be found in [2]. For the haptical rendering few special collision detection systems have been developed: H–Collide, I–Collide see: [3]. These systems are usually based on OBB and they focus on detection of one surface contact point.

For the system with two levels of computation hierarchy similar approach could be found in ArmLib[4]. This project uses an equation of a single plane which is maintained by the fast internal loop while the second task updates this plane with much slower rate.

3 Method Overview

Our goal was to develop the method which could be used generally to haptically visualize the same data sets as are used for graphical visualization.

The algorithm we present here, is divided into two parts running in two different environments. The first part is running in the normal user space mode and its purpose is to select a small subset of triangles from the large virtual scene. The second part is running in the realtime environment and has limited capabilities. The computation time is bounded and also the memory access is limited in this environment. So the algorithm has to be simple and fast. This task works with some small neighbourhood for a given point and surrounding triangles proportionally influence the resulting force.

Using two separate algorithms where one is used to pick small surrounding virtual environment from the large one and the second task is resolving haptic feedback within this smaller subset, might be viewed as a special case of 3D traversal exploiting frame-to-frame coherence. For the hierarchical representation of the scene we use BVH of FDH which will be briefly described later. We use two levels of BVHs. The first level contains all objects and it is used to detect collision between them. The second one is used to select few triangles from the colliding object.

4 Algorithm

In this section we describe how the system processes triangle sets. We present new algorithm used for calculation of reacting forces which also does smooth shading of normal vectors.

4.1 Preprocessing

For OpenGL rendering number of various optimization have been developed. With todays graphics cards we do not have to care too much if we will draw several hundred triangles more or less. However, with the haptic rendering the situation is different. We need to eliminate as much triangles as we can before processing them in the force loop.

Usually it is better when the scene consists of large triangles. But at certain size large triangles cause the problem as they need too large bounding volumes. To create more compact bounding volumes we have to split larger triangles into the smaller ones. Small triangles can be more easily sorted in a balanced BVH.

On the other hand too small triangles which might appear in some detailed models have to be reduced otherwise the selected environment would be too small

and user would shortly escape from 'precached' triangle set. For this purpose right now we preprocess triangle sets with surface simplification algorithm[5].

Preprocessing algorithm consists of following steps:

- create the list of triangles and find common edges
- with respect to sharp edges fix or fill missing vertex normals
- check if adjanced triangles have the same normal vectors in common vertices; in the case normals differ add two fake triangles (fig.1) with only two different points which will assure continuous change of the normal vector.
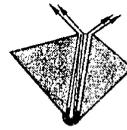
Figure 1: Adding two fake empty triangles.

- split large triangles
- final validation of normal vectors

4.2 Computation
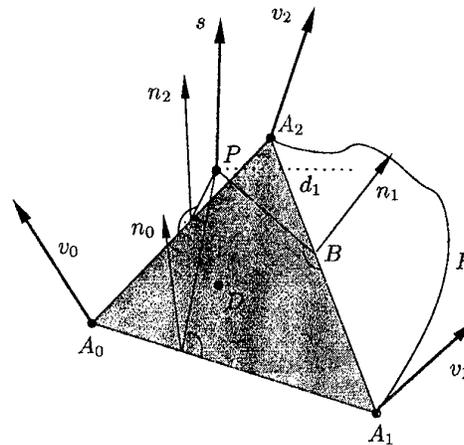
Figure 2: Force calculation.

Algorithm 1. for the small triangle set works as follows: For each triangle (fig.2) we check first if it has the proper orientation and distance with respect to the current position P of PHANToM. Then we continue with the following step. For each edge of the triangle

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Algorithm 1 Force calculation

$force = (0,0,0)$
$maxforce = 0$
for all $T \in object$ **do**
  $d \Leftarrow distance(P,T)$
  if $d > 0$ **and** $d < RADIUS$ **then**
    for $i = 0$ **to** 3 **do**
      $B \Leftarrow nearestpoint(edge(T,i),P)$
      $n_i \Leftarrow interpolation(T,i,B)$
      $R \Leftarrow plane(B,n_i,edge(T,i))$
      $d_i \Leftarrow distance(P,R)$
    end for
    if $d_0 \geq 0$ **and** $d_1 \geq 0$ **and** $d_2 \geq 0$ **then**
      $n_0 \Leftarrow \frac{n_0}{d_0}, n_1 \Leftarrow \frac{n_1}{d_1}, n_2 \Leftarrow \frac{n_2}{d_2}$
      $n \Leftarrow n_0 + n_1 + n_2$
      $D \Leftarrow intersection(n,T)$
      if $|\overrightarrow{DP}| < RADIUS$ **then**
        $s \Leftarrow f(\overrightarrow{DP})$
        $force \Leftarrow force + s$
        $maxforce \Leftarrow max(maxforce,|s|)$
      end if
    end if
  end if
end for
$force = \frac{force}{|force|} * maxforce$

---

we find the closest point and by linear interpolation we compute the normal vector at this point. Normal vector and edge define plane R. If the point P is bellow this plane we stop processing this triangle. Now we have three normals and distances from planes. Each normal is divided by its distance from the plane R to get proportional force. Summing all three of them we get the total force which is pushing the user away from this triangle. Now we could also compute virtual contact point (VCP) D as the intersection of the line, which goes through the point P in direction of the resulting normal, with the triangle's plane.
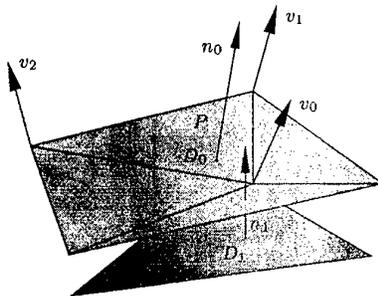
Figure 3: Overlapping triangles.

We resolve all VCPs and we remove those which are actually hidden bellow some other triangles (fig.3). This could be easily achieved just by checking if the line between VCP and real position P is not intersecting another triangle with VCP. Finally we combine all forces together. Resulting force is actually reasonably good approximation which is a compromise between the speed of calculation and the precision of the resulting force.

Now we have smooth normal vectors without any bouncing change in the direction, but we still do not know whether user actually penetrates the surface. To solve this problem we use the following procedure:
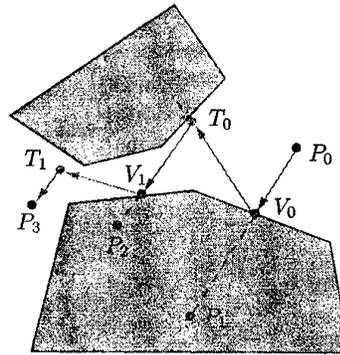
Figure 4: Penetration of the surface.

If during our calculation there is no intersection on path between two consecutive points e.g. P_0 and P_1 (fig.4) with any of processed triangles then the user is not inside the object.

If such point is found then we use the VCP (V_0) for the force calculation. In the following iteration we add difference vector $(\overrightarrow{P_1 P_2})$ to V_0 and we try to find new intersection points. We take into account only those triangles where we detect the movement from inside to outside half space. In the case of more than one intersection we pick the closest point (T_0) and use it for calculation of the new VCP (V_1). If there is no such point we use current VCP.

5 Fixed Direction Hulls

To select a small amount of triangles from a subspace we need to use very fast method. For static scenes we have achieved good results with Fixed Direction Hulls also known as k-Dops (Discrete Oriented Polytops) see fig.5. Details can be found in [6],[7].

FDHs have almost the same processing speed as AABBs, but they bound objects more tightly, just like OBBs. An advantage of FDH is lower query time.
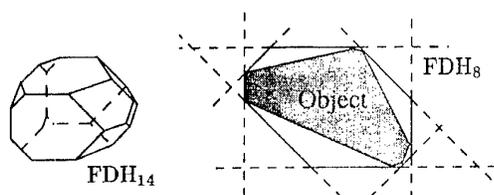
Figure 5: FDH_{14} and 2-D example (FDH_8).

On the other hand their disadvantage is that, there is no simple solution for rebuilding FDH after rotational transformations. Hence we prefer this method for static scenes where only few objects move (user's hand, in our case). We use BVHs which are composed from FDH_{14}. One FDH_{14} is internally represented by 14 floating point numbers which define 14 cutting planes with given normals. The first 6 planes are the same as in AABB. Most of the computations when testing collisions in rarely populated scenes, have the same averrige complexity as when using AABB.

6 Implementation Details

For implementation of this system we developed driver for hard real time OS RT–Linux. We are able to test wide spectrum of update rates. Hence in this area we are exceeding the possibilities of the original software supplied with PHANToM device. While the standard implementation for Window NT operates on 1kHz update rate we are able to use rates up to 10kHz[2] with the possibility to change this speed in runtime.

For our experiments we use dual processor system with two 470MHz Celerons running RT-Linux 2.4.5 and Matrox G400 3D acceleration graphics card.

With our demonstration application we use polygonal models consisting from around 20000[3] triangles. We achieve FDH query time within the range of 10ms and less (typically around 3ms) while the hard real-time loops runs with 64 selected triangles and the system still show around 50% idle time with 3kHz update rate.

7 Conclusions and Future Work

Currently we can process only static scenes, but we prepare implementation of dynamic algorithm which will allow us to update triangle sets and to do a smooth transition between two sets.

[2]according to our experiments [10] this appears to be rather a hardware limit for this device with PCI card.

[3]so they could be displayed with acceptable frame rate on the graphics card

Availability

The latest informations about our software, which is available under GPL, can be found on our web page: http://decibel.fi.muni.cz/phantom/

Acknowledgements

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Haptic Rendering of Molecular Conformations

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Abstract—Current computational simulation are capable of producing enromous amounts of data. Complete understanding of their features presents a challenge even if very sophisticated visualization techniques are deployed. Computational analysis of conformational behaviour of biologically active compounds represents such simulation. We investigate methods how haptic rendering may contribute to better and faster understanding of the simulation results. This paper presents current progress in our research.

I. MOLECULAR FLEXIBILITY AND CONFORMATIONAL BEHAVIOUR

Many molecules exhibit an important chemical property — flexibility. Biological activity of large molecules is directly related to their flexibility. The flexibility can be described in terms of *conformational behaviour* of the molecule. Undergoing the behaviour, the molecule changes its shape (*configuration*) only, no chemical bonds are either created or broken, as well as the absolute configuration on atoms (or other chiral centres) does not change. Roughly speaking, internal potential energy of the molecule is a function of the configuration, therefore, in general, not all the configurations are favoured equally. By *conformations* we mean local potential energy minima, i.e. the configurations that are more stable than the others. Then the conformational behaviour is the process of traversing among conformations via transition states.

Various computational methods of discovering conformations of a molecule and describing its conformational behaviour were proposed. It is beyond the scope and purpose of this article to provide even an overview. In our application we use results of the CICADA family of programs performing heuristic search of conformational space [1]. They produce a graph of interconnected conformations and *transition states*, i.e. saddle points in terms of potential energy. Two edges of the graph that share a common transition state represent a traversal path of minimal energy barrier between a pair of conformations.

II. HAPTIC MODEL

In this section we focus on the description of the model being deployed in our application and its mathematical aspects. Various implementation issues like program structure, performing exhaustive computation off-line etc. are discussed in detail in Sect. III.

A. Virtual Energy and Haptic Steering

We build the model on the principle of *haptic steering*, i.e. the user is provided with a virtual tool bound to the haptic device. With the tool she is able to interact with the virtual model. The interaction enforces changes in the virtual world that incorporate changes of the potential energy of the model. According to well-known physical laws the work, i.e. the energy produced or consumed by a system, can be computed by integrating force interaction along a path. Hence, the force feedback can be computed as a spatial gradient of the energy.

The model, despite depicting a micro-world scene, should behave intuitively in terms of macro-world physical laws in order to be convincing. In our everyday life we witness consequences of the second thermodynamic law — spontaneous energy minimization. Any natural system without an external intervention does not stay in an instable state, it follows its potential energy gradient until reaching a local minimum. Therefore, in order to achieve an intuitive, convincing behaviour of the virtual model, we have to simulate the energy minimization. For this purpose we introduce a concept of *virtual energy* that covers both the properties of the model we intend to render as well as physical properties that resemble a real-world object.
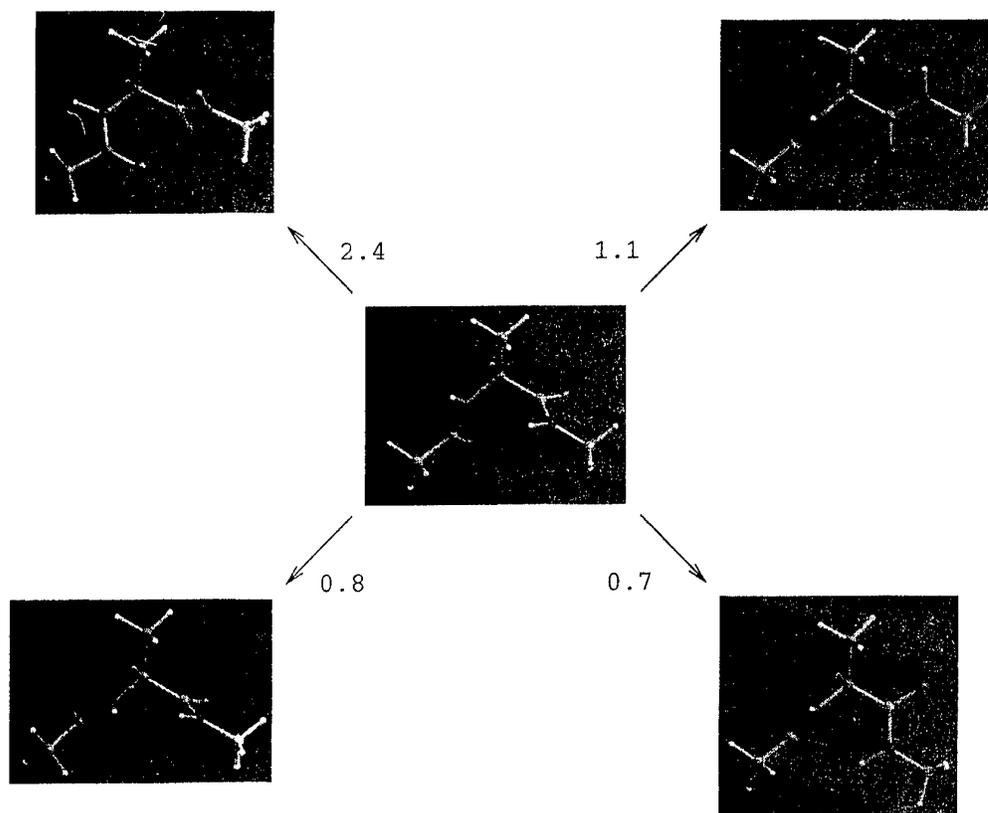
Fig. 1. Example conformation and four transition states of the alanine amino acid. The numbers show energy barriers (in kcal/mol)

B. Molecular Model Setup

The current implementation restricts the model to a chosen conformation and its surroundings, i. e. it spans upto the set of enclosing transition states. An example is shown in Fig. 1. We are able to compute an arbitrary point on a path between the conformation and a transition state. However, for the purpose of haptic interface, we have to cover the intermediate configuration as well. It is generally acceped as an affordable simplification that the conformational paths can be expressed in terms of *torsions*, i.e. twisting the molecule along a particular bond (or more bonds simultaneously) — this can be seen in Fig. 1.

Therefore, given position on the paths, we are able to construct a merged configuration[1] by aver-

[1]It has to be emphasized that this merge is artificial, with no direct background in chemistry. Its purpose is building a continuous state space that has to be present in a haptic model. However, we are really interested in the precomputed conformational paths only.

aging those twist angles.

The user is presented a van der Waals molecular surface (atoms are represented by spheres, overlapping in general, see Fig. 2) both in the haptic and graphical interface. A 3-DOF haptic device is attached to a virtual *probe*, an approximately water-sized sphere.

C. Energy and Force Computation

Virtual energy of this model depends on the probe position and the actual configuration of the molecule, and obeys the following rules:

- *Penetration of the surface by the probe is strongly penalized but not completely forbidden.* The interaction of the probe with the surface is the only way of enforcing a shape change, therefore the configuration change should be favoured. On the other hand, the amount of penetration is a direct and proven clue to the computation of force feedback, e. g. [2], [3], [4].
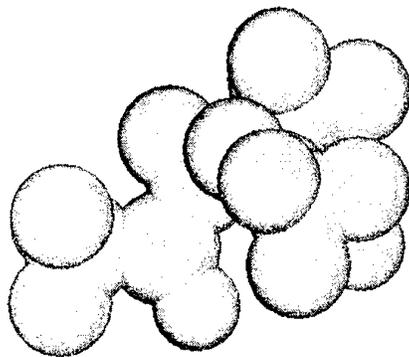
Fig. 2. Van der Waals surface of the alanine amino acid

- The configuration paths between the central conformation and the transition states are supposed to go through "valleys" of the true potential energy. Therefore *the precomputed paths are favoured in comparison to other configurations.* In addition, according to the input data structure we are given direct information on the potential energy on those paths only.
- Auxiliary terms that selectively penalize shift of atoms from their initial position (see [5]) are included. As a consequence *shape modifications close to the probe are easy to do* while the molecule is still fixed in space.

In each iteration of the interface driving loop we are given current coordinates of the probe. For the purpose of energy minimization, we treat it as a configuration constraint on the model.

The degrees of freedom of the model are expressed in terms of its free variables. Basically, there are two classes of them: positions on the precomputed conformation–transition state paths which represent the actual shape of the molecular model, and overall shift and rotation of the molecule defining an absolute position of the model in 3D space.

Given values of the free variables the shape of the molecule can be computed. The virtual energy follows the results of chemical calculation in case of paths between the central conformation and transition states, and is raised artificially (but coincidently with chemical expectations) to form barriers in areas between those paths. Then the molecule is located in 3D according to the second class variables. Now the probe-penetration and position-stabilizing terms can be computed as well.

The minimization starts from the last known state, i. e. free variable values. The energy minimization outputs a favoured shape and position. Those are shown directly by the graphical interface. As the energy contribution of the probe interaction with the surface is proportional to the resulting amount of penetration only, the force interaction can be derived from it directly.

From the user's point of view the molecular model resembles a slippery flexible object. It is possible to modify its shape by pushing the probe against it. Certain shape changes (those corresponding to the energy "valleys") are strongly prefered to others.

III. Implementation Issues

Let's focus on the computational requirements of the above model now. The computations can be classified as follows:

- *shape and position from the free variables,* (hence the force interaction) — fast enough to be computed inside the haptic interface loop (i. e., at 1–5 kHz rate),
- *energy minimization* — typically several hundreds shape computations, cannot be done inside the haptic loop.

Therefore we perform all the energy minimizations offline, on a regular grid of the probe positions. For the PHANToM device we use $200 \times 260 \times 85$ grid covering most of the device workspace. Moreover, different states (i. e., free variables vector) can be reached if the same probe position was approached from different previous states. Therefore we have to introduce another dimension (a *level*) to the grid, and keep track of transitions between the levels as well. Fortunately, level transitions are quite rare,

the grid size is usually increased by factor less than 2. With the given resolution the grid size is less than 10M points. We do not need high resolution of the free variables (1 byte is enough), and a typical conformation of molecules we work with can be described with upto 20 variables. As the state space is continuous we can traverse the grid in 6 orthogonal directions only, keeping the information on level transition in 4 bits. Therefore we end up with maximal grid file size 250 MB, which is generally affordable.

At run time, we compute trilinear interpolation of free variables' values according to the probe position in the grid. The force interaction is computed from the interpolated values.

The prototype application consists of three programs: offline grid computation, force feedback device (PHANToM) driving, and visualization. The current implementation of the energy minimization uses the NAG numerical library, restricting us to the SGI platform by our license terms, but this is not a general concern. The PHANToM driving runs on a RT-Linux machine using a driver developed at our site[2]. The driver allows high refresh rates (over 10 kHz) of the haptic device as well as loading critical parts of the code into the Linux kernel. In this way a guaranteed response time of the device driving is achieved.

We use VMD — a publicly available chemical visualization tool[3] for the visual rendering of the scene. VMD is a complex tool, besides different visual representations of the molecular model it allows real-time measure of geometry properties (distances, angles, ...) etc. The system defines a network communication protocol (originally designed for interaction with the NAMD molecular dynamics program) that is used to feed it with geometry data from the force feedback driving.

IV. Conclusions and Future Work

We build a haptic model of a molecule and its behaviour in surroundings of a chosen conformation. The model is realistic in the means that it strictly follows results of chemical calculation in "valleys" of potential energy, i.e. the areas that are interesting to the user. The information on energy of the current state of the model is delivered via the force feedback. This proves to be a natural and in-tuitive representation of the quantity. As the model is highly interactive it provides an immediate insight on the behaviour.

The work presented in this article is a continuation of recent research [6], [5]. There are two principal improvements in the current implementation:

- The model follows real precomputed conformational paths instead of relying on bond flexibility.
- Most of the exhaustive calculation is performed offline. Therefore the interactivity of the model improved significantly.

In the future we are going to focus on two extensions of the current model. The first one is overcoming the restriction of the user's workspace to a single conformation. Once the user delivers sufficient force in a proper direction to overcome an energy barrier of a particular conformational path, the molecular model should "flip" to the other conformation. We believe this is a technical problem only as the energy function as defined in this article overlaps near transitions states not regarding from where the state is approached.

The second possible extension we can see is more challenging. In order to explore more complex molecules in their full features more haptic devices (maybe more DOF's per device) are required. However, straightforward increasing the number of DOF's increases the dimension of the precomputed grid file which is not affordable generally. Therefore we shall have to look for a smarter solution.

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Design of a Multiple Contact Point Haptic Interface

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Abstract

This paper addresses key perceptual and psychophysical issues concerned with the design of a multiple contact point haptic device. The majority of commercially available haptic devices operate based on a principle of point interaction. Thus, contact between the operator and the simulated virtual environment occurs only at an arbitrary single point, typically the tip of a stylus or thimble used for interaction. However, this can severely impair, or even exclude, perception of object material properties. It is shown that a haptic interface mechanism incorporating several points of contact, corresponding to the tips of different fingers, for example, may facilitate more optimal acquisition of information regarding object properties. An example of how several grounded devices may be positioned to combine their workspace is presented, achieving a workspace of roughly 20x30x15 cm.

1. Introduction

When haptically exploring an object, it has been shown that the explorer unconsciously adopts a series of stereotypical hand movements, in order to extract the desired information in an optimal fashion [4]. Each exploratory procedure (EP) is associated with a particular object dimension, for which it is the optimal and preferred method for determining the property under unconstrained haptic exploration. Experimental results clearly indicated that in a free exploration t ask, hand movement was related to desired knowledge. EPs adopted during free exploration are usually optimal, if not necessary, for extracting the information required.

When using a haptic interface in order to explore a simulated or remote environment, it is inevitable, given the mechanical constraints imposed by the design of such devices, that performance of EPs is impaired, and in some cases totally occluded. Thus, the user is forced to adopt sub-optimal exploration strategies in order to extract properties of objects. This problem is particularly accentuated for those devices that operate on a principal of point interaction via a thimble or probe.

Given such constraints, table 1 summarises the principle EPs and their availability during point interaction. Hence, lateral motion, pressure and contour following are unaffected by the point interaction method, though the cues they elicit will differ from those obtained via direct contact. Unsupported holding, given the formal definition above, is not possible. However, it is possible to simulate weight sensations by allowing virtual objects to be "stuck" to the distal point of the probe. In theory, static contact is also possible, though temperature actuators have yet to find widespread application in the field. Finally, enclosure is impossible to perform via point interaction, as at least two points are required to begin attempting to mould to an object's global shape.

It has been shown that material properties of objects (for example, stiffness and texture) obtain a higher salience under purely haptic exploration, whereas structural cues are more easily obtainable and, hence, more salient for discrimination under visual exploration [2].

However, results suggest that perception of material properties, such as texture, is impaired due to the bandwidth of currently available haptic interface technology [7, 11, 12]. Thus, operators of haptic interfaces are forced to adopt a "visually mediated" approach to object discrimination, that is to say, that performance must rely on visual stimuli provided by a suitable display, or that the user must gather information regarding object properties that are more readily encoded by vision, such as size and shape.

Current haptic interface technology, however, provides no facilities for the enclosure EP, which is optimal for global

shape and volume. Point interaction devices are also deleterious to the execution of contour following, which becomes time consuming and difficult due to the greater memory demands for temporal integration of cues. It was shown that exploration via a single contact point increases response times in tasks requiring comprehension of geometric data [5]. A similar effect was observed between full handed and single fingered exploration of objects[3].

Exploratory Procedure	Description	Availability under point interaction
Lateral Motion	Movement back and forth between skin and object surface.	Available, though cues will be temporally varying (vibration) instead of spatially varying.
Pressure	Applying normal force.	Available
Static contact	Resting passively without moulding.	Available, though no temperature or distributed force cues are available through probe.
Unsupported Holding	Object is lifted and maintained.	Available, by attaching simulated object to distal point of probe.
Enclosure	Hand maintains simultaneous contact with as much of object as possible.	Unavailable in absence of multiple contact points.
Contour Following.	Smooth, non-repetitive movement with a contour of the object.	Available. Difficult to execute due to small contact area.

Table 1: *Availability of EPs with point interaction.*

2. Multiple Contact Point System

Given the limitations of currently available point interaction devices, a system is proposed in which several commercially available devices (the PHANToM (www.sensable.com)) are combined in order to facilitate multiple fingertip interactions. It is envisaged that the system will allow grasping and enclosure procedures previously unavailable with haptic devices, and will also potentially improve efficiency in extraction of object properties. For example, increasing the number of fingers stimulated by similar tactile sensations increases the perceived vibration magnitude by a rule of diminishing returns; thus, by using multiple stimulation points it may be possible to increase the perceived sensitivity range [6].

Srinivasan and Basdogan [8] identified multi-finger displays as an important future development in the field of computer haptics, though early exponents of the idea were Atkinson et al. [1], who outlined an idea for a "magic glove" which used miniature gas jets to stimulate the users hand. It was also proposed by Lederman and Klatzky [5] that multiple end effectors may be important for providing additional kinesthetic information.

We have adopted a design strategy incorporating several "grounded" interfaces, as opposed to an "ungrounded"

device, such as a glove, or exoskeleton, as such devices have previously been shown to impair performance, whereas it is widely accepted that grounded interfaces such as the PHANToM are capable of supplying realistic force cues.

For example, Turner et al. [9] present results pertaining to a system for dexterous telemanipulation. The user wears a force feedback augmented instrumented glove (CyberGlove ® from Virtual Technologies) which transfers the user's movements to a two fingered dexterous robot hand mounted on the end of a 4-DOF industrial robot manipulator. Forces applied to the fingers are uni-polar, serving to only straighten the finger. The results indicated that the single axis of force feedback presented by the system did not increase speed of performance for simple telemanipulation tasks. Subjects pointed out that the force feedback could be misleading in a "block stacking" test, whereas provision of force cues actually had a negative effect on performance in a "knob turning" test. These examples serve to illustrate the importance of the device used to display force cues, and how they affect task performance when they are limited, unavailable or inappropriate to the task at hand. The force feedback system had a cut off frequency of 40 Hz, which means it would have difficulty displaying higher frequency slip sensations and vibrations, which are important in manipulation tasks.
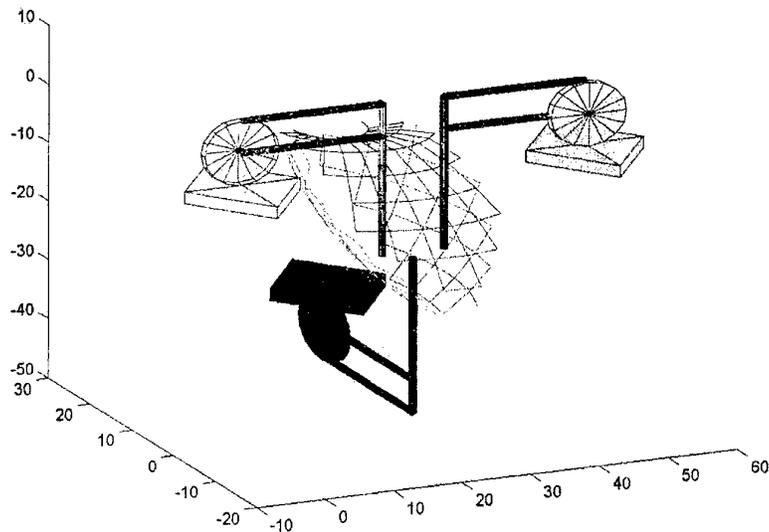
Figure 1. *Workspace of three PHANToM composite system.*

3. Workspace Configuration

The advantage of ungrounded devices is that they are often designed with regards to the range of movement / degrees of freedom of a particular human joint or limb, such as is the case with hand or arm exoskeletons. Ungrounded devices, such as the PHANToM, or Impulse Engine (www.immersion.com) often have a much more limited and less intuitive workspace.

As the composite device will incorporate several grounded interfaces, it is inevitable that their combined workspace will amount to less than that which is afforded by a single device of that type. It is an important factor in the design of the interface, however, to consider the extent of this available workspace, and how this will facilitate employment of stereotypical grasp mechanisms (e.g. pinch, key grasp etc.), and EPs.

Figure 1 illustrates one such suitable configuration for the three PHANToM devices. Thus, two PHANToMs are placed opposite each other, facing each other in the reset position. The final PHANToM is positioned immediately below the first two devices, and is inverted. The workspace is roughly 20x30x15 cm. A typical configuration for a two PHANToM 3.0 system offers a workspace of 30x40x40 cm [10].

It is also important to establish the range of flexion and extension available to the fingers and wrist, and the range of grips that can be performed. With three contact points, it is, in theory, possible to perform pinch grasps, tripod pinch (pen grasp) and key grips. However, more investigation is required to fully quantify the extent to which these procedures can be executed under a given 3 PHANToM setup.

4. Future Work

It is planned to investigate several other possible configurations, in order to ascertain which arrangement will offer the best workspace, and possibilities for user interaction techniques. A similar study involving two PHANToM devices highlighted the difficulties involved in calibrating the two devices [10]. Results showed that careful calibration of the two devices produced an average position error of below 1mm between the physical point and the point in the virtual space. Inevitably, this problem will be more complex with 3 devices, and potentially detrimental to the illusion of physical contact and grasp stability in the simulated environment.

Typical grasping mechanisms employed by users have been considered, though formal verification of which

grasps can be performed and their efficiency must be investigated.

5. Conclusion

This paper has outlined the need for consideration and development of multiple contact point haptic interfaces. It was illustrated that current devices tend to impair performance of stereotypical EPs, and inhibit acquisition of information regarding object properties. This mostly occurs due to the point interaction method of simulating contact, though the devices bandwidth and physical properties are also a contributory factor. It is envisaged that a device incorporating several, grounded, point interaction type devices will allow more natural exploration of simulated environments, potentially increasing their efficiency, and ease of use.

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Stable Haptic Interaction with Virtual Environments Using an Adapted Voxmap-PointShell Algorithm

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Abstract

Despite a lot of research in recent years stable and realistic haptic interaction with virtual environments keeps an unsolved problem. Among different approaches the Voxmap-PointShell[TM] (VPS) method seems very promising due to constant sample rates, independent of the static environment. But there is still the stability problem to be solved globally. In this paper some adaptations based on the VPS are presented, including the dynamic object modeling and the force calculation method, to reduce the distractions of the calculated collision forces to increase stability. The PointShell points lie exactly on the surface of the dynamic object, to get a smoother surface representation. A variation of the collision force calculation leads to a reduction of the "voxel noise", that appears due to the discretization of the volume space. A design framework for the virtual coupling is presented, that enables the automatic configuration for different haptic devices. The validity will be shown with different kineasthetic hand controllers.

1. Introduction

There are numerous haptic rendering algorithms for virtual simulations, differing in object and surface modeling. Object models are mostly approximate descriptions of the simulated objects, used in the virtual environment. In many rendering algorithms, the geometrical complexity of the particular modeled objects is restricted due to high rendering times. In the VPS approach of McNeely, Puterbaugh and Troy [6], the virtual environment consists of objects divided into dynamic and static objects. Dynamic objects can freely move through the virtual space, whereas the static objects are fixed in the world coordinate system. With a haptic device, a human can touch the static objects (static environment) with the dynamic object, and the rendered collision forces will be fed back to the operator.

The haptic rendering update rate is independent from the complexity of the static environment, thus qualifying for real time applications. The environment of static objects is collectively represented by a single spatial occupancy map called a voxmap (volume map). This is created by discretizing the static environment space, which is partitioned into regions of free space, object surface, and object interior. The collection of the discrete volume elements (voxels) build the voxmap. The dynamic object is described by a collection of points (PointShell), which models its surface. Each point is assigned a surface normal vector, pointing inwards. The haptic rendering algorithm includes a fast collision detection technique based on probing the voxmap with the surface point samples of the PointShell. By using the normal vectors of the PointShell, an approximate collision force can be easily computed in constant time for each point-voxel interpenetration. Figure 1 shows a PointShell colliding with the voxmap. For each PointShell point, contained by a surface voxel, the depth of interpenetration is calculated as the distance d from the point to the tangent plane. This plane passes through the voxel center and has the same normal vector as the PointShell point normal vector.
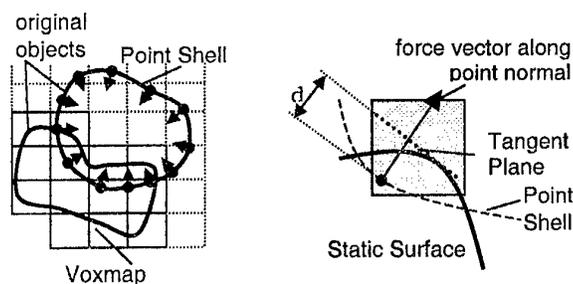

Figure 1: Voxmap-PointShell-Model[TM]

So the time consumed to render a single frame depends only on the number of PointShell points. The real time capability qualifies this algorithm for online haptic interactions between a human operator and a virtual environment. For enhancing haptic stability, McNeely et al. [6] employ a 'virtual coupling' scheme, which connects the user's haptic motion with the motions of the dynamic object through a virtual spring and damper. This scheme was embedded in the haptic rendering algorithm. But mechanical properties of different haptic devices are not treated by this virtual coupling, and it is difficult to tune the system to obtain a stable haptic feedback.

In contrast, the approach described in this paper decouples the stability problem from the haptic rendering, as also proposed by Adams and Hannaford [1], where the virtual coupling was treated as part of the haptic interface (device and virtual environment). This allows the usage of an arbitrary haptic rendering algorithm independent from the haptic device. Almost no changes of the virtual environment parameters are required, when the haptic device changes. In chapter 2, we present adaptations to the VPS based object modeling and force calculation, for reducing the distractions of collision forces to get more stability. The 'virtual coupling' is described in chapter 3. Chapter 4 shows some results of experiments, where the validity of the methods can be seen. The paper closes with the conclusion in chapter 5.

2. Extending the VPS Algorithm

2.1 Exact PointShell Creation

The calculation of the contact force takes place in the force voxel layer which is one voxel deep. Due to the design of the VPS method the effective force layer depth around static objects amounts to half a voxel. So it can be seen easily, that surface deviations of the PointShell object, with an amplitude of more then a half voxel size, have considerable influence on force distractions. This surface variance appears due to the PointShell creation described in the original VPS, where the object first was voxelized, and the collection of all surface voxel centers build the PointShell (Fig. 3, 1-3).

Next, the extended PointShell creation is presented, where the points lie on the triangulated object surface (anti-aliasing), not only to improve the accuracy, but also to stabilize the collision force. The example in Figure 2 shows the same collision situation of a dynamic and static object, with the two different PointShell models. In the upper scene (Fig. 2 a), the PointShell was built with the original algorithm, where the distance between the

PointShell points and the object surface is up to $\frac{\sqrt{3}}{2}e$,

where e denotes the voxel extension. This surface deviation is very high compared to the force layer depth

of e/2. In the case of Figure 2 a) the PointShell was created using the voxel raster shown with dashed lines. With this rough surface approximation only one of the four PointShell points effects a collision force, although the 'real' dynamic object surface cross three force layer voxel. Figure 2 b) shows the effected collision forces using the exact PointShell model, creating a smoother force field.
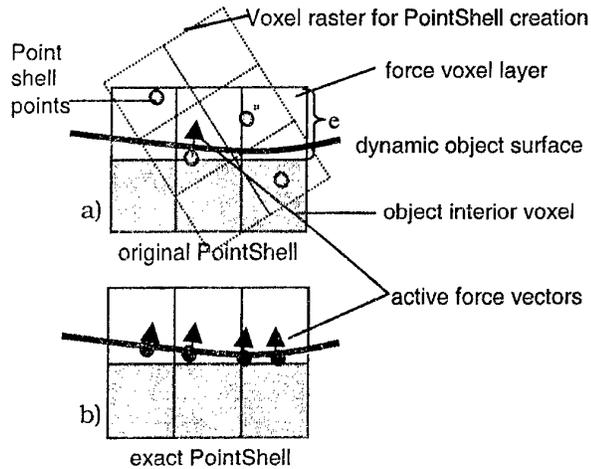
Figure 2: Different collision force effects in comparison between the original PointShell and our exact Point Shell

The exact PointShell creation process steps are shown in Figure 3. The first two steps are equal to the original PointShell creation. In order to guarantee a proper detection of collisions between dynamic and static objects, the distance between two neighbored PointShell points is limited according to the voxel resolution of the static environment. Hence the 'naive' PointShell is built by the sum of all center points of the resulting surface voxels, after creating the VoxMap of the dynamic object with the same resolution as of the static environment (Fig. 3, 1-3).
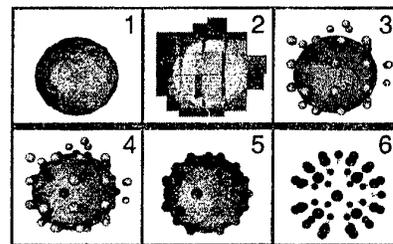
Figure 3: Steps of the exact PointShell creation algorithm

A smoother surface representation can be achieved by projecting each center point on to the triangle surface

(Fig. 3, 4-5). Two additional requirements for the new position have to be fulfilled:
1) inside the primary voxel
2) minimal distance to the voxel center

This two requirements can be inconsistent with one another, whereas the first requirement has the higher priority and the second should be optimized as far as possible. The first condition keeps the maximal neighbor point distance such that an unrecognized interpenetration of the static and dynamic object is prevented. The extension of the spatial gap between two PointShell point neighbors is restricted to the minimal spatial extension of a static object surface part (3 voxel extensions, if a force field is used as described by McNeely [6]). The property of the shortest distance tries to keep the original distance of the point neighborhood as far as the other conditions allows, for a convenient point distribution.

Algorithm: The following algorithm shows the correct point-surface-projection, keeping the above requirements with the defined priority. The object surface is described by a number of triangles. Due to the condition, that the projected point must be contained by the respective voxel, only the triangles with a common intersection point with that voxel have to be considered. For each triangle the following steps have to be done. First calculate from the voxel center the perpendicular nadir p_0 on the triangle surface. Now four cases have to be considered:

Let:
- V be the set of all points contained by the respective Voxel;
- VS be the set of all points lying on the surface of the respective Voxel; $VS \subseteq V$;
- T be the set of all points lying on the observed triangle;

then:
case 1: $p_0 \in V$ and $p_0 \in T$:
    the result is p_0;
case 2: $p_0 \in V$ and $p_0 \notin T$:
    return point $p_r \in \{T \cap V\}$, which has the shortest distance to p_0;
case 3: $p_0 \notin V$ and $p_0 \in T$:
    return point $p_r \in \{T \cap VS\}$, which has the shortest distance to p_0;
case 4: $p_0 \notin V$ and $p_0 \notin T$:
    if ($p_r \in T$ with the shortest distance to p_0) $\in V$
    then the result is p_r,
    else the result is equal to the result of case 3;

Figure 4 shows two examples of case 4. The treatment in case 4 is generally valid, therefore all cases can be handled by the following algorithm:

```
Algorithm :

projectPoint(Voxel, Triangle)
p₀ =        perpendicularNadir(Voxel.centerpt, Triangle.plane);
pᵣ =        trianglePointWithShortestDistanceToPoint(p₀);
if          (Voxel.contains(pᵣ))
then        return(pᵣ)
else        intersection_lines = intersect(Triangle, Voxel.surface);
            for each Line ∈ intersection_lines
                pᵢ = linePointWithShortestDistanceToPoint(p₀,Line);
                p_result = min(distance(pᵢ,p₀), distance(p_result,p₀));
return p_result;
end;
```

For each original PointShell point (voxel center), map it on the corresponding triangles, and choose the result point with the shortest distance to the voxel center. The set of all mapped points build the exact PointShell. Now the PointShell vectors can be calculated from the normal directions of the triangles intersecting the relevant voxel.
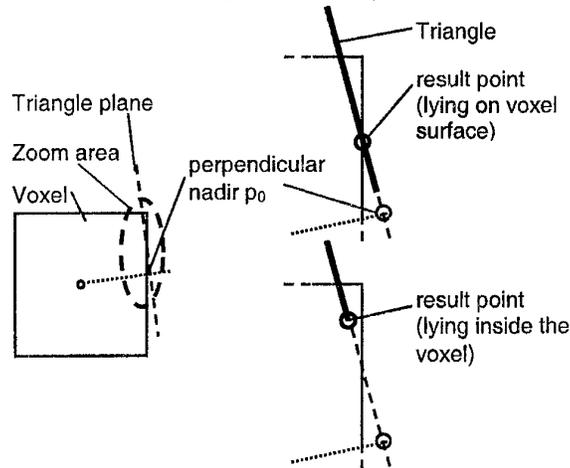
Figure 4: Two examples showing the projection treatment of case 4

2.2 Adapted Collision Force Calculation

Further force discontinuities appear, when PointShell points cross static voxel borders. Especially under sliding motion with a relatively constant interpenetration between the dynamic and static object, this effect, shown in Figure 5 (a, b), causes instability and notably disturbs the operator's correct sense of touch (vibrations). The presented variation of the VPS collision force calculation [6], leads to smoother transitions at voxel borders. In contrary to hierarchical methods, which increase the calculation time, the presented method does not need a finer resolution (granularity) of the static environment.

Instead of providing a general solution to the force stability problem, our adapted force calculation specifically targets the force noise for dynamic objects sliding over a plane of adjacent surface voxels. When

PointShell points cross the border between these adjacent voxels, instability occurs if the direction of the relevant point normal vector is not perpendicular to the sliding plane. Figure 5 a) shows a dynamic object colliding with a static object under sliding motion. Figure 5 b) and c) demonstrate the interesting area (marked with the dashed line in 5 a)). Figure 5 b) shows the problem that appears with the original force calculation method. When the PointShell point crosses the voxel border, the calculated force value is reduced to zero, which influences the overall collision force. Instead of using the individual PointShell normals to calculate the collision force, the average of all collision point normals is used to calculate the interpenetration distance d of each PointShell point (Figure 5 c)). This average direction is a more stable approximation of the sliding plane normal, and the mentioned problem can be mitigated.
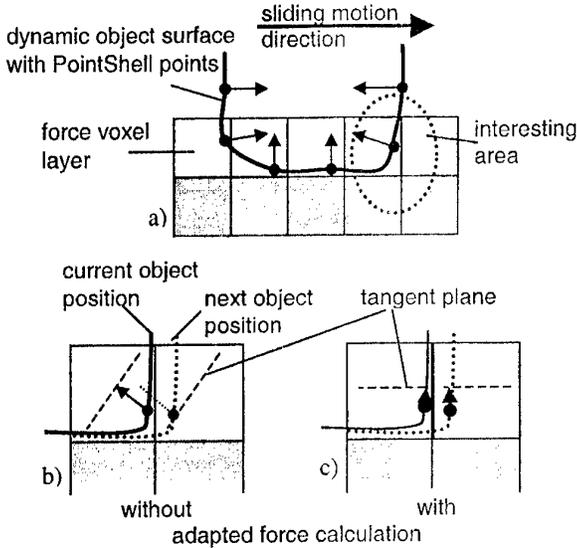
Figure 5: Force stabilization under sliding motion

3. Virtual Coupling

The schemes described above only reduce force noise, but there are still remaining distracting forces causing an unstable system. The direct way to reach the required stability is to use a 'virtual coupling' scheme between the operator and the virtual environment. A design framework for the virtual coupling is presented, that allows a consistent interaction between the haptic rendering (VPS) and different haptic devices, because for the overall stability, the dynamic properties of the haptic device play a key role.

In many other approaches (e.g. McNeely et al. [6], Adams and Hannaford [1]) the virtual coupling is treated and parameterized as a spring-damper system, which is a good mechanical interpretation, but leads in most cases to a heuristic optimization of the parameters. The spring-

damper system is used to reduce the force steps, produced by discontinuities and discretization, for the human user.

The virtual coupling can also be seen as a dynamic shaping filter, as it is done in this approach (Fig. 6). The dynamics of the calculated contact force are reduced such that neither the haptic device nor the force reflection loop with the human become unstable.
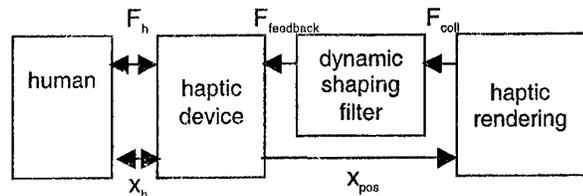
Figure 6: Signal flow diagram of the haptic simulation

Filter Construction

The filter should keep the role of the virtual coupling, thus the physically model of the virtual coupling (the spring-damper system) is used as a model for the construction part.
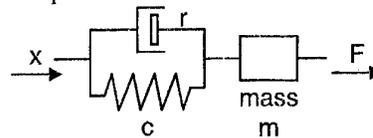
Figure 7: Mechanical spring-damper system

With this mechanical representation (Fig. 7) the following equation can be built:

$$F = c \cdot x + r \cdot \dot{x} + m \cdot \ddot{x}$$

For the filter, the translation value x must be replaced by the collision force as input, which is generated by the haptic rendering algorithm. This replacement can be done under the condition that the collision force depends directly on the penetration distance, which is true with this haptic rendering algorithm ($F_{coll} \sim x_{pos\,(collision)}$).

With $\quad T = \sqrt{\dfrac{m}{c}}, \quad w_0 = \dfrac{1}{T}, \quad d = \dfrac{r}{2\sqrt{m \cdot c}}, \quad K = \dfrac{1}{c}$

this function leads to the PT$_2$-element with the following transfer function (continuous time):

$$H_f(s) = K \cdot \frac{w_0^2}{w_0^2 + 2 \cdot d \cdot w_0 \cdot s + s^2}$$

The continuous time filter can be transformed to the discrete time filter H$_f$(z) with the Tustin-Approximation:

$$s = \frac{2}{T_A} \cdot \frac{z-1}{z+1},$$

$$H_f(z) = K \frac{w_0^2}{w_0^2 + 2 \cdot d \cdot w_0 \cdot \dfrac{2}{T_A} \cdot \dfrac{1-z^{-1}}{1+z^{-1}} + \dfrac{4}{T_A^2} \cdot \dfrac{(1-z^{-1})^2}{(1+z^{-1})^2}}$$

The parameters used with this filter function can easily adjusted to the dynamic properties of the haptic device, without changes in the haptic rendering algorithm. Whereas the sample time T_A is chosen by the cycle time of the rendering algorithm and haptic device, the sufficient stability can be reached by adjusting the cut-off-frequency w_0 and the damping factor d.

Typically a human can sense kineasthetic impression with a bandwidth of approximately 1kHz [3] and can make controlled movements with a maximal bandwidth of 10 Hz. Studies at the DLR resulted in a bandwidth of 2 Hz in which a human performs a desired task (no reflexes). To perceive realistic kineasthetic impression the dynamic of the force controller (implemented at the device) plays the key role and limits the achievable bandwidth. That means that the force dynamic of the virtual environment can be limited to 5Hz without loosing a realistic impression of the scene.

4. Experiments

The validity will be shown in experimental results using the Phantom T-Model (Fig.14) and the DLR- light weight robot (Fig. 13) as kineasthetic hand controller [7]. In the virtual test bed the static scene consists of a cup, whereas a sphere is used as dynamic object manipulated by the operator (Fig 15).

4.1 Experiments to the Adapted Collision Force Calculation

For a benchmark of the force distractions, the results of the collision force calculations are evaluated in two experiments. The dynamic sphere was moved over the static object with a predefined path and a constant penetration. The experiments differ with respect to the surface conditions of the static object, which typically occur in discrete space models like the voxel map. The surface condition depends on the orientation of the surface plane related to the main axis planes of the voxel grid coordinate system. Force distractions, appearing in sliding motion, primarily influence the collision force direction. For demonstrating this effect, only the force parts vertical to the collision plane normal (the intuitive collision force direction) were recorded. In each experiment this record is done for both the original and the adapted collision force calculations. The direct comparison between them is depicted in the following diagrams, made for each experiment.

Experiment 1: sliding motion over a plane surface
The sliding path of the dynamic object is in this experiment a circle movement over a plane surface of the static object. In Figure 8 all the distraction arrowheads are

recorded, by keeping the axis origin at the sphere center position.
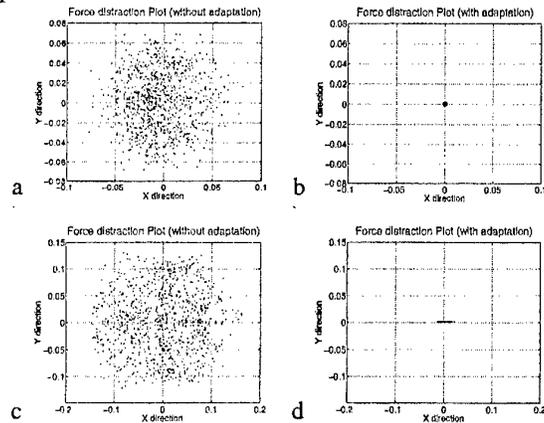
Figure 8:   Collision force distractions of experiment 1

In the experiment related to Figure 8 a) and b) the sliding surface of the static object was oriented along the voxel grid main axes, whereas 8 c) and 8 d) presents the results of the motion over a not voxel grid raster oriented plane. With the adapted force calculation the distraction reduction is appreciable in both cases.

Experiment 2: sliding motion over a curved surface
In this experiment the sphere slides on a circle path around the superficies surface of a cylinder, with also a constant penetration depth into the cylinder (Fig. 10). This shows the collision force distraction behavior with many different surface condition cases. Figure 9 a) shows the distractions of the collision force over the time calculated with the original algorithm and Figure 9 b) shows the distractions with the adapted algorithm. Of cause there are still remaining distractions with the adapted form coming from the different surface conditions, but a high reduction of these distractions can be seen with the adapted collision force calculation.
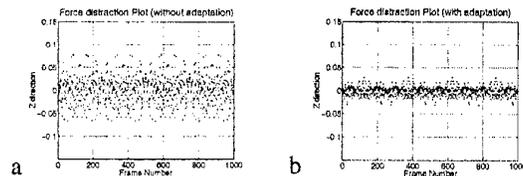
Figure 9: Collision force distractions in one direction of experiment 2
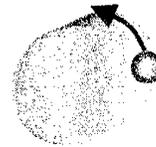
Figure 10: Benchmark for the virtual coupling

4.2 Experiments to the Virtual Coupling

To evaluate the virtual coupling, a sphere is moved over a cylindrical static object with a constant penetration (Fig. 10).
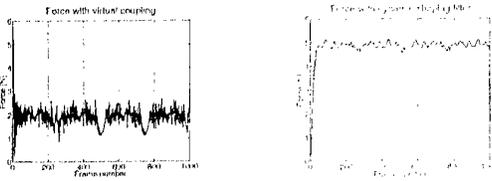
Figure 11: Force plots for different virtual couplings

In Figure 11 shows the results of a heuristic tuned virtual coupling and the dynamic shaping filter explained in chapter 3. In hardware-in-the-loop experiments, the virtual cup (Fig. 15) was touched by the virtual sphere using the DLR Light-Weight robot (LWR) (Fig. 13) and the Phantom T-Model (Fig. 14) as haptic hand controllers. The following diagrams (Fig. 12) shows the collision forces (thin line) calculated by the haptic rendering algorithm and the corresponding output force (thick line), which was returned as feedback force to the hand controllers by the virtual coupling element. Two kinds of collisions were tested, an abrupt collision, hitting the cup with the sphere (Fig. 12 a,c), and a steady collision, sliding with the sphere over the cup surface (Fig. 12 b,d).
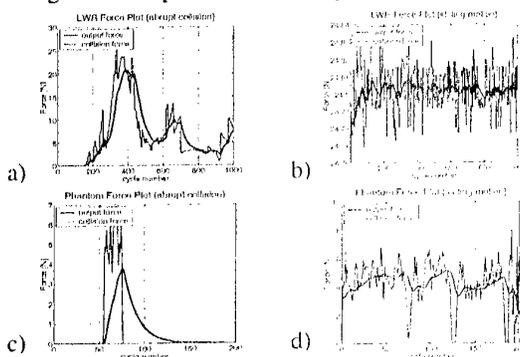
Figure 12: Force plots of the experiments with the Phantom and the LWR

5. Conclusions

In this paper some efforts were done to improve the stability and immersion of haptic feedback. Our approach is based on the VPS method, due to its constant sample rates. First the object modeling was improved towards an exact surface representation. This not only increases the accuracy, but also avoids some force distractions during contact situation with static objects. The force calculation itself was adapted such that the voxel noise, occurring during sliding motions over static objects, is substantially reduced. This leads to a smoother force evolution within

the task. Finally, a design framework for virtual coupling was presented. It takes into account the dynamic properties of the human operator and of the hand controller. This approach leads to a more stable haptic interaction with virtual environments as it is shown in the presented experiments.

Further work in the fields of improving the realistic haptic feedback extending the VPS, and of automatic design of the virtual coupling will be done.

Figure 14: Phantom T-Model from Sensable Technologies Inc.

Figure 13: DLR Light-Weight robot as kineasthetic hand controller
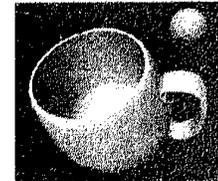
Figure 15: Virtual test bed

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Mutual Calibration of a Co-Located Haptics Device and Stereoscopic Display

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Abstract

We describe a calibration technique for a hand-immersive virtual-reality environment – the Reachin Display [1]. The technique we present allows us to calibrate both the haptics device and the stereo display environment simultaneously where calibration of the stereo display utilises the haptics device and vice versa. The calibration procedure is described and we present a modular architecture for constructing calibration functions and show how fine control over the individual calibration parameters that are used can be obtained.

1. Introduction

The Reachin Display [1] comprises an articulated haptics device [2] and a stereoscopic visual display. The working volumes of these two components are arranged to coincide so as to effect a co-located hapto-visual display, i.e. the user can feel the object in the same place as he sees it. This is accomplished by using a semi-transparent mirror to reflect the scene being drawn giving the effect that the objects appear in space in the same place as the hands and the haptics device (see Figure 1). The greatest benefit of such a system is that it allows the user to utilise their sense of proprioception to quickly and accurately locate objects within the workspace. Also there is a much stronger sense of realism than the traditional set-up.

Co-located displays require accurate calibration in order for the user to perceive the combined haptic and visual displays as a single multi-sensory environment. Also, if the mirror in the display is semi-transparent then the user sees both the real objects in the workspace (such as their hands) as well as the virtual objects displayed by the monitor. In this *augmented reality* mode (which is used during calibration) any error in calibration will be obvious and disturbing. We would like to be able to acquire an accurate calibration in an easy way with as little

work needed from the user as possible. For example, the task of setting the parameters manually requires a lot of work and any change to the set-up invalidates the calibration. Since the set-up can vary quite a lot we would like to be able to generate the calibration automatically.
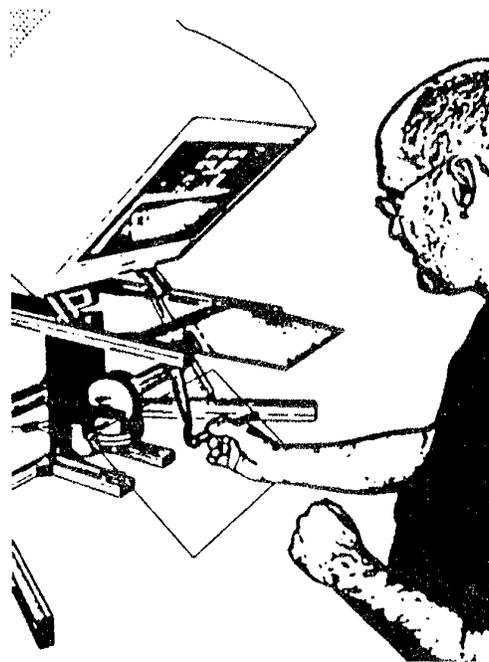
Figure 1: User using the Reachin Display. The user looks through the mirror and thereby experiences the objects in the same space as his hands.

The calibration actually consists of two parts. One part is the translation of the arms' position of the haptics device into a position in the stereo display. This is not trivial since the haptics device in theory can be mounted in any position and orientation on the display. Hence a movement to the left in the haptics device coordinate

space can be a movement in any direction in the stereo display environment. The other thing that needs to be calibrated is the visual display of the scene. We need the objects to be the right size (the size specified by the user) and the perspective to be right so that the stereo environment does not differ from the real world. This means that a real object and a virtual object of the same size should appear to have same size anywhere in the stereo display work area.

We present a calibration technique where both these parts can be calibrated. The calibration of the stereo display environment utilises the haptics device and the calibration of the haptics device utilises the stereo display environment.

2. Calibration procedure

During the calibration process the user sees both the real stylus of the haptics device as well as a virtual model of the stylus moving within the stereoscopic display. When everything is calibrated correctly these two objects should coincide accurately in position, orientation and size. When they do not, the user may click the button on the stylus to freeze the virtual stylus, then move the real stylus so that it coincides accurately with the virtual stylus and then release the button. This records a *correction sample*. This sample consists, in our case, of the encoder angles of the arms of the haptics device and the screen coordinates for the left and right eye of the position of the virtual stylus. The user can specify several correction samples and these samples are then used by the software to calibrate some subset of more than 12 independent *calibration parameters*.

3. Calibration functions

A *calibration function* is a multi-valued vector function from a set of values (called *real* values) and a set of calibration parameters to another set of values (called *virtual* values). When the user clicks the button, they specify the virtual values of the correction sample and when they release the button they specify the corresponding real values.

In our case the calibration function consists of several stages. We begin with *relative encoder angles* read directly from the encoders on the arms of the haptics device. In our application there are 3 encoders measuring position and 3 for orientation of the stylus. These angles are *relative* to the angular positions of the encoders when the haptics device was last sent a *reset* command. Therefore we offset these values by the 6 *reset angle* calibration parameters to calculate the *absolute encoder angles*. Normally the device has a standard reset position in which the reset command is supposed to be called at. This defines the position where the reset angles are all

zero and therefore the relative encoder angles also are the absolute encoder angles. However this reset position is not always reachable by the haptics device (e.g. the mirror in the display can be in the way) and even if it is it can be quite hard to put it in the reset position with good accuracy. So instead of doing this we include the reset angles in the calibration, which eliminates all such problems.

These encoder angles may then be transformed into a Cartesian position and stylus orientation according to known geometry information such as the lengths of the haptics device arms. This position is then further transformed into the *world coordinates* of the rendering software by means of a calibration translation, rotation and scaling. This is the coordinate space that a user of the Reachin Display uses to specify objects in.

Finally the world coordinates are projected onto the stereoscopic screen with one position for the left eye view and one for the right eye view. This transformation is controlled with OpenGL [4][7] parameters and can be divided into several parts. First the world coordinates are transformed by a *model view matrix* into *eye coordinates*. The eye coordinates are the coordinates of the objects looking into the world through a camera with a specified position and orientation. Since we use a stereoscopic display we must make two such transformations, one with the camera in the position of the left eye and one with the camera in the position of the right eye. After this transformation a *projection matrix* is applied and the coordinates are normalised. The projection matrix is set up by specifying an asymmetric view frustum for each eye. The view frustum is constructed from field-of-view angles, focal distance and inter-ocular distance (see Figure 2). This gives us the screen coordinates for the left and right eye (also called normalised device coordinates) and this is the end product of our calibration function since these define the perceived 3-dimensional position in the display.
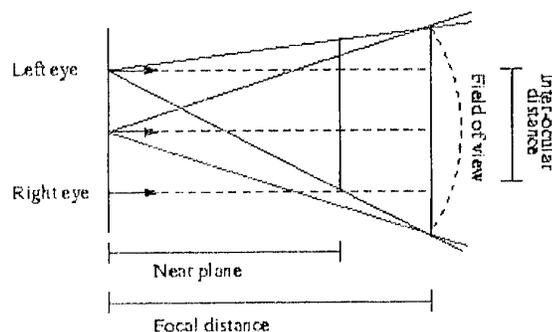

Figure 2: The asymmetric view frustum for the left eye. The centre view is the normal view when stereo is not used and the view from the left eye is the corresponding view used in stereo mode for the left eye. A similar frustum is used for the right eye.

We then define an *error function* based on the discrepancy between the measured real values transformed by the calibration function and the measured virtual values. Specifically the discrepancy is defined to be the distance-squared between the virtual values and the transformed real values. So the error for a correction sample is

$$e(r,v,c) = \left(f(r,c) - v\right)^2$$

where r are the real values of the correction sample, v are the virtual values, c are the calibration parameters and f is the calibration function. If we have several correction samples the total error is the sum of the errors of the individual samples.

This gives us a single error value and the task of the calibration procedure is then to adjust nominated calibration parameters so as to minimise this error function. This is essentially a numerical minimisation function in multiple dimensions. We use a variable metric method to perform the minimisation. The method used is the Broyden-Fletcher-Goldfarb-Shanno variant of the Davidon-Fletcher-Powell minimisation algorithm [3]. This method requires us to provide the gradient of the function to minimise.

Let $J_c(r,c)$ be the matrix whose columns are the partial derivates of f with respect to the calibration parameters c. This is a sub-matrix of the full Jacobian of f. Using this function we may define the error gradient with respect to the calibration parameters c as

$$G(r,v,c) = 2\left[f(r,c) - v\right] \cdot J_c(r,c)$$

This is a sub-vector of the full gradient of e, containing only the partial derivatives of e with respect to c. In the case that the error is summed over several correction samples, the error gradient is simply the sum of the gradients for each sample. How to get hold of the Jacobian function is explained in the next section.

The problem of the minimisation is that it is easy to find a local minimum in the error function and hence we might not get the optimal solution. In order to prevent this we make several minimisations from different starting points and choose the smallest minimum we can find of all the minimisations. Of course this does not always find the global minimum either, but at least we have improved our chances to get a better minimum than if we had just used the first one we found.

5. Calibration modules

When implementing the calibration functions into a calibration program we would like to be able to make changes to them easily. We would, for example, like to be able to choose which calibration parameters to calibrate and which to leave unchanged. We would also like to be able to extend a calibration function with extra parameters without having to rewrite any code from the previous function. To accomplish this we use a number of *calibration modules* to construct the calibration function. A calibration function can consist of one or more of these calibration modules. If we want to do a change to the calibration function (e.g. add a rotation) we just construct a new calibration module defining this transformation and insert it into the calibration function.

A calibration module defines a function f from a set of values A to another set of values B. The values of A can be divided into *input parameters* and *calibration parameters*. The calibration parameters are the parameters that are to be adjusted to get the best calibration while input parameters are the positional/geometric values to be transformed by the module. For example, if the module specified a translation in Cartesian coordinates it would take six parameters. Three of them would be calibration parameters specifying the translation at each axis and three would be input parameters specifying the original coordinates which we want translated.

Each module also defines two Jacobian functions. One of the functions, J_i, returns the Jacobian matrix for f with respect to the input parameters and the other function, J_c, returns the Jacobian matrix of f with respect to the calibration parameters. These Jacobian functions can be quite complicated and in many cases they would be intractable to code by hand. Because of this we use the symbolic mathematics software Maple™ to automatically generate the code for the calibration modules. This software allows us to specify the function of the calibration module symbolically. Partial derivatives and Jacobian matrices can then easily be generated with the software and we use the automatic code generation tool to get optimised functions for evaluating both the Jacobian function and the normal function of the calibration module. This way the calibration modules become "black boxes" of code, which can be composed into larger calibration modules, which allows for an efficient and extensible run-time implementation.

When two of these modules have been defined we can compose them into one single calibration module performing the composed transformation of the two individual modules. The only restriction is that the number of output parameters of the first module matches the number of input parameters of the other module. When composing two calibration modules into a single one we must create composed versions of the function and the two Jacobian matrices. For the function value it is quite straightforward.

$$f_c''(r,c'') = f_c''(r,c\,|\,c') = f'\left(f(r,c),c'\right)$$

where f is the function of the first module and c are the calibration parameters for the first module. The primed versions are same but for the second module. r is the input parameters for f. Note that the calibration parameters for this new function are the composition of the two vectors of the calibration parameters for the individual modules.

To derive the composite Jacobian matrices we use the chain rule for vector valued functions. The Jacobian function with respect to the input parameters is given by

$$J_i''(r,c'') = J_i''(r,c \mid c') = J_i'(f(r,c),c') \times J_i(r,c)$$

where J_i, f, and c are the Jacobian function, the function and the calibration parameters for the first module respectively. The primed versions are the same but for the second module. Note that the matrix multiplication enforces the restriction that the number of input parameters of the second module must be the same as the number of output parameters of the first one. The Jacobian function with respect to the calibration parameters is acquired by

$$J_c''(r,c'') = J_c''(r,c \mid c') = [A \mid B]$$

where

$$A = J_i'(f(r,c),c') \times J_c(r,c)$$
$$B = J_c'(f(r,c),c')$$

In this way we can compose as many modules as we want into the final calibration function and it is easy to make changes to it since we can just remove or add the calibration modules that we would like to use. If we want the calibration parameters for a certain module to remain the same during a calibration we just have to return a zero matrix as J_c. This way we can easily control which parameters to calibrate.

6. Implementation and results

We implemented the calibration program in the Reachin API [6] for use in the Reachin Display. We used the Python script language [5][8] for the implementation according to the model described. To make it run faster the black boxes of the calibration modules were implemented in C++.

We found that it was not good trying to calibrate all parameters at once unless the calibration from the start is acceptable. In our tests the minimiser only finds local minima with quite large errors if we do this. This results in some very bad calibrations. We found that the best calibration was acquired by first calibrating only the haptics device (transformation between encoder angles and world coordinates) and not change the OpenGL parameters. Most of the time this is enough since the

default standard OpenGL parameters provided with the Reachin Display are general enough. However to achieve a better calibration and get the sizes to match better we can use the new calibration as starting point and let the minimiser find a minimum from there. This usually results in the best calibrations.

If this strategy is used the result is good. We get a precision to within a few millimetres in the recommended work area of the haptics device. The precision outside this area is also good but differs a little depending on the sample set used. As a worst case the calibration can be off by a centimetre but this is usually in the extreme positions of the haptics device and does not really matter since it should not be used in these positions anyway. To get a good calibration at least 5 correction samples are needed. Any less than that the calibration is fine at the sample points but is poor in the space between them. It is also important to have the samples spread out to cover as much as possible of the work area, otherwise the calibration could get bad in the area without any sample.

7. Discussion and conclusions

The simple calibration utility makes it easy to make individual calibration files for each user of the device. This is preferred to having a general calibration for all users. The problem of not having individual calibrations is that if, for example, two people of different heights were to use the display they would have a different distance from the eyes to the mirror and hence the same calibration would appear different for each of them. To make it work they both have to have their head in the same position and have the same inter-ocular distance, which will mean that at least one of the users will experience poor calibration.

The calibration can never be better than the sample set given to the calibration routine. Since these samples are based on a user's visual experience there is bound to be errors while specifying the samples. It is impossible to get the samples exactly right and hence the calibration will always have this extra error measure which it cannot compensate for. The calibration will always be adversely affected by any poor samples given by the user.

Currently the biggest problem is finding a global minimum in the presence of many local minima. The current strategy of randomly restarting minimisation sometimes results in slow performance that does not always find the global minimum. In future we intend to explore alternative minimisation routines that are better able to cope with these types of functions. Nevertheless the performance of the current system is satisfactory for our purposes since calibration only needs to be performed occasionally but should be as accurate as possible.

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A Method to Compute the Interaction Force during Imposed Motions

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Abstract

We present a method to compute the interaction force during an imposed movement. First, we show how to incorporate a kinematic constraint into the equation of motion of a simple but realistic model of the arm. Second, we apply this method to predict the interaction force during an imposed movement of the arm. The results of these simulations are compared to the interaction force recorded when a robot moved the hand of blindfolded subjects according to a predetermined trajectory. The most salient characteristics of the interaction force could be reproduced by assuming that the subjects supported the weight of their arm without attempting to anticipate or resist the imposed movement.

1. Introduction

While the subject of compliant motion has generated a huge literature in robotics [1,2], remarkably little is known about how humans control their movements when they must comply with an external constraint. In addition, most of the studies with human subjects dealt only with passive external constraints such as a rigid surface [3]. For example, McIntyre et al. [4] examined whether subjects monitored the force through sensory feedback or relied on the compliant properties of the arm to slide a hand along a rigid surface. In contrast, our study focuses on the interaction force arising during an *imposed* movement of the arm. Such movements occur when two humans shake hands together or when robots are used in the rehabilitation of stroke patients [5].

The interaction force in such a situation depends on three factors at least: the kinematic characteristics of the imposed motion, the mechanical properties of the arm, and the activity of the subject (e.g. reflex or voluntary contraction of the muscles anticipating or resisting the imposed motion). The main objective of this paper is to describe a method to assess the relative importance of these factors in the interaction force.

In the Methods, we show how to incorporate a kinematic constraint on the hand position into the equation of motion of a simple but realistic model of the arm to predict the interaction force during an imposed movement. We also describe a procedure to correct errors during the integration
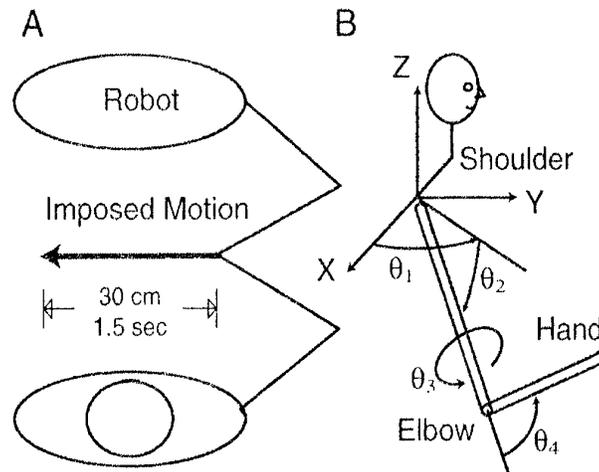
Figure 1. *A*: A schematic view of the hand movement imposed by the robot. *B*: Depiction of the four degrees of freedom of the arm model used in the simulations (θ_1: elbow azimuth, θ_2: elbow elevation, θ_3: humeral rotation, θ_4: elbow flexion).

which may cause the simulations to diverge from the constraint over a long period of time. In the Results, we apply this method to predict the interaction force under two different hypotheses about the activity of the subjects during an imposed motion. The results of these simulations are compared to the interaction force recorded while a robot moved the hand of blindfolded subjects (Fig. 1A). Finally, we briefly discuss what these preliminary results suggest about the activity of the subjects in this task.

2. Methods

The Arm Model. The arm was modeled as two connected cylindric bodies (Fig. 1B). The first body (upper arm) was connected to the torso by a spherical joint (shoulder) with three degrees of freedom (elbow azimuth, elbow elevation and humeral rotation). The second body (forearm) was connected to the first one by a hinge (elbow) joint with one degree of freedom (elbow flexion).

The equation of the motion of the arm model is:

$$F(\theta,\dot{\theta},t) + L(\theta,\dot{\theta},t) + G(\theta) = M(\theta)\ddot{\theta} + B(\theta)\dot{\theta}\dot{\theta} + C(\theta)\dot{\theta}^2 \tag{1}$$

where $\theta = [\theta_1\ \theta_2\ \theta_3\ \theta_4]^T$, $\dot{\theta} = [\dot{\theta}_1\ \dot{\theta}_2\ \dot{\theta}_3\ \dot{\theta}_4]^T$ and $\ddot{\theta} = [\ddot{\theta}_1\ \ddot{\theta}_2\ \ddot{\theta}_3\ \ddot{\theta}_4]^T$ are the joint angles, joint velocities and joint accelerations,

respectively. Terms on the left side of the equation define the torques acting on the system: $G(\theta)$ is the four dimensional vector of torques defining the effect of gravity at the joints, $L(\theta,\dot\theta,t)$ is a 4x1 vector of torques defining the force applied by the robot to the hand to keep it on the predefined trajectory, and $F(\theta,\dot\theta,t)$ is the 4x1 vector defining all other torques acting at the joints. The last term includes the friction and elastic torques resulting from the viscoelastic properties of muscle, as well as the active torques (i.e. those due to reflex and voluntary muscle contractions). This term must be specified to test specific hypotheses about how the arm is controlled during the locating phase. The terms on the right side of the equation describe the torques related to the motion of the system: $M(\theta)$ is the 4x4 inertia tensor (or mass matrix), $B(\theta)$ is the 4x6 matrix of Coriolis coefficients ($\dot\theta\dot\theta = [\dot\theta_1\dot\theta_2 \ \dot\theta_1\dot\theta_3 \ \dot\theta_1\dot\theta_4 \ \dot\theta_2\dot\theta_3 \ \dot\theta_2\dot\theta_4 \ \dot\theta_3\dot\theta_4]^T$), $C(\theta)$ is the 4x4 matrix of centripetal coefficients ($\dot\theta^2 = [\dot\theta_1^2 \ \dot\theta_2^2 \ \dot\theta_3^2 \ \dot\theta_4^2]^T$). The Coriolis and centripetal terms must be added to the equation because the frames of reference associated with the coordinates (joint angles) used in the model are not Newtonian. Explicit expressions for these matrices can be computed with standard methods [6]. Because they are cumbersome, we do not report them here, but they may be obtained from the author upon request.

The joint angles θ must satisfy the functional endpoint constraint:

$$P(\theta(t)) - T(t) = 0 \qquad (2)$$

where $P(\theta(t))$ is the hand position as a function of the joint angles and $T(t)$ is the hand position imposed by the robot. Because the constraint holds for all values of t, it holds also for all derivatives of $T(t)$. The first time derivative of the constraint is:

$$\frac{d}{dt}\{P(\theta) - T(t)\} = \frac{\partial P(\theta)}{\partial \theta}\dot\theta - \dot T(t)$$
$$= J(\theta)\dot\theta - \dot T(t) = 0 \qquad (3)$$

where $J(\theta)$ is the 3 by 4 Jacobian matrix:

$$J(\theta) = \begin{bmatrix} \frac{\partial P_x}{\partial \theta_1} & .. & \frac{\partial P_x}{\partial \theta_4} \\ .. & .. & .. \\ \frac{\partial P_z}{\partial \theta_1} & .. & \frac{\partial P_z}{\partial \theta_4} \end{bmatrix} \qquad (4)$$

Computing the second derivative of the constraint yields:

$$\frac{d^2}{dt^2}\{P(\theta) - T(t)\} = \frac{d}{dt}\left\{\frac{\partial P(\theta)}{\partial \theta}\dot\theta - \dot T(t)\right\}$$
$$= \frac{\partial P(\theta)}{\partial \theta}\ddot\theta + \frac{\partial^2 P(\theta)}{\partial \theta_i \partial \theta_j}[\dot\theta_i\dot\theta_j] - \ddot T(t) \qquad (5)$$
$$= J(\theta)\ddot\theta + H(\theta,\dot\theta) - \ddot T(t) = 0$$

where

$$H(\theta,\dot\theta) = \begin{bmatrix} \dot\theta^T H_x(\theta)\dot\theta \\ \dot\theta^T H_y(\theta)\dot\theta \\ \dot\theta^T H_z(\theta)\dot\theta \end{bmatrix} \qquad (6)$$

and $H_x(\theta)$, $H_y(\theta)$ and $H_z(\theta)$ are the Hessian matrices:

$$H_x(\theta) = \begin{bmatrix} \frac{\partial^2 P_x}{\partial \theta_1 \partial \theta_1} & .. & \frac{\partial^2 P_x}{\partial \theta_1 \partial \theta_4} \\ .. & .. & .. \\ \frac{\partial^2 P_x}{\partial \theta_4 \partial \theta_1} & .. & \frac{\partial^2 P_x}{\partial \theta_4 \partial \theta_4} \end{bmatrix} \qquad (7)$$

The equation of motion together with the above constraint defines a differential-algebraic problem [7]. This problem can be solved by using the constraint to calculate the value of the unknown term $L(\theta,\dot\theta,t)$ in the equation of motion. First, the equation of motion is rewritten as:

$$M(\theta)\ddot\theta = Q(\theta,\dot\theta) + L(\theta,\dot\theta,t) \qquad (8)$$

where $Q(\theta,\dot\theta)$ is the four dimensional vector:

$$Q(\theta,\dot\theta) = -B(\theta)[\dot\theta\dot\theta] - C(\theta)[\dot\theta^2] + G(\theta) + F(\theta,\dot\theta,t) \qquad (9)$$

and $L(\theta,\dot\theta,t)$ is the vector of torques defined by:

$$L(\theta,\dot\theta,t) = J^T(\theta)\lambda(\theta,\dot\theta,t) \qquad (10)$$

where $J^T(\theta)$ is the transpose of the Jacobian matrix and $\lambda(\theta,\dot\theta,t)$ is a three dimensional vector representing the unknown force that the robot must exert to maintain the hand on the predetermined trajectory (see later). Then, the value of $\lambda(\theta,\dot\theta,t)$ can be found by solving equation (8) for $\ddot\theta$:

$$\ddot\theta = M^{-1}(\theta)\left\{Q(\theta,\dot\theta) + J^T(\theta)\lambda(\theta,\dot\theta,t)\right\} \qquad (11)$$

Substituting this expression in equation (5) (i.e., the second time derivative of the constraint) yields:

$$J(\theta)M^{-1}(\theta)\left\{Q(\theta,\dot\theta) + J^T(\theta)\lambda(\theta,\dot\theta,t)\right\} + H(\theta,\dot\theta) - \ddot T(t) = 0 \qquad (12)$$

If the 3 by 3 matrix $J(\theta)M^{-1}(\theta)J^T(\theta)$ is invertible, $\lambda(\theta,\dot\theta,t)$ can be computed:

$$\lambda(\theta,\dot\theta,t) = [J(\theta)M^{-1}(\theta)J^T(\theta)]^{-1}$$
$$\left\{-J(\theta)M^{-1}(\theta)Q(\theta,\dot\theta) - H(\theta,\dot\theta) + \ddot T(t)\right\} \qquad (13)$$

and substituted into equation (10) to yield an ordinary second order differential equation:

$$\ddot\theta = M^{-1}(\theta)\left\{Q(\theta,\dot\theta) + J^T(\theta)[J(\theta)M^{-1}(\theta)J^T(\theta)]^{-1}\right.$$
$$\left. -J(\theta)M^{-1}(\theta)Q(\theta,\dot\theta) - H(\theta,\dot\theta) + \ddot T\right\} \qquad (14)$$

Numerical integration. To integrate equation (14), we used an algorithm described in [8] which is an implementation with step size control and dense output of an explicit Runge-Kutta method of order 5. Because rounding errors may lead the solution to diverge from the constraint, we also followed a stabilizing strategy which consisted in projecting the joint angles and velocities obtained at each integration step onto the subspace defined by the constraint [7].

Let us assume that the joint angles θ_0 at the end of an integration step do not satisfy the constraint. The problem is to find another set of joint angles θ that minimizes the distance:

$$\frac{1}{2}\|M(\theta_0)(\theta - \theta_0)\|^2 \qquad (15)$$

(the matrix $M(\theta_0)$ is not necessary but it modifies the norm in a way that makes sense in this context) under the same

endpoint constraint:

$$P(\theta(t)) - T(t) = 0 \tag{16}$$

By differentiating equation (15) with respect to θ and using the method of Lagrange's multipliers, we obtain the following $F(\theta,\mu)$ system of equations:

$$F(\theta,\mu) = \begin{bmatrix} M(\theta_0)(\theta - \theta_0) - J^T(\theta_0)\mu \\ P(\theta) - T(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{17}$$

Because the forward kinematics operator $P(\theta)$ is nonlinear, the system cannot be solved directly. The solution can be found by using Newtons's iterative method, by repeating the following two steps. In the first step, the following linear system is solved using a standard method (e.g. LU decomposition with back-substitution):

$$\nabla F(\theta_k,\mu_k)\begin{bmatrix} d\theta_k \\ d\mu_k \end{bmatrix} = \begin{bmatrix} M(\theta_0) & J^T(\theta_0) \\ J(0) & 0 \end{bmatrix}\begin{bmatrix} d\theta_k \\ d\mu_k \end{bmatrix} = -F(\theta_k,\mu_k) \tag{18}$$

where $\nabla F(\theta_k,\mu_k)$ is the gradient of $F(\theta,\mu)$. In the second step, the new values for the joint angles and Lagrange multipliers are found by computing

$$\begin{bmatrix} \theta_{k+1} \\ \mu_{k+1} \end{bmatrix} = \begin{bmatrix} d\theta_k \\ d\mu_k \end{bmatrix} + \begin{bmatrix} \theta_k \\ \mu_k \end{bmatrix} \tag{19}$$

If the initial values $[d\theta_0, d\mu_0]$ are not too far away from the solution, the method converges rapidly (the number of iterations was set to ten with initial values $[d\theta_0, d\mu_0] = [\theta_0, 0]$).

The joint angle velocities are dealt with in a similar fashion. Let θ be the new joint angles computed above, and let $\dot\theta_0$ be the joint angle velocities obtained at the end of an integration step. Then the problem is to find the joint angle velocities that minimize:

$$\frac{1}{2}\|M(\theta)(\dot\theta - \dot\theta_0)\|^2 \tag{20}$$

while satisfying the first time-derivative of the constraint:

$$J(\theta)\dot\theta - \dot T(t) = 0 \tag{21}$$

The following system is obtained by differentiating equation (20) with respect to $\dot\theta$ and using again Lagrange's multipliers method:

$$\begin{bmatrix} M(\theta)(\dot\theta - \dot\theta_0) + J^T(\theta)\mu \\ J(\theta)\dot\theta - \dot T(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} M(\theta) & J^T(\theta) \\ J(\theta) & 0 \end{bmatrix}\begin{bmatrix} \dot\theta \\ \mu \end{bmatrix} = \begin{bmatrix} M(\theta)\dot\theta_0 \\ \dot T(t) \end{bmatrix} \tag{23}$$

This system is linear in respect with $\dot\theta$ and μ :and can be easily solved by standard methods.

The interaction force. Finally, we show that the three-dimensional vector $\lambda(\theta,\dot\theta,t)$ has a straightforward interpretation in terms of the interaction force. In vectorial notation, the work is the dot product between the force and displacement vectors. Because the work (energy) required to maintain the hand on the trajectory must be the same when computed in different coordinate systems [6], we have:

$$F^T\delta x = \tau^T\delta\theta \tag{24}$$

where δx is an infinitesimal displacement of the hand in space, $\delta\theta$ is the corresponding displacement in joint space, F is the force applied by the robot to the hand, and $\tau = L(\theta,\dot\theta,t) = J^T(\theta)\lambda(\theta,\dot\theta,t)$ is the torque component added to the equation of motion to account for the endpoint constraint (equation 10). By definition, the Jacobian $J = \delta x/\delta\theta$ relates joint velocity to and cartesian velocity. Thus, substituting $\delta x = J\delta\theta$ and $\tau = J^T(\theta)\lambda(\theta,\dot\theta,t)$ in equation (24) and simplifying yields:

$$F = J^{-T}\tau = J^{-T}L(\theta,\dot\theta,t) = J^{-T}J^T\lambda(\theta,\dot\theta,t) = \lambda(\theta,\dot\theta,t) \tag{25}$$

where J^{-T} is the pseudo-inverse of the transpose of the Jacobian. Thus, $\lambda(\theta,\dot\theta,t)$ is the force applied by the robot to the hand to maintain it on the predefined trajectory and, by Newton's Third Law, $-\lambda(\theta,\dot\theta,t)$ is the force applied by the hand to the extremity of the robotic arm.

Experimental procedure. We recorded the interaction force for ten blindfolded subjects while a robot (MANUTEC R15, Siemens) moved their hand laterally, from the right to the left (Figure 1.A). These data were recorded as a part of a series of experiments on pointing movements toward kinesthetic targets [9]. Subjects were instructed to let the robot guide their hand to some position in space which they should memorize. The velocity profile of the imposed motion was either lognormal, gaussian or inverted lognormal (Figure 2.A). All movements lasted 1.5 s and were 30-cm long. The interaction force was recorded by a six degrees of freedom force transducer (Mini 40, ATI) mounted below the handle grasped by the subjects at the extremity of the high impedance robotic arm.

3. Results

In this section, we briefly show the results of some simulations and compare them to experimental data. Figure 2.B shows the interaction force for each velocity profile, averaged across participants. The magnitude and orientation of the interaction force varied considerably during the movement. For the lognormal velocity profile, the magnitude of the force was maximum at the beginning of the movement while the opposite was true for the inverted lognormal velocity profile. Force variations during the movement are less obvious for the gaussian velocity profile, partly because their magnitude is small. The shoulder and elbow positions were not recorded. Thus, the comparison between simulated behavior and data will concern mainly the interaction force.

In the simulations, the length, diameter and mass of the two cylinders modeling the upper- and forearm were 30 cm, 4cm, 1.43 kg and 34cm, 3 cm, and 1.32 kg respectively. The initial hand position was 40 cm in front of and 25 cm below the shoulder. In the first set of simulations, we assumed no other forces than those directly related to the inertial properties of the arm. Thus, we set

$$F(\theta,\dot\theta,t) = 0 \tag{26}$$

A   Velocity Profile


B   Data

E   Simulation

F   ForceMagnitude
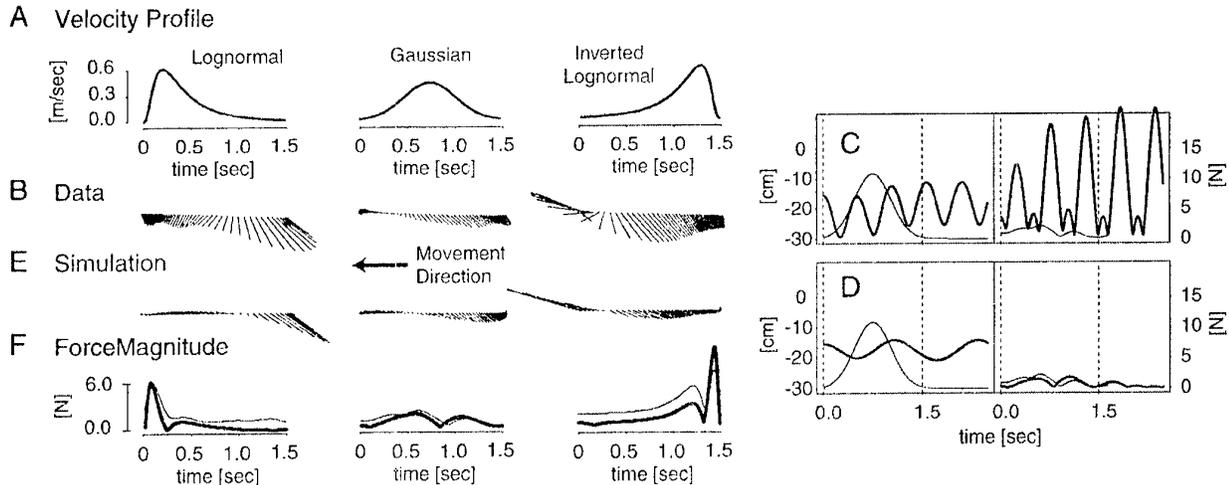
Figure 2. *A*: Velocity profiles of the imposed motions. *B*: Interaction forces during the imposed motions. The origins of the short lines indicate the position of the hand every 20 ms. The direction and length of these lines denote the orientation and magnitude of the interaction force at the same instant in time. *C*: Simulation of the arm movement and interaction force in the gaussian velocity profile condition. *Left panel*: Elbow position relative to the shoulder along the vertical axis (*thick line*) and hand velocity (*thin line*). *Right Panel*: Predicted (*thick line*) and average (*thin line*) interaction force. *D*: Simulations with the weight of the arm supported by the deltoid (same format as 2.C). *E*: Predicted interaction force for the three velocity profiles (same format as 2.B). *F*: Magnitude of the predicted (thick line) and actual (thin line) interaction force.

in Equation (3). The left panel of Figure 2.C shows the time course of the predicted elbow height (thick line), and of the hand velocity (thin line) in the gaussian velocity profile condition. The right panel contrasts the predicted (thick line) and actual (thin line) magnitude of the interaction force. The simulation was extended to 2.5 s to visualize the behavior of the arm after the end of the movement. Under the sole influence of gravity, the elbow swung like a pendulum even after the end of the movement because there was no damping in the system. The oscillations in the interaction force reflect the swinging motion of the elbow.

Because this behavior is totally unrealistic, we assumed in the next set of simulations that the subjects actively supported the weight of their arm to counteract the effect of gravity. The parametrization of the joint angles in our model afforded a simple way of adding an elastic force to keep the elbow elevated:

$$F(\theta,\dot{\theta},t) = K_g \begin{bmatrix} 0 \\ \pi/2 - \theta_2 \\ 0 \\ 0 \end{bmatrix} \quad (27)$$

where K_g = 1.565 Nm/rad. The value of K_g did not change throughout the movement and was adjusted so that the elbow would not depart from its initial position if the hand remained immobile at the center of the workspace. This elastic force may be thought of as a very simple model of the deltoid muscle. Figure 2.D shows that the simulations were much more satisfactory. Although some residual oscillations of the elbow remained because the system was not dampened, the predicted force matched the actual force much better. Figure 2.E shows that the predicted interaction forces for the three velocity profiles are remarkably similar to the data (compare with Figure 2.B). Finally, Figure 2.F compares the time course of the magnitude of the predicted

and actual interaction force. The actual vs. predicted peaks of the force magnitude were 5.4 vs.6.1 N, 2.0 vs 2.4 N, and 7.2 vs. 10.2 N for the lognormal, gaussian and inverted lognormal velocity profiles respectively. For both asymmetric profiles, the timing of the large peak of force was well predicted (the coefficients of correlation between the time-courses of the actual and predicted force magnitudes were .87, .77, and .92 for the lognormal, gaussian and inverted lognormal velocity profile respectively).

4. Discussion

In summary, we presented a method to predict the interaction force when the hand is constrained to follow a predetermined trajectory with a specific velocity profile. This mathematical tool was used to analyze the actual dynamic behavior of the arm when the hand was moved by a robot.

We were able to reproduce the most salient features of the interaction force by assuming that an upward elastic torque supported the weight of the arm throughout the movement. Like the equilibrium point [10] and the virtual target hypotheses [11, 12], this scheme emphasizes the role of the muscles' elastic properties in addition to the inertial properties of the arm. Because the definition of this force makes no reference to either the final or current position of the hand, these results suggest that the subjects did not try to anticipate the displacements of the hand

The magnitude of the interaction force was smallest when the imposed motion most resembled natural movements (gaussian velocity profile). However, such an observation cannot be interpreted as evidence that the subjects responded differently to natural vs unnatural stimuli since the predicted

Overview of the Delta Haptic Device

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Computing and machines keep getting more versatile, powerful and complex. This trend opens the door to a new level of interactivity between humans and computers. New applications bring together the human intelligence and the machine ability to carry complex tasks. The benefits of such symbiosis are safer, faster and more productive applications. However, fluent collaboration between man and machine require new tools that allow for a wider range of information to be exchanged. This encourages the development of force-feedback devices, which exploit the often under-estimated human sense of touch. This paper describes an overview of the Delta Haptic Device developed at the EPFL, which offers 6 active degree-of-freedom together with an outstanding mechanical behavior.

INTRODUCTION

The increasing need for enhanced human-computer interaction (HCI) is pushing for new interfaces that allow humans and machines to exchange a wider range of information. As a consequence, applications involving new interaction modalities such as machine vision and virtual reality are being developed. Among these new interfaces, haptic devices are promised a place of choice. Not only does haptic make difficult manipulation tasks possible or easier, it also opens the door to a wide range of new applications in the fields of simulation and assistance to human operators.

Numerous applications can benefit from haptic technology, ranging from teleoperation [2],[13] to nanomanipulation [6], as well as medical simulators and surgical aids [1]. Moreover, force-feedback devices are moving to the consumer market, and are invading the gaming industry as well as unexpected other areas such as automobile industry (BMW's new Z9 for instance).

The Virtual Reality and Active Interfaces (VRAI) Group at the Swiss Federal Institute of Technology (EPFL) is working on innovative haptic solutions combining state-of-the-art parallel mechanics with dedicated control electronics, which can be coupled with any application through a simple API.

RELATED RESEARCH

A significant research effort has been conducted towards the use of haptics in HCI ([5], [8], [11], [13]), or more specifically on what are the mechanical and control constraints that come into play when developing haptic devices ([7], [9], [10], [11], [14], [15]). A non exhaustive list that summarize some of the most important criterions in haptics is given below:

- the *mechanical system* should have low inertia, high stiffness with low friction (force threshold) and no backlash (mechanically induced force discontinuity).

- the force *actuators* should enable back-drivability, offer a high dynamic range, a sufficient maximum force, a sufficient force output resolution and a sufficient force and torque precision.

- the *position sensors* need to have a good position sensing resolution (depending on control loop refresh rate).

- *force sensors* should be added as close as possible to the human user. When well tuned, they greatly improve the overall system performance.

- the *local control loop* must have a high frequency (typically > 1kHz) to ensure (1) that vibrations are kept under a sensable level and (2) that control stability is achieved at the desired contact stiffness.

- the *global force interaction* low-frequency loop, typically linked to a graphical environment, needs to be as high as possible.

DEVICE DESCRIPTION

Our innovative high-end force-feedback system called the Delta Haptic Device meets the high standards required for industrial applications by combining high strength, high stiffness and high sensitivity. It is shown on Figure 1. This system is based on the patented Delta robotic structure [3], which provides three translational degree-of-freedom (DOFs). A dedicated mechanical wrist plug-in provides 3 rotational DOFs (shown in figure 1) and is based on the Paramat structure (figure 3). All of the DOFs are fully active and generate forces and torques that are way beyond the ability of currently available devices on the market. Dedicated electronics and signal processing provide the high-quality control required for credible force rendering. Figure 2 shows an overview of the control system.
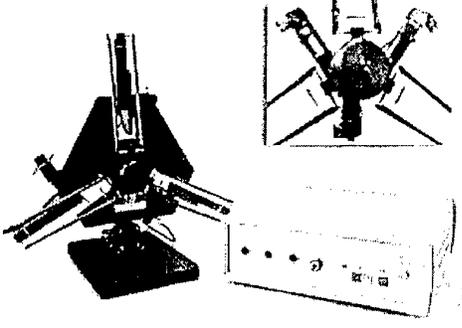
Figure 1: Delta Haptic Device

The overall performance of such a haptic system is closely related to how convincingly the human sense of touch can be tricked. There are many functional components in a generic haptic device, which contribute to the overall system quality. They can be split in two main groups: the mechanical elements as shown in figure 2, and the control elements, shown in figure 4.
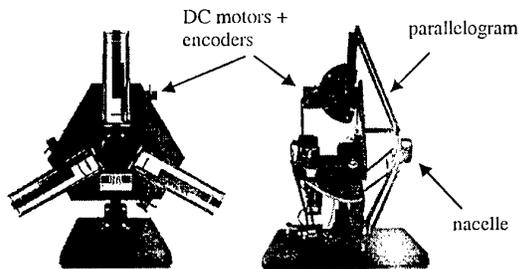
Figure 2: the DELTA structure
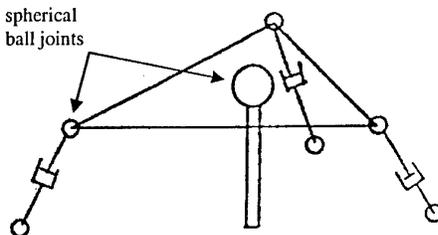
Figure 3 – the PARAMAT structure

The mechanical system displays very interesting properties, thanks to its parallel structure and robust components. The main advantages are:
- low inertia / light weight of the mobile parts
- high stiffness
- high force/torque
- large workspace
- no backlash

The design of our 6 DOFs system addresses most of the issues described above (see "Related Research"). The system specs are summarized in the following table:

TABLE I : system specs

Property	Value
workspace	cylinder Ø360mm x 200mm +/- 20° for each rotation
force torque	25N 0.2 Nm
resolution	< 0.1 mm (translation) < 0.04° (rotation)

The controller described in figure 4 is responsible for two tasks: communication with the PC, and low-level safety. Its main purpose is to command the motor amplifiers and transmit the device position back to the PC. However, since the forces generated by the Maxon motors can be significant, low-level security features have been introduced, namely:

- *check speed velocity* of the nacelle. If the speed goes beyond a given threshold, the controller cuts the power to the device motors and electromagnetic brakes are applied

- *check structure position limits*. If the nacelle is set to an extreme position nearing the structure limits, power to the motors is cut to avoid shocks
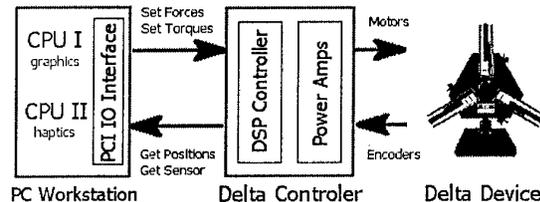
Figure 4: DHD control architecture overview

FUTURE WORK

We are currently working on integrating a force sensor into the nacelle of the Delta Haptic Device. The consequences of this modification are:
- lower friction/force
- lower inertia of the system

Preliminary results show a dramatic improvement of these characteristics.

Our research effort for the near future will lead to the development of plug-in haptic tools that will enhance the application range of the device. At the same time, the

haptic device will be integrated in a generic human-computer interaction solution involving virtual reality and environment sensing in real-time. Several partnerships are being conducted, and a spin-off company (www.forcedimension.com) is currently being created that will deal with the commercialization of the Delta Haptic Device.

CONCLUSION

We have developed an innovative haptic device called the Delta Haptic Device that combines a parallel mechanic structure with dedicated electronic and software. Our device has 6 degrees-of-freedom and its technical specifications are beyond currently available haptic devices, in particular as far as workspace, force and torques are concerned.

Our research effort for the near future will lead to the development of plug-in haptic tools that will enhance the application range of the device. At the same time, the haptic device will be integrated in a generic human-computer interaction solution involving virtual reality and environment sensing in real-time.

Several partnerships are being conducted, and a spin-off company is currently being created that will deal with the commercialization of the Delta Haptic Device.

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Selective attention and the perception of visual-haptic asynchrony

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Abstract

This paper demonstrates that the perceived simultaneity of a visual-haptic stimulus pair is influenced by selective attention. The results provide an explanation for the individual differences in the perceived simultaneity, as found in a previous study.

1. Introduction

Multimodal information is of great advantage in the daily perception and manipulation of our environment compared to information obtain through a single sensory modality. Because of this, it is often desirable to use multimodal displays in man-machine interaction. To benefit from multimodal displays, users must be able to experience a coherent perception of the (virtual) environment by integrating input from multiple modalities. One perceptual attribute that provides an important basis for intersensory integration is temporal synchrony. Synchronisation is, however, a well-known problem in multimodal interfaces. Due to physical and technical constraints, such as computer processing time, interface signals are often delayed with respect to each other and/or the action of the user. Asynchronous feedback can seriously disrupt many aspects of virtual environment simulations, e.g. it impedes the completion time of manipulation tasks (Ferrell, 1966). Knowledge about temporal sensitivities of the human perceptual system is therefore essential in the design of man-machine interfaces.

This research focuses on the sensitivity of human observers to time delays between visual and haptic stimuli. In a previous study (Vogels, 2001) we measured how large the temporal delay between visual and haptic stimuli may be before participants start noticing that the stimuli are asynchronous. Participants moved a force-feedback joystick such that a graphical object on a monitor would hit a virtual wall. The collision of the object with the wall was felt through the joystick, which generated a counter force slightly before, after or at the moment of collision. The maximum visual-haptic delay that participants tolerated was on average 45 ms. The range in which stimuli were judged to be synchronous was centered around a visual delay of about 7 ms. However, this so called point of subjective simultaneity (PSS) was liable to individual differences.

It was suggested that one of the factors that might play a role in the variability of the PSS is the way in which participants divide their attention between the two modalities. Researchers have shown that manipulating the attention of the participant can influence the perception of simultaneity. The stimulus cued by the experimenter is usually perceived earlier. This effect has been shown for stimuli presented to the auditory and tactile modalities (Stone, 1926), stimuli presented within the auditory modality (Needham, 1936) and stimuli presented within the visual modality (e.g. Stelmach and Herdman, 1991). However, some studies failed to find an effect of attention (Cairney, 1975; Jaskowski, 1993) and claimed that the shift in the PSS was an effect of response bias rather than attention. Spence and Driver (1997) showed some appropriate methods for distinguishing attention from other confounding factors.

In this research the influence of attention to one modality on the perceived simultaneity of visual-haptic stimuli was studied. In order to assess whether participants were indeed directing their attention to the cued modality, we used a reaction time procedure. On each trial either a visual stimulus, a haptic stimulus or

an asynchronous visual-haptic stimulus pair could be presented. When one stimulus was presented participants were required to make a discrimination response regarding the modality of the stimulus. When both stimuli were presented participants were required to make a temporal order judgement. Attention was manipulated on each trial by presenting a cue that predicted which modality would be presented or which modality would be presented first. To ascertain that a possible effect of cue on temporal order judgement was due to attention and not to a criterion shift, we tested whether participants reacted faster on validly cued trials than on invalid trials without being less accurate.

2. The experiment

This experiment investigated the influence of selective attention to one modality on the perception of visual-haptic asynchronies.

2.1. Participants

Participants were eight students, which were being paid for their participation. The mean age was 20 years. All participants were right handed.

2.2 Procedure

Participants were seated behind a computer screen and held a force-feedback joystick (SideWinder Force Feedback Pro) in their right hand. Participants were instructed to focus on a fixation cross on the middle of the screen. At the beginning of a trial an arrow was displayed for 2.0 s. After an empty time interval of 1.0 to 1.5 s a stimulus or stimulus pair was presented. The stimulus could be a black square of 20 pixels wide on the middle of the screen or a counter force of 5.5 N generated by the joystick. When both stimuli were presented they were separated by a delay that ranged from –240 ms to 240 ms. The delay was defined to be negative when the visual stimulus was delayed and positive when the haptic stimulus was delayed. Participants were asked to respond as soon as possible by pressing a key that corresponded to the modality that was presented or the modality that was presented first.

The arrow at the beginning of the trial predicted which modality would be presented or which modality would be presented first. An upward arrow pointing to the fixation cross corresponded to the visual modality and an arrow pointing to the right, where the joystick was located, corresponded to the haptic modality.

Participants were instructed to direct their attention to the cued modality.

The experiment actually consisted of two types of trials: reaction time trials (RT) in which one stimulus was presented and temporal order trials (TOJ) in which two stimuli were presented. In the RT condition the two within-subjects factors were stimulus modality (visual or haptic) and cue validity (valid or invalid). There were 224 (70%) valid trials, where the stimulus modality was correctly predicted by the cue, and 96 (30%) invalid trials. Cue validity was the same for both modalities, which were presented equally often. In the TOJ condition the within-subjects factor was cue modality. There were 160 trials with a visual cue and 160 trials with a haptic cue. In each cue condition 16 different delays were presented, 10 times each.

Participants had a lot of practice before the experiment started. They also participated in a control experiment in which only 160 TOJ trials were presented without the cue. This experiment severed as a baseline for the perception of temporal order.

3. Results

We first analyse the RT data to determine whether participants were able to focus their attention to the cued modality. Trials on which an incorrect response occurred were discarded from the analysis. In addition, trials on which the RT differed more than 3 standard deviations from the mean RT were removed. These criteria removed less than 4% of the data. Mean RTs are shown in Table 1. We performed an ANOVA on the RT with stimulus modality and cue validity as within-subjects factors. There was a significant main effect of stimulus modality ($F_{1,7}=11.47$, p=0.012), with participants responding more rapidly to the haptic stimulus (M=361 ms) than to the visual stimulus (M=414 ms). The effect of cue validity was also significant ($F_{1,7}=9.38$, p=0.018), with participants responding more rapidly on validly cued trials (M=362 ms) than on invalid trials (M=413 ms). The interaction effect was not significant. When the data for each participant was analysed separately, two participants did not reveal an effect of validity. Therefore, these participants were not included in the following analysis

Table 1: Mean reaction time (in ms) and the standard error for the visual stimulus and the haptic stimulus.

| Target modality | Cue validity | | | |
| | Valid | | Invalid | |
	Mean	SE	Mean	SE
Visual	391	52	437	36
Haptic	332	39	391	33

The TOJ data was plotted as in Figure 1 and fitted with a psychometric function to determine the offset of the curve, i.e. the delay at which the percentage 'visual first' and 'haptic first' are equal. This delay is called 'point of subjective simultaneity' (PSS). We performed an ANOVA on the PSS with cue modality as the within-subjects factor. The effect of cue modality was highly significant ($F_{1,5}=47.7$, $p<0.001$). The mean PSS was –59 ms for the visual cue and 52 ms for the haptic cue. We also compared the PSS values with those obtained in the control experiment. The mean PSS in the absence of a cue was 35 ms and differed significantly from the PSS with a visual cue ($F_{1,5}=29.5$, $p<0.003$) and with a haptic cue ($F_{1,5}=35.4$, $p<0.002$). The PSS values for each participant are shown in Figure 2.

Figure 2: The PSS for each participant in the case of a visual cue (black), no cue (grey) or a haptic cue (white).

Because the visual and haptic stimuli were not presented at the same spatial location, it is impossible to determine whether the effect was due to spatial attention or to attention to one modality. The RT data, however, demonstrated that the shift in the PSS was really an effect of attention. If, for instance, participants had lowered their criterion for the cued modality, they would have made more erroneous responses on trial with an invalid cue.

The results provide an explanation for the individual differences in the perceived simultaneity, as found by Vogels (2001). When participants do not receive any instructions about their attention, they divide their attention between the two modalities in their own preferred way.


Figure 1: The TOJ data for one participant. The proportion responses "visual first" is plotted against the delay between the visual and haptic stimulus. The modality of the cue was visual (triangles) or haptic (circles). The data was fitted with a psychometric function (dark line).

4. Discussion

The results of this experiment clearly show that the perceived simultaneity of visual-haptic stimuli is influenced by selective attention. The PSS shifted towards visual delays when participants directed their attention to the visual stimulus and towards haptic delays when participants directed their attention to the haptic stimulus. This means that if the visual and haptic stimuli were presented simultaneously, participants would perceive the stimulus to which they were attending as occurring earlier.

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The Role of Haptic Feedback in the Training and Assessment of Surgeons using a Virtual Environment

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Abstract

Haptic feedback plays an important role in the development of high fidelity virtual training environments for surgeons. The coupling of virtual simulation environments with instrumented data collection methods would allow quantification of performance. This work demonstrates the use of such a system to achieve quantitative evaluation of suturing performance. Force application, time to task completion, length and straightness of the suture have been measured. The paper concludes that performance improved over trials in terms of time to complete and accuracy of the length of suturing. Force feedback affected force application, task completion time and the straightness of suturing.

1. Introduction

There is increasing interest in the development of virtual reality (VR) systems for the training of surgeons. VR offers many benefits to training. These include a reduction in costs and associated patient risk, flexible access to training material and the possibility of self-paced learning [1][2]. The trainee is able to develop surgical skills to a proficient level before transferring them into the operating theatre. The fidelity of the VR simulation is crucial to ensure that skills transfer effectively.

Strong sensory feedback is an important requirement for realistic surgical simulation [3]. Current systems vary in the quality of the visual and tactile information provided to the user. This is due to the many technical challenges to ensure accuracy [4][5].

The ability to identify tissue properties and apply the appropriate handling technique is an important skill for the trainee to acquire [6]. A realistic simulation should provide the user with force feedback in order for the surgeon to be able to detect tissue components. These forces are small and exact, while difficult to recreate [3].

Similarly, in order to produce virtual tissue, knowledge is required of real tissue properties and their respective handling forces. Methods to collect force application data therefore are required. [7].

SensAble's PHANToM desktop device has been incorporated into many current simulation designs [8][9]. It provides the user with force feedback when virtual objects are manipulated.

Using the PHANToM, this paper aims to demonstrate the effect of force feedback information on performing a basic surgical task. The effect of feedback is then related to force application and improvement of the task.

2. Method

2.1 Participants

Twenty students took part in the experiment. They had an average age of twenty -five years (range eighteen to forty-five). They were all right hand dominant. Each undertook a total of ten trials.

2.2 Equipment

For the experimental setting, the SensAble PHANToM desktop unit [10], run in Windows NT 4.0, was utilised in conjunction with a suturing simulation [11]. The device provides resistance to the users movements with 3

degrees of freedom force feedback and 6 degrees of freedom position sensing.
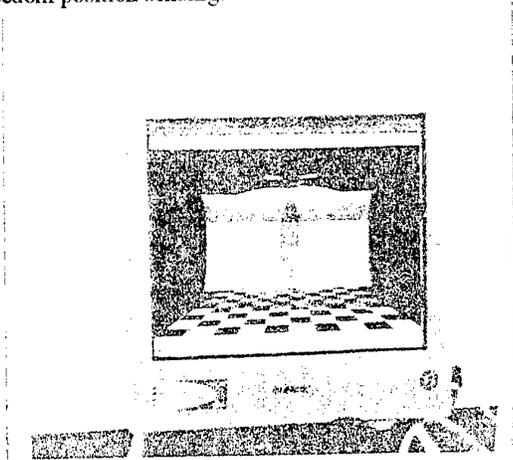
Figure 1: The display of the suturing simulation.

The suturing simulation consisted of a virtual wound, needle holders and needle and thread. Sutures could be placed in the skin excision. The tissues deformed in a manner similar to actual tissue, when pressure was applied. Force feedback was provided to the user through the haptic end-effector of the SensAble PHANToM device.
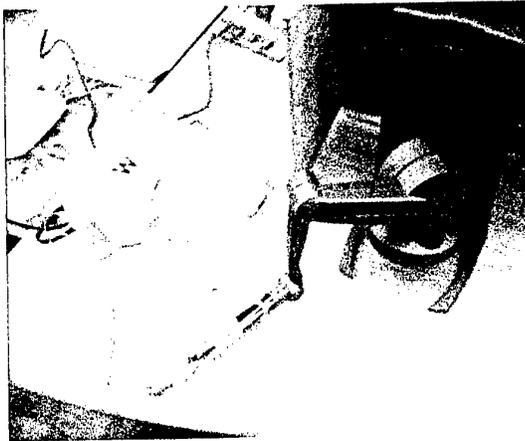
Figure 2: The experimental setting: the needle-holders attached to the SensAble PHANToM device.

A pair of needle holders was loosely attached to the end-effector. As a consequence, they moved in correspondence to the virtual instruments. The needle holders were instrumented with strain gauges to allow measurement of the forces applied during their manipulation. This data was fed directly into Microsoft Excel, to be further formatted for statistical manipulation.

2.3 Procedure

The task was demonstrated and explained to each subject by the experimenter. Each participant then performed two test sutures to familiarise themselves with the task and the experimental setting.

The participants were asked to form one suture across the skin excision. It was specified that the point of needle insertion should be approximately 2cm off the edge of the excision. This point was marked on the simulation. Once the suture had been formed the thread was pulled tight to bring the skin edges together with minimum overlap and tissue distortion. The target requirement was a 4 cm straight stitch.

Data collection began at the first movement of the needle by the participant. Time was measured automatically. The Daz Wizard program was initiated concurrently to allow the force measurement from the needle-holders. After each trial the resulting stitch was projected and traced onto acetate.

Each participant completed 10 trials. In each, a full suture procedure was formed in a clear wound. The experimental time allowed for each trial was limited to 40 seconds. The participants were assigned to one of two conditions. For the first the PHANToM device provided force feedback to the user and for the second force feedback was not applied.

3. Results

The results were analysed to determine the effect of force feedback on task performance. The effect of trial was further analysed to investigate how performance changed over time.

3.1 Effect of trial

A paired sample t-test revealed that over the trials the time to complete a stitch was significantly reduced (p=0.01). There was a significant change in the length of the stitches (p=0.04). The other measures were unaffected by trial. Detailed measurements for trial 1 and

10, in relation to their average (overall), can be seen in table 1.

Condition	Trial	Time (s)		Force (N)		Length (cm)		Straightness score	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Force Feedback provided	1	28.24	12.87	5.59	2.36	2.19	1.49	4.6	1.96
	10	10.89	1.98	5.76	2.01	2.92	0.74	5.4	0.7
	Overall	20.17	12.48	5.67	2.14	2.52	1.19	5	1.49
Force Feedback withheld	1	22.79	9.74	3.94	1.58	2.27	1.39	4.6	1.84
	10	18.98	11.65	4.38	2.19	3.39	1.48	5.7	0.67
	Overall	20.53	10.49	4.16	1.87	2.8	1.47	5.15	1.46

Table 1: Effect of trial and condition.

3.2 Effect of condition

An independent samples t-test revealed that the presence of force feedback significantly affected the force applied during suture production (p=0.021). A greater level of force was applied when the feedback was activated. The time to complete the stitch was affected by the presence of force feedback (p=0.048). Feedback resulted in an overall reduction of stitch completion time. Using the Mann-Whitney test, straightness was affected by feedback (p=0.018). With feedback higher scores for straightness were achieved.

4. Discussion and conclusions

Performance has been shown to improve over trials. This is shown by a reduction in the time to complete and improved accuracy of the length of the stitch.

To increase the realism of surgical simulations, force feedback should be provided during manipulation of virtual tissue. The results indicate that force application increases as does time to complete, with the provision of force feedback. This would be expected in order to overcome the haptic effects. The affect on force application demonstrates the importance of accurate haptic feedback. Virtual tissues should respond appropriately to allow anticipation of real tissue behaviour and for skills transfer to take place. Future work should demonstrate how force application is affected by variations in the level of the force feedback.

The importance of collecting force application data for task performance has been demonstrated. This information has been derived through instrumented collection of data in a simulation environment. The advantage of an external method of instrumented data collection is its transferability between the operating theatre and simulated models. Determining the appropriate levels of force application for particular tissues provides a means of assessing the validity of a simulation, enables provision of feedback during training and supports the establishment of benchmark levels for assessment.

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Haptic Assistance to Improve Computer Access for Motion-Impaired Users

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Abstract

This paper describes a pilot experiment which examines the effectiveness of using force-feedback technology to assist motion-impaired computer users in target selection tasks. Two measures to evaluate the effectiveness of force-feedback assistance are proposed. The radius of curvature of the cursor path and the cursor speed along the path can capture differences in cursor movements that might be lost in a single measure such as time to target. Experimental results indicate that force-feedback implemented as non-directional viscous damping has a beneficial effect for some, improving times to target by up to 50%. Future work includes developing other forms of haptic assistance, developing new measures for evaluation, and investigating the implications of kinaesthesic impairment.

1. Introduction

People with motion impairments have the same desire to use computers as able-bodied people [1], but the typical keyboard and mouse arrangement for computer interaction often presents difficulties. Consequently, there is a need to improve computer access, either by using entirely new modes of input or by augmenting existing ones. Focusing in the latter area, this paper describes a pilot experiment that examines the effectiveness of using haptic feedback to enhance human-computer interaction. In particular, this work investigates the use of a force-feedback pointing device as a means of assisting motion-impaired users in target selection tasks, and extends the work reported in [3].

To determine the effectiveness of various forms of haptic assistance, methods of performance evaluation are required. In other work, measures have been developed for the evaluation of different pointing devices [4]. For the current study, where the pointing device remains constant but the form of haptic assistance changes, these measures can also be applied. One of the most common is movement time. This method of evaluation, however, is based on a single measurement per trial, and although it may be able to establish that a difference exists,

determining the cause of the difference is more likely to be accomplished through analysis of cursor movement *throughout* the trial [4]. This paper describes two measures for characterising movement throughout a trial – the cursor velocity along the cursor path and the radius of curvature of the cursor path.

2. Method

A pilot study was performed to investigate the effectiveness of force-feedback technology as a means of assisting motion-impaired users in target selection tasks. Four volunteers were contacted through the Papworth Trust, a charitable organisation dedicated to the care of motion-impaired people. A description of each user is given in Table 1. All participants were familiar with computer and mouse use, as well as with the task to be completed. Force feedback was provided with a Logitech Wingman mouse.

Table 1. Computer users from the Papworth Trust

User	Description
PI3	Athetoid CP, spasm, wheelchair user
PI5	Athetoid CP, deaf, non-speaking, ambulant
PI6	Athetoid CP, ambulant
PI7	Friedrich's Ataxia, tremor, wheelchair user

For the task, participants were presented with 16 "target" circles arranged in a larger circle around a central "home" circle, as shown in Figure 1. The computer users were required to select each target in a random order determined by the software. The circles became red to indicate the active target. Selection was achieved by dwelling inside the target for 250ms. After successfully dwelling on an active target, participants had to select the home circle before the next target was activated.

This task was performed under 4 damping conditions – *None, Acceleration Damping, Velocity Damping,* and *Combined Damping.* In *None*, no force-feedback was applied and the Wingman operated as a normal mouse.
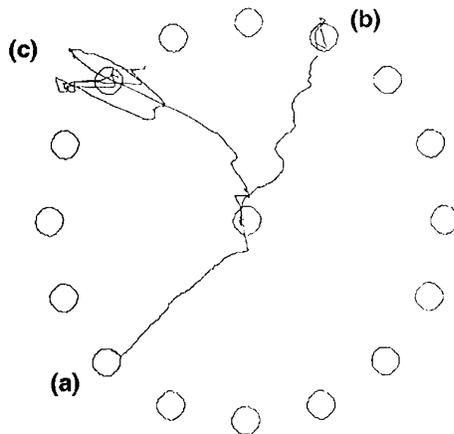
Figure 1. Cursor paths for PI7

Distance travelled (x10 pixels)

Figure 2. Plots of the reciprocal of radius of curvature for the cursor paths shown in Figure 1

Non-directional damping was implemented as a viscous force that increased linearly with mouse acceleration (*Acceleration Damping*), mouse velocity (*Velocity Damping*), and a combination of the two (*Combined Damping*). In *Combined Damping*, the velocity damping was at half the strength of the acceleration damping.

Each cursor path was recorded by logging the cursor position and system time each time a mouse message was processed by the operating system. Consequently, cursor position was sampled at irregular time intervals, but at an average rate of approximately 40 samples per second.

3. Performance Measures

In work that has been ongoing in the characterisation of cursor paths, several different measures have been investigated. Here, two of the more intuitive measures – the instantaneous cursor speed along the path and the instantaneous radius of curvature of the path – are described, and their abilities to elicit differences in the cursor paths are illustrated.

3.1. Cursor Speed

Instantaneous cursor speed is approximated as the Euclidean distance between two sample points divided by the time elapsed between them. Cursor speed is a measure that can be particularly sensitive to detecting the occurrence of spasm. During some large spasms, high cursor speeds have been observed, ranging from 3 pixels/ms to 8 pixels/ms. This is in contrast to the speeds observed in controlled movements by able-bodied individuals, typically less than 2 pixels/ms.

Although high cursor speeds cannot always be attributed to spasm with absolute certainty, it is reasonable to relate a high cursor speed with an uncontrolled, and

therefore undesirable, movement. Observations of the speeds of able-bodied and motion-impaired users suggest that a threshold of 3 pixels/ms can capture the difference between controlled and uncontrolled movement. The number of times the cursor speed exceeds this threshold can be used to measure the frequency at which uncontrolled movements occur. It will later be demonstrated that damping as a form of haptic assistance can help reduce the frequency of occurrence of high-speed uncontrolled movements.

3.2. Radius of Curvature

A curved path can be represented geometrically as a series of differential arc segments, each formed from the arc of an associated circle having a particular radius of curvature [2]. The radius of curvature, calculated here for an arc length of 10 pixels, can provide information about the number of "twists and turns" in the path. A small radius (e.g. <10 pixels) indicates a sharp turn, and a large one (e.g. >50 pixels) indicates relatively straight motion.

Figure 1 shows the cursor paths for three targets. All three paths have similar time to target values ((a) = 3609ms, (b) = 3974ms, (c) = 4635ms), and so an analysis based on this single measurement would not have revealed any differences among them. A look at the cursor paths, however, shows that the behaviours are quite different. The radius of curvature plots (Figure 2) are able to elicit these differences. The values are plotted as the reciprocal of the radius of curvature, so that high values indicate highly curved movement and low values indicate relatively straight movement.

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4. Results

Figure 3 shows the average time to target for the various damping conditions (6 sequences per damping condition per participant, 16 targets per sequence). It appears that all forms of damping have a favourable effect for PI3, reducing times by over 50%. The damping does not appear to have a great effect on times for the other participants. It may be that the nature of their impairments does not benefit so explicitly from the damping, or that the benefit is balanced by the extra motor load produced in moving the mouse. This will be studied further.

Given the reduction in time to target for PI3, the cursor speeds were studied further. Table 2 shows the number of times the cursor speed exceeded the threshold of 3 pixels/ms for the four different conditions. The various forms of damping appear to reduce the frequency of uncontrolled, high-speed movements by 70-90%.

5. Conclusion

A pilot study has been performed to investigate the effectiveness of force-feedback technology to assist motion-impaired users in target-selection tasks. Two measures for evaluating the effectiveness of haptic assistance have been proposed. The radius of curvature of the cursor path and the cursor speed along the path can capture characteristics of the movement *throughout* a trial which may otherwise be lost in a single measure such as time to target.

In the experiment, haptic assistance was implemented as non-directional viscous damping. The force-feedback appears to be beneficial for some, reducing the time to target by over 50% for one user with spasm. Since force-feedback must be applied appropriately to be of benefit, future work includes developing and evaluating other forms of haptic assistance.

For evaluation, further studies will be conducted to determine the reliability of measures within individuals, across individuals, and across tasks. The measures will be applied to evaluate the effect of various forms of haptic assistance. Further study of the cursor paths will be conducted to gain insight that may lead to the development of more appropriate forms of haptic assistance. Finally, the implications of kinaesthesic impairment on haptic assistance remain to be investigated.

Acknowledgements
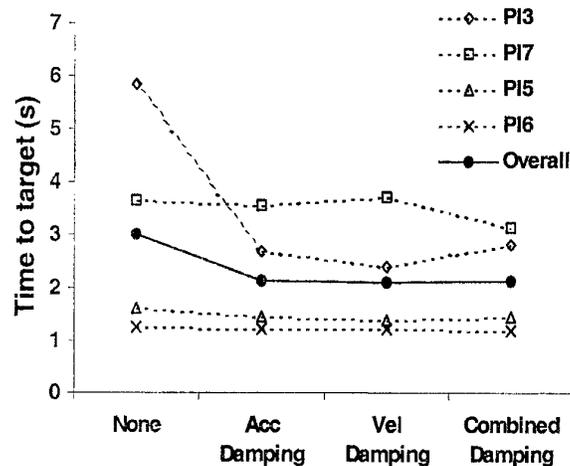
Figure 3. Time to Target vs. Damping Type

Table 2. Thresholding of cursor speed for PI3

Condition	No. of times above 3 pixels/ms
None	70
Acceleration Damping	20
Velocity Damping	6
Combined Damping	14

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When Touch Forms Vision - Object Recognition as a Function of Polysensory Prior Knowledge

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Abstract

We investigated how various forms of prior knowledge influence learning speed and recognition performance of previously unfamiliar three-dimensional (3D) objects. The learning objects were three 'molecule' models each of which was composed of four spheres. Prior knowledge was varied in terms of the sensory modality (visual versus haptic versus visuohaptic) employed during a so-called exploration phase. Following this exploration subjects were trained in a visual learning task with a fixed set of two-dimensional (2D) views of the learning objects. We found a significant effect of sensory modality employed during the exploration phase on both learning rate and recognition performance in the subsequent visual learning task. Specifically, a short period of haptic or visuohaptic exploration reduced learning duration by about 60% relative to conditions with either none or visual-only exploration. Computer simulations on the basis of the behavioural data suggest that prior haptic exploration stimulates the evolution of object representations which are characterized by an increased differentiation between attribute values and a pronounced structural encoding.

1. Introduction

Concerning the quality of internal representations underlying human object recognition there are two dominant views. On the one hand, it has been postulated that objects are mentally represented by three-dimensional (3D), object centred, part-based descriptions [1,2,3]. On the other hand, more recent studies have provided evidence for the notion that 3D objects are in fact represented in terms of multiple, viewer centred, two-dimensional (2D) views, among which the visual system interpolates if necessary [4,5,6].

Experimentally, both hypotheses have been mainly tested in studies where the test object was presented from different perspectives and where the change of the error rate or response latency has been measured in identification tasks as a function of viewing angle. However, it has been shown that the two alternative explanations are not readily distinguished within this paradigm. First, the dependency from viewpoint is itself dependent on object familiarity [7], demonstrating the necessity to take into account learning processes. Second, a closer inspection of the apparent complementary approaches shows that the assumed viewpoint-invariance of the 3D hypothesis holds only under certain conditions [8]. Conversely, representations in terms of multiple 2D views may become quasi-independent from viewpoint, if the number of views is sufficiently large, or if the interpolation mechanism between views becomes more efficient due to training.

A further complication arises from the fact that it is still unclear to what extent depth information is used for building internal representations of 3D shapes. There is evidence that the influence of binocular disparity (shown to be strongest contributor to depth information in recognition) declines with increasing familiarity [9]. In contrast, experiments in the field of haptic object recognition demonstrate that the identity of familiar objects may be established very quickly and seems to be mediated mainly by 3D structural information [10,11]. The latter result would suggest a participation of polymodal sensory systems in the ontogenesis of mental object representations.

In this study we have investigated, within a supervised learning paradigm, how prior knowledge of objects in various sensory modalities influences learning speed, recognition performance and the ability of spatial generalization. The learning objects were molecule-like models made up of four spheres. Prior knowledge was varied in terms of the sensory modality (visual versus haptic versus visuohaptic) employed during a so-called exploration phase. Following this exploration subjects were trained in a visual learning task with a fixed set of two-dimensional

(2D) views of the learning objects. Learning speed was measured as the number of training cycles that were necessary to reach a given criterion concerning the classification of the learning views. In a subsequent generalization test, recognition was assessed by the ability to correctly assign a set of novel 2D views of the previously learned objects. To gain further insight into the nature of the mental object representations acquired during learning additional computer simulations were conducted. The simulations employed a recognition model based on relational evidence theory [12] which allows to characterize object representations in terms of components and relational rules.

2. Method

The experiments employed a set of three objects. Each object was composed of four spheres, with three of them forming an isosceles triangle and the fourth being placed perpendicular above the centre of one of the base spheres rendering the objects similar to 'molecule' models. The objects were generated both as virtual models and as physical models. Virtual models were constructed and displayed on a SGI O2 workstation using the Open Inventor software package. The physical models were constructed of styrofoam balls. From the virtual models, 2D views were generated as perspective projections of the objects onto the screen plane of the computer display. Two sets of views were generated, a training set comprising 22 images and a test set comprising 83 images. The two sets were obtained by sampling the viewing sphere in 60 deg steps (training set) and 30 deg steps (test set), respectively, and by eliminating all views that were redundant due to object symmetry. At the viewing distance of 1m the images appeared under a visual angle of 1.5 deg.

The experiment was divided into three parts, a so-called exploration phase, a supervised-learning phase and generalisation test. During the exploration phase the participants were allowed to familiarize themselves with the objects. The subjects were divided into three groups that differed concerning the sensory modality employed during the exploration: visual, haptic, visuohaptic. Haptic and visuohaptic exploration was done by grasping and manipulating the physical object models. In the purely haptic case the subjects were blindfolded. Visual exploration was mediated by actively rotating the virtual object models on the screen by means of the computer mouse. In each case, the exploration phase lasted for 3 minutes and was followed immediately by the visual-learning phase. In addition, there was a fourth (control) group where subjects started immediately with the visual learning without any prior exploration.

The supervised learning procedure consisted of subsequent learning units (see [13]). In each unit the each view of the learning set was presented three times in random order. The exposure duration of each view was 250 msec, and each presentation was followed by the corresponding object label displayed for one second. The learning unit ended with a recognition test to assess the learning status of the subject. Here each view of the learning set was shown once for 250 msec and labelled by the observer. The sequence of learning units continued until the subject had reached the learning criterion of 90% correct responses in the recognition test. After having completed learning the observers continued with the generalisation test. Here all views of the test set were shown in random order. Each test view had to be assigned to the previously learned objects.

3. Results

The results show that learning duration, measured by the number of learning units necessary to reach the criterion, was significantly affected by sensory modality employed during the exploration phase. Specifically, the short haptic exploration phase reduced the learning duration by about 60% as compared to the control condition. Haptic exploration also distinctly improved the ability to recognize novel views of the previously learned objects in the generalisation test, from a level of about 60% to about 75% correct responses. The advantage in learning and generalisation was the same no matter whether the haptic exploration was accompanied by sight (in the visuohaptic condition) or not (in the haptic condition). However, a purely visual exploration of the objects (visual condition) yielded no significant advantage relative to the control condition, neither in terms of learning speed nor generalization.

To explore how prior knowledge acquired during the exploration phase specifically affected the ontogenesis of the object representations during the subsequent visual learning we conducted computer simulations on the basis of the confusion error data. The simulations employed CLARET, a recognition model based on relational evidence theory [12]. CLARET involves a process of rule induction, in which a taxonomy of rules is created to discriminate between objects. The rules refer to relational attributes, such as distance, angle or size ratio, that are used to describe object structure. Starting from an initial rule, defined by an attribute range which is satisfied by the relations of all existing objects, rule refinement proceeds in two ways: (1) By re-partitioning the attribute space via clustering, thus producing rules of increasing attribute specificity, and (2) by incorporating relational information in terms of rules which include other rules in their body. Thus the resulting rule hierarchy is characterized by two properties: attribute specificity and relational depth.

Since the behavioural data revealed a distinct dichotomy between subjects with haptic versus those with non-haptic prior object experience, the data of the subjects were divided into two groups, haptic and non-haptic, respectively. The simulations yielded for the haptic group a high degree of differentiation between values along the feature dimensions, with an optimal fit around a value of 5 partitions. In contrast, observers with no prior experience tended to differentiate between attribute values much more coarsely, with an optimum partition number around 1-2. Concerning relational depth, only the fit for the haptic but not for the non-haptic group improved as more rules were included in rule generation. This warrants the conclusion that object rules in the former case extend over multiple object components whereas they remain confined to isolated component pairs in the latter.

4. Conclusion

We have shown that a prior haptic exploration of 3D objects leads to a substantial facilitation in visual learning and generalisation. Computer simulations suggest that theses facilitation may be due to a different representational format of the underlying mental object representations. Accordingly, prior object knowledge acquired via the haptic sense stimulates the development of representations that are characterized by a high degree of attribute differentiation and an enhanced use of relational information. The present results are preliminary in the sense that they do not yet allow conclusions concerning the dimensionality of mental representations of 3D objects. However, the observed dependency of visual learning on haptic information indicates that such object representations may have an intrinsic polymodal quality, thus questioning the validitiy of purely vision-based accounts of object recognition.

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Haptic Rendering of Volumetric Anatomic Models at Sub-voxel Resolution

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Abstract

In this paper, a new approach for haptic rendering of high resolution voxel-based anatomic models is presented. For visualization the surface location is determined by a ray-casting algorithm at sub-voxel resolution. Since the same algorithm is used for the haptics as well, a very high level of detail is achieved for haptic feedback. Both graphical and haptic representation is congruent.

The interaction forces are calculated based on a collision detection between an arbitrary sized sphere-shaped tool and an arbitrary complex anatomic model. Forces are calculated at an update rate of 6000 Hz and sent to a 3-Degree-of-Freedom (3-DOF) Phantom device [7]. Compared to point-based haptic rendering, the unique combination of the sphere-based approach in combination with sub-voxel rendering provides more realistic and very detailed tactile sensations.

1 Introduction

Today haptic rendering is mostly based on traditional computer graphics methods where objects are represented by polygons only. However, using a surface based representation to create a model for medical applications, the knowledge about the interior structures of the organs is lost. This knowledge is very important when simulating interactive cutting operations such as required for surgery simulations.

In addition we realized that today 3-DOF haptic rendering is mostly point-based, i.e. only one point is used to calculate collisions and forces. This induces several problems:

- Discontinuities (e.g. sharp edges) on the surface can lead to discontinuities in the haptic display
- The virtual tool can reach points which can not be reached by the simulated real world tool

Our approach uses a tool-based collision detection which was inspired by [1]. For collision detection and force calculation we used a sphere-shaped tool which simulates a drill as it is used in petrous bone surgery.

1.1 Previous work

The voxel-based approach to haptic rendering presented in [1] enables 6-DOF manipulation of a modestly sized rigid object within an arbitrary complex environment of static objects. One drawback of this method is that the haptic rendering is at voxel level accuracy only. Our approach differs from this work primarily in the surface representation. While our model is also using a voxel representation, the exact location of the surfaces is calculated by a ray-casting algorithm at sub-voxel resolution. That leads to smooth surfaces while even small surface details can be represented.

2 Methods

Mainly the following three aspects are involved in our approach:

1. The collision force on the surface of the objects can be computed by an algorithm which was inspired by [1].
2. To calculate correct forces for deeper tool-object penetrations, a modified proxy algorithm [4,5] was used.
3. In contrast to other representations, our model does not include an explicit representation of the surface. It is rather calculated by a ray-casting algorithm at sub-voxel resolution [2]. Such calculations are computationally expensive and thus they should be minimized to the extend absolutely necessary.

2.1 Representation of the tool

The tool is represented by a number of points which are distributed at preferably equal distances over the tool surface, together with the inward pointing surface normals (Fig. 1). In our case all inward pointing normal vectors are ending at the center point of the sphere. To get an adequate representation of the shape while reducing computation to a minimum, we used 26 sample points on the surface. Depending on the size of the sphere more point samples might be required.
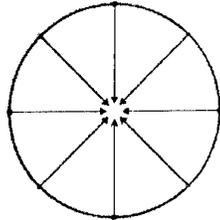
Fig. 1: Representation of the tool
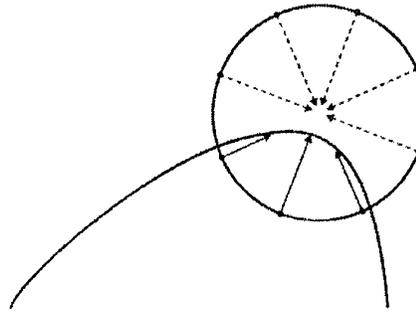
Fig. 2: Calculation of collision force

2.2 Haptic rendering of the surface

When a collision occurs, two parameters of the collision force must be calculated:

- Direction and
- Magnitude of collision force

First of all, the surface points of the sphere are checked, whether they are inside or outside the object. All surface points which are inside the volume are traced in direction of the inward pointing normal until the surface is found (Fig. 2) or the sphere center point is reached. All found vectors are added and the direction of the resulting vector is the direction of the force vector which must be applied to the haptic device. The problem of calculating the magnitude of the force vector is still under investigation; so far, we use a heuristic method which averages the magnitudes of the surface vectors. This leads to deeper penetration while more tool points are in contact with an object.

2.3 Proxy object algorithm

Any haptic device has a limited force which can be applied to it. When the user pushes harder, it is possible that the physical position of the tool immerses completely into the virtual model. In this case a calculation of the force direction as described above is not possible anymore because the sphere center point is in the object itself. To overcome that limitation a modified proxy object [5,6] was implemented. In free space, the position of the proxy object and of the device is identical. When the haptic device moves into an object, the proxy remains on the object's surface. When the proxy position is known, the resulting force vector is proportional to the difference vector between the proxy and the device position.

In order to update the proxy position while the device is moving, the distance between the device position and the proxy must be locally minimized by regarding the surface constraints. Since searching for the local minimum would be computationally very expensive in our model, a new algorithm was implemented. Whenever more than a certain number of surface sample points are in contact with an object, the way back to the proxy is traced until the number of contacts is below the limit or until the proxy is reached. At that location the force vector is calculated as described above and the proxy is set to that position.

2.4 Implementation

The system was implemented on a Compaq SP750 workstation. The workstation has two Pentium III Xeon processors at 866 MHz and is equipped with 2GB RAM. As haptic device we used a 3-DOF Phantom Premium 1.0A [7]. Our system was running under SuSE Linux 7.1. For connecting the device directly to the system, we used the open-source PHANToM Linux-driver from [4].

The haptic process runs at an update rate of 6000Hz. The most time consuming calculation is the calculation if a point is in contact with the objects. By using 26 sample points on the sphere, 60 such calculations are executed at every haptic update on average.

3 Results

With our approach we achieve high quality haptic rendering of arbitrary complex anatomic models [9] as shown in figure 3. The perception of spatial relationships is greatly enhanced with haptic feedback. Even very small surface details or small objects like nerves and vessels can be sensed realistically due to our sub-voxel based approach. As a major application of our method we are working on a system for the simulation of middle ear surgery (fig. 4). Here, the haptic device is used to simulate drilling into the mastoid bone [8]. Using a sphere-based collision detection proved to be much more realistic than using point-based haptic interaction. Drilled holes and tubes in the bone could be intuitively probed with the haptic device.

4 Conclusions and future work

The approach presented here overcomes several problems of point-based haptic rendering. The shape based collision detection makes interactions more realistic, especially for the use in surgery simulations. Another important advantage is that surface details can be sensed as expected from the graphical representation. Sub-voxel rendering leads to both a graphical and haptical realistic and high detailed display.
While the current implementation is limited to sphere-shaped tools, future implementations will extend this to more general shapes. The calculation of the collision force magnitude will be investigated further to improve haptic rendering at locations with many tool object intersection as they appear in deep clefts.

Fig. 3: Sub-voxel rendered anatomic model
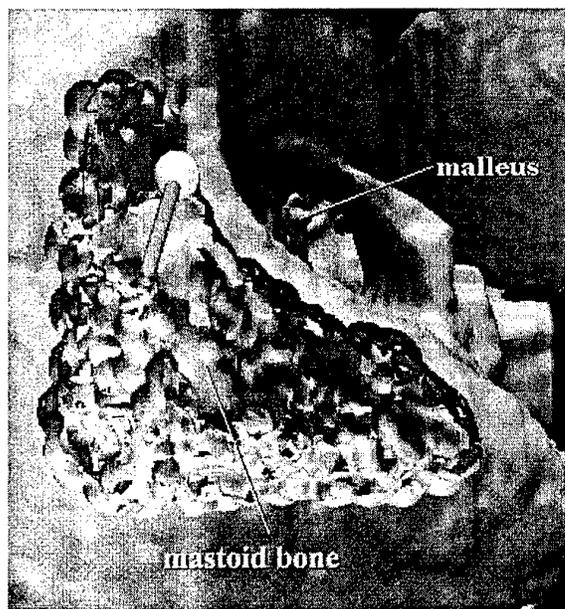
Fig. 4: Simulation of middle ear surgery

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'Tacitus' Project: Identifying Multi-Sensory Perceptions in Creative 3D Practice for Development of a Haptic Computing System for Applied Artists.

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Abstract

This paper outlines the major motivating factors concerning a novel collaborative project between Edinburgh College of Art and Edinburgh Virtual Environment Centre. The "Tacitus" project will investigate the use of multimodal virtual environments, specifically, the haptic modality, with regards to the creative processes employed by designers working within the field of applied arts. The salient areas of research are described, and the methods by which information regarding these areas will be obtained are considered. Initial investigations have revealed a strong need to mimic the traditional applied artists' workspaces, with co-location of visual and haptic cues a priority.

1. Introduction

The advent of new virtual media and haptic computing means that technology offers not only new tools but also the prospect of entirely new ways of developing work in virtual space. Current computer interfaces are often alienating, impoverished worlds, with little to support the intuitive heuristic working practices of applied artists. Applied artists are designer makers and artist craftsmen, i.e. people who work creatively with their hands, using a chosen material and often with an element of functionality. Examples of applied arts disciplines include ceramics, glass, jewellery, furniture, textiles, metalwork, bookbinding, and calligraphy.

Many art and design students are denied the opportunities presented by Information Technology (IT), due to their fear or dislike of computers. Perhaps even more importantly, this also deprives many IT based developments of their potentially valuable input [1].

Central to the field of applied arts is the notion of "intelligent making"; a mix of formal knowledge, tacit knowledge, physical and mental skill, contextual awareness, innovation, and personal creative autonomy [2]. An applied artist's instinctive grasp of constructing and visualising in three dimensions, their spatial thinking and sense of touch are integral to their process of creativity. Makers combine all their sensory modalities, such as sight, hand motions, and sound in order to explore and bring intended qualities to the object they are making. Results can only be achieved through ongoing dialogue between the maker, materials and process [3].

In October 2000, with the above indications, Edinburgh College of Art (ECA) and Edinburgh Virtual Environment Centre (EdVEC) began a three-year collaborative research project, funded by the Arts and Humanities Research Board. The principal aim of their user-centred project is to investigate the development of three-dimensional haptic and multi-sensory computer applications for creative processes in applied arts and design.

2. Project Overview

The main aims of the "Tacitus" project can be summarised as follows:

- To explore the potential advantages of being able to work, think and respond to physical and visual stimuli, in a virtual, fully three-dimensional, non-gravity context, with particular reference to the education of designers and artists and the development of three-dimensional work.

- To discover the degrees of haptic and other multi-sensory feedback required within digital systems to assist designers and artists to work more intuitively.

- To develop viable software applications and virtual 'hand tools' to enhance the creative practice of applied artists.

Initial studies indicate that a central notion to the development of the project will be that of tacit knowledge regarding material constraints. In the case of the creative process of applied artists, material constraints provide an affordance to the imagination, rather than a barrier. An artist must understand the potential of materials, tools and techniques, whilst having the skill to control the actions required to achieve creative intent. For example Figure 1 illustrates a silversmith forming a vessel from a flat sheet of metal. Audio, tactile and proprioceptive cues are all necessary for the skilful and controlled manipulation of the material.
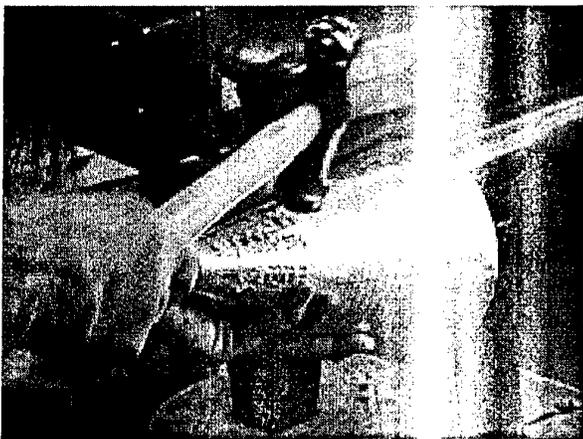
Figure 1. Silver vessel in the process of being formed from flat sheet.

This view of constraints is in stark contrast to the traditional notion of virtual reality (VR), which allows us to interrupt the sensory feedback loop with the perceived

world, and therefore facilitates the omission of material and physical constraints. While this presents many advantages for data visualisation and manipulation, to the applied artist, it removes an essential catalyst to their creativity. Hence, research will initially seek to identify material properties, tools and processes that are salient to the creative process of the applied artist.

Glass blowing (Figure 2) is a good example of the complex skills and tacit knowledge artists possess in regard to properties and constraints of a material and tools used to manipulate it. Temperature, viscosity and adhesive properties must all be judged accurately with split second timing for a successful outcome. In transference to a virtual environment, some of these variables may be removed or controlled with benefit to the artistic process. However, post work interviews determined that a constraint such as a gravitational field is fundamental to the tacit knowledge and skills of these artists. Hence this constraint must be embodied to some degree in any virtual environment, if the artist is to transfer their skills and tacit knowledge to the virtual workspace.

Figure 2. Skilful co-operation of glass artists to produce a complex artefact.

3. Methodology

The first series of studies will seek to establish a data resource on fundamental user requirements, in order to begin developing haptic computing for applied artists. These are in progress at Edinburgh College of Art, first studying students and staff working in the departments of Design and Applied Art, followed by studies of selected professionals working in a variety of disciplines and using a range of materials, tools and skills.

3.1 Key Areas

In order to establish a meaningful data resource for development of a haptic computing system, the initial studies will be focused in three areas.

A: Conceptual Approach

The pathways into the initial creative process of design, e.g. experimenting, sketching, modelling, testing, searching, playing. Factors in the design process that support creativity.

B: Skills / Tools / Materials

The range of, and preferred, tools and materials employed, and the creative effects that can be achieved via use of these. The material tool qualities and properties, and the skills required to achieve effects.

C: Computers

Limitations of current computer graphics and 3D design applications, for example, range and intended use of available design software, assessment of the software's capacity to accommodate range of design processes and creativity, and a "wish list" for ideal virtual design tools and environment.

3.2 Data Acquisition

3.2.1 Stimulated Response. Interview during the design procedure would be highly disruptive to the artists' thought process, and difficult, due to the vast amount of information that must be conveyed regarding procedures, tools and materials. Therefore, photography and video are currently being employed to obtain a record of artists' working methods in process, as opposed to staged demonstration. Subsequent review of the tapes, and post-work interviews will allow detailed investigation of individual artist's tacit inferences.

3.2.2 Questionnaires / Self-analysis. Focussed debate and questionnaires will be employed to encourage ECA staff and students to articulate the reasons for preferred materials and tools, and virtual environments that would help to enhance the creative process. Two of the researchers on the project are applied artists of international status. Their self-observation during initiation and development of their own work will provide a valuable resource.

3.2.3 Further Studies. Further stages of the research project will investigate tacit knowledge, haptic and other

senses. Data from these studies will be used in an iterative process to evolve digital systems to assist designers and artists to work more intuitively and support development of virtual hand tools and viable software application to enhance creative practice.

4. Initial Findings

4.1 Haptic Device Implementation

The specific aims of the project dictate the choice of haptic device to be employed to a high degree. The artists and designers who would use the equipment had subjective requirements on the method of operation, which also constrained choice. This required that the virtual object being manipulated, and the tools being used to do so, should occupy a position in physical space similar to that when working in real life and that the mode of working should feel the same.

The equipment finally chosen also had to have reached a commercial stage of development with adequate support and have a reasonable development environment.

The Reachin (www.reachin.se) system, based on the PHANToM (www.sensable.com) haptic device was chosen for the project. The main reasons for this choice were the relative product maturity of the PHANToM, the co-location design of the real probe with its virtual depiction, and the high level Reachin API development environment. Figure 3 illustrates the high degree of similarity present between a typical jeweller's workbench, and the Reachin system.

Figure 3. Comparison between traditional jeweller's working position and co-located haptic/visual display.

4.2 Questionnaire Results

A general questionnaire completed at project presentations by ECA students, and by professional applied artists revealed the following points concerning computer and tool use within the field of applied arts:

- A wide variety of preferred hand tools, therefore the

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need to categorise these tools so that generic properties across the disciplines can be extracted and analysed.

- Of ECA students across all disciplines in applied arts, 46% use computers, software named included AutoCAD, CorelDraw and PhotoShop.
- All students in furniture, but no students in jewellery and metalwork, used computers for designing.
- Of professional applied artists invited and attending a presentation about the project, 84% use computer with 23% specifically for design. This high percentage could be reflected in the interest of those attending in computer applications.

These preliminary results show a relatively low use of computers within the applied artist community, while there was a wide variety of hand tools employed. It was also observed that single tools are often used for a number of different purposes (e.g. a welding torch can be used to cut, bend or join material), and are therefore very flexible in the hands of a maker. This suggests that the inherent rigidity of current software tools is a barrier to the creative process.

5. Conclusion

This paper has outlined the primary research goals of the Tacitus project, which seeks to develop a multimodal virtual environment capable of meeting the needs of applied artists, craftsmen and designers. In particular, the project will focus on the use of tacit knowledge by artists and designers, and the role of material constraints and properties in the creative process.

Our goal is not to imitate the working practices and environment of the craftsman, but to create a generic virtual environment that can be applied to a variety of 3D creative disciplines, in which the applied artist feels comfortable and uninhibited by the novel synthetic environment and yet can bring their experience and knowledge to extend their levels of creativity more fluidly using a new digital medium.

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Concept of a Tactile Intelligent Sensory Substitution System

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Abstract

In this paper we present a novel approach to communication using the human's tactile sense. We propose an intelligent tactile information system that has the capability to generate a language suitable for tactile stimulation. This unknown language has to be evolved by an adaptive encoder in interaction with the user. The system is composed of four functional units: input device, learning encoder, tactile interface and mans perception.

1 Introduction

Human beings communicate with their natural and technical environment by using different channels for information exchange, e.g. seeing, hearing, smelling, touching, speaking, gesturing etc. Most part of human perception is processed through the visual and auditory channel, while the tactile channel remains rather unused. Although seldom used for technical supported communication tactile perception is a powerful information channel e.g. demonstrated by the Tadoma method [8] or by the users of braille displays.

There are versatile applications using the tactile sense [2] [4] [11]. Handicapped people can use the tactile channel as substitute for the lost channel of perception [3]. As an additional possibility private communication is possible because it is non-audible and non-visible and therefore not easily monitored by unwanted listeners. Furthermore the tactile sense can be used as a spatial orientation guide.

It is reasonable to subdivide the flow of information in a tactile information system from the real world to human perception into four units: an input device, an encoder, a tactile interface and human perception.

The input device receives the signals and transforms them into a convenient electronic representation. The encoder processes the information in a suitable way so that the tactile interface, the connection to the human being, can be optimally controlled. The final unit of a tactile information system is the individual itself with its cortical information processing that finally enables perception.

The complete information process from the input device to human perception is extremly complex and furthermore unknown. At the moment it is impossible to model this information process in a sufficient way. Thus we recommend that the adequate information processing is attained by an adaptive system in close interaction with a learning scheme.

We propose tactile systems should consist of an input device, an adaptive encoder [5], an actuator and human perception. The adaptive encoder is trained in special learning sessions [1] to obtain the required capabilities.

2 Architecture

The adaptive tactile system consists of four units as depicted in figure 1: input device, adaptive encoder, tactile interface and perception by the user.

- The INPUT DEVICE is designed to pick up the signals from the input space. There are different input spaces possible e.g. acoustical, visual spaces or data sources (computer). It is reasonable to preprocess the input data to achieve that the time for the adaption of the encoder becomes short. For example acoustical input could be filtered and classified into patterns of phonemes [9] [10] to reduce dimension of the data without destroying the relevant information.

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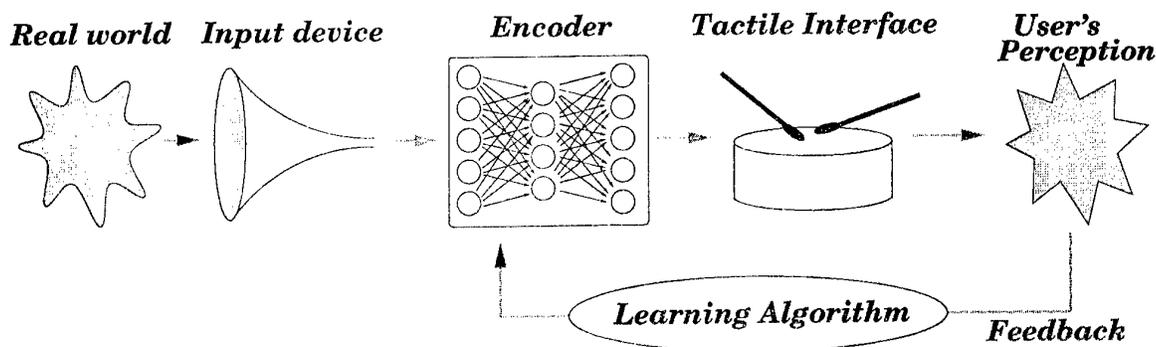
Figure 1: Scheme of tactile information system, consisting of Input Device, adaptive Encoder, Actuator, User's Perception

- The ENCODER obtains the preprocessed data from the input device. It processes the data and translates the information into a language adequate for tactile human perception. At the moment this language is unknown and thence the translation is impossible to calculate. A neural network with its approximation capabilities offers a feasible approach to solve this problem. Thus the encoder becomes versatile and adaptive with respect to the type of input signal and the individual user's perception.

- The TACTILE INTERFACE is the connector from the encoder to the user. The stimulators of the interface can be of different types such as vibratotactile or electrotactile [6] [7]. In the skin exist diverse types of mechanoreceptors. To obtain a higher bandwidth of information it is advantageous to be able to excite the receptors separately. Additionally the consumption of power should be low because the tactile information system needs to be portable.

- The USER is the unit of the system where the perception is finally generated. Tactile perception will be different for different users so that the individual adaptation of the encoder is a great advantage. For this adaptation feedback of the user is required. The presentation of the feedback depends on the implementation of the learning algorithm. The user too has to adapt himself in a way that he learns to interpret the presented tactile stimulation. The aim is to achieve a sensory substitution. Then the former tactile perception is replaced by a new type of perception resulting for example in an ability of hearing by means of the tactile sense.

3 Handling the system

We propose to install the tactile system in three phases:

- In the first phase the user has to be sensitized to this specific type of stimulation.

- During the second phase the system is adapted. For this purpose a finite set of the encoder's input signals, representative for the input space of the tactile system, is generated. To allow the user to distinguish and learn the presented patterns as good as possible, the parameters of the encoder are adapted by the learning algorithm having regard to the user's appraisal of the stimulation (feedback). As there are two learning parts in the tactile system (adaptive encoder and user), a learning scheme has to be carefully developed so that the two parts interfere in a constructive way.

  Although presenting only a finite set of input patterns, the encoder should afterwards be able to map unknown but similar patterns to a tactile stimulation that can be recognized and interpreted by the user. This generalization is a well-known feature of the neural network implemented in the encoder.

- Finally the system is adjusted and ready for day-to-day use. It may be necessary to readjust the system from time to time.

4 Conclusion

The introduced tactile information system offers an efficient way of communication. It establishes an additional channel of information exchange. With the use

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of an adaptive encoder the tactile information system evolves a language suitable for tactile stimulation. By the aid of sensory substitution the information is received by the subconscious mind and does not divert the user from other tasks. With different types of input spaces the tactile information system offers a variety of novel fields it can be applied to.

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FACTORS UNDERLYING FABRIC PERCEPTION

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'Words and images behave in different ways. A picture of a miniskirt performs a different function than the naming of it. Barthes suggest that words make the image "intelligible: [that] it is not the object but the name that creates desire (Barthes 1990) ... Orality implies community. Not only do we dress up; we talk about it' [1]

Abstract. The above suggests *'oral texture'* as a method of communication or *'ideal and emotive novelisation'*, a utopian standard of image and self-transformation, set by the fashion, textiles and lifestyle perception makers. It is a system that has been used to sell or seduce magazines (imagery and supporting text) to the reader (wearer) since the late 19th Century and blurred into the realms of retail sales and marketing, especially on-line. Society understands and indulges in this method of aesthetic communication, and for women, it is meant to represent *'women's mass culture'*. [Naomi Wolf][1]

This paper describes two fabric-touch experiments where the term *'oral texture'* applies in the collection of adjectives and metaphors (fabric perceptions). The purpose of this study was to qualitatively record subjective responses to familiar fabrics, using a Repertory Grid (factor analysis) model [2], to preliminary establish subjective and objective responses to fabrics, and through analysis, the factors underlying fabric perception and discrimination between fabric 'types'.

10 fabrics were selected. Each subject evaluated fabrics using their index finger in a forward and backward motion, with visual observation. The experiment was carried out in three phases. The first experiment was used as a Pilot Study. Data was assembled from 1 experienced textile/fashion professional/academic. The second round of data was assembled from 20 female subjects who are currently 1st year fashion and textile design students. Through the experience of the pilot experiment, it was found that these qualitative responses were split into two categories, 1. Surface Texture and, 2. Emotional/Cognitive/Mood associations. After analysis, principal factors for each category evolved. These factors were then labelled. Results are summarised and discussed.

Using the "experiment" experience, the students were than asked to select their own fabric of choice and evaluate it in a similar manner (this was not limited to evaluation by index finger, as the experimenter was not present. After discussion it was found that the method of multiple finger pinch, as illustrated in Figure 1 was primarily used, it being the most natural method of touch next to 'touch-stroke' (see Figure 9) [3]. Qualitative data was collected, as before. They were then asked to visually respond in a "virtual" manner by creating a "mood board" using Adobe PhotoShop (a combination of selective imagery related to texture, colour and style, evoking emotion and memory). This work is also discussed and some examples are shown later on in the paper.

Figure 1. Finger Pinch
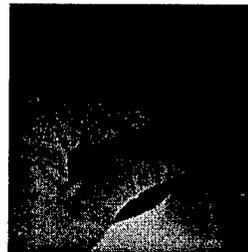
1. Introduction

1.1 Background

When a person runs their finger across the surface of a fabric, or when we travel out on a shopping trip for clothing where we engage in a selection process that involves touching and trying on clothing, a complex multi-sensory, emotional and cognitive experience takes place. A memory is stirred, an emotion, feeling and association is evoked and a decision is made, an impression becomes embossed in the mind. When we shop for clothes for example, this eruption of activity extends itself into a manifestation of building and development of the 'self'. Decisions and motivations are based on anticipated reality of preference, personality, emotion and moods, for audience or non-audience participation.

In terms of fabric/texture, clothing/fashion perception and virtual technologies, little has been established that sufficiently deals with this complex relationship. Within the realms of technology, it is easy to be misguided. Human factors can become disguised or blurred into generalisation or unimportance when ideally, a complementary strategy; a human-centred system is necessary that combines novel, therapeutic and logical variables. A system that involves textiles and fashion, will rely heavily on emotion, motivation, creativity, abstract and illogical input (human). *"People excel at qualitative considerations, machines at quantitative ones. As a result, for people, decisions are flexible because they follow qualitative as well as quantitative assessment, modified by special circumstances and context. For*

the machine, decisions are consistent, based upon quantitative evaluation of numerically specified, context-free variables. Which is to be preferred? Neither: we need both". [4] If the machine can learn as we do, see as we do, feel as we do then the bridge between people vs. machines can be broken and their role as 'assistant' be reconciled with.

The emphasis of this research is in the early development of a valuable tool that eventually retailers, designers and consumers should all potentially benefit from.

1.2 Methods and Analysis

The repertory grid theory has been used successfully to study consumer behaviour. "Kelly (1955) proposed that people act on the basis of specific hypotheses, or expectations, concerning the functioning of their environment, i.e. people are assumed to be 'scientists', developing hypotheses concerning the best course of action to take in a given situation" [2]. This has been labelled a "mental model" [2], processes through which people evaluate their own surroundings and products and who possess different levels of experience and expertise. The theory is based on the assumption that people focus on positive and negative or reward and punishment aspects for any given experience. In terms of fabric perception we will say the 'opposites', however in terms of subjective emotion we may also say positive or negative. The theory was labelled "personal construct theory" [2]. A method of 'triads' is used to collect data. On this occasion for example, the experimenter presented 10 different fabrics (product) where the individual had to select three fabrics at a time, decide which two were the most similar and describe why they differed from the third. This was performed in rotation until all possible combinations had been covered (10).   For example if you have a fine silk, a velvet and a leather it could be said that the silk and the velvet are the pair, both being incredibly smooth, soft, silky, reflective, glossy and somewhat oily to touch. The leather, even though it is smooth is different, it feels moist, matty and spongy to the touch. In terms of emotion/cognitive/other, the velvet and the silk could be seen as feminine, gentle, sensuous, thoughts of beauty, weddings, and party dresses, majestic happiness, decadence, gothic styles and old dusty houses spring to mind, whereas the leather could be deemed as masculine, sexual, feelings of power, fetishism, being tough, strong, possessing animal instincts, cowboys, the night, it can be deemed somewhat threatening - leather clothing, bohemia and wild rock chic's attitudes, and a sense fearlessness when worn, see Figure 2, below [5].

Figure 2.

'There's no doubting that leather represents masculinity and that's what our girls want (regardless of their sex)' (Robert Stoller, Observing the Erotic Imagination, 1985 [6] *'Leather still emerges with a tough, give-'em-hell attitude, which should satisfy the Thelma and Louise in every woman...'* (Anna Wintour, Vogue, September 1991) [1]

Principal components analysis, a multivariate analysis technique, (originated by Pearson, 1901 and developed by Hotelling – 1933) [7] was used here. Given a set of observed uncorrelated (unrelated) variables the data was reduced down to the underlying dimensions based on total variation, providing fewer variables or correlated 'principal components' to examine and be used as an objective data source.

1.3 Fabric and Clothing/Fashion Perceptions

One of Lederman's reasons for why our knowledge of touch has not significantly developed as rapidly as our visual sense is, *"there is a general reluctance in our society to discuss touch-related matters".* [8] Vision seemingly dominates our attention whereas touch can therefore be seen as a private and complex emotional and cognitive experience, especially when anticipating, seeing and feeling the skin / body in touch with fabric via clothing (image creation), a *'second skin'.* [9] Encased within our clothing, unconsciously or consciously our individual arrays of texture, colour, design and style choices act as a metaphor for the self affecting our behaviour, emotion and moods, levels of motivation, self esteem/confidence representing itself as a visual and tactile mirror of the self, of our society and culture. [10]

Through history, for example in the early 19th Century England, the textures favoured at that time, ' *indicated, for men, both natural (Greek) man and virtue; for women, childish frailty'.*

'Wool: National pride, simplicity, modern revision of classicism, cult of nature; matte texture is tantamount to smooth skin and natural virtue (Sir John Reynold's objection to Michelangelo's "play of light over rich texture" that inspired sensuality); mallability allows it to be molded to a man's curves; moral strength.
Broadcloth (on women): Androgyny
Wood: Natural man, modern craftsmanship
Leather: National pride, shiny foot-fetish fodder, naturalism
Cotton: Colonial acquisition
Silk: Exotic / innocent (depending on how it is woven) for women; for men, outdated, Rocco, wrinkling, light-reflecting focus on artifice rather than on nature

Muslim (white, for women): Waifish innocence; ditto bouncing hair[11]

However, *'In her study on fetish clothing, Valerie Steele argues that since the nineteenth century there has been a slow but definite turn to the so called masculine "hard" materials, especially leather and rubber. With the beginning of the modern age, she concludes, the need for a certain materiality constantly grows, and apparently it has to fulfil a specific desire for a contact, which can only be expressed in a tactile and haptic manner'.* [6]

This desire has become somewhat unisex, especially in terms of the growth in wearing casual inspired clothing and in the development of interactive, smart fabrics and wearable computers that are promised to enhance lifestyles for convenience sake. The term 'cyborg' is fast becoming a reality.

However, the other perspective, 'fashion' based a constant change of trends, will always remain, *'To transform yourself into a Romany princess is divine – if it turns you up and puts you at your ease. But don't get lost in someone else's dream: there is enough adventure in fashion to find your own'* (1970) Diana Vreeland, Editor in Chief of Vogue, 1963-1970 [1]

1.4 Aims & Objectives

The aim is to develop a multi-modal virtual reality model that incorporates a tactile (haptic) dimension, and to satisfy and soothe the physical perceptions, responses and emotions related to motivations for wearing and selecting clothes (essentially aspects of 'the self'). Existing and developing technology has the potential to offer solutions to this problem.

There are variables associated with this hypothesis. These can be categorised as follows: fabric/texture perception and motivation, style/design perception and motivation both tied to self/self-image (personality and emotional response). [12] This study provides some insight into what motivates an individual in terms of fabric and texture and some of the social implications involved.

This research could be used to refine texture simulation in haptic technology and for an objective or subjective non-verbal communication system within a virtual environment

2. Methods

2.1 Pilot Experiment

Stimuli. 10 different fabrics (familiar), listed as follows, mounted flat on MDF wood measuring 3" x 3", taped down at two sides:

Figure 3. Fabrics for Pilot Study
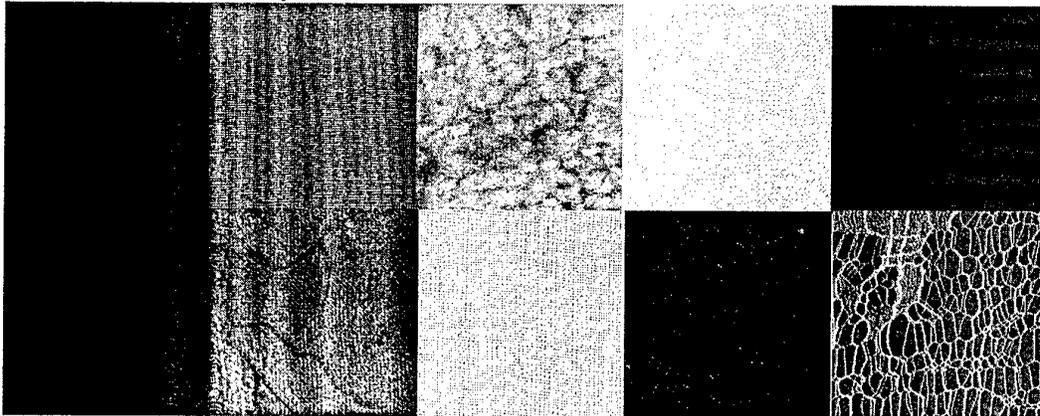
1.   Fleece *(100% Polyester)*
2.   Lycra *(83% Polyamide, 17% Elastane)*
3.   Sheepskin
4.   Silk *(100% Silk)*
5.   Corduroy *(100% Cotton)*

6. Leather
7. Velvet *(100% Viscose)*
8. Irish Linen *(100% Cotton)*
9. Denim *(100% cotton)*
10. Lace *(65% Polyamide, 35% Cotton*

Subjects. 1 textile/fashion professional (academic/research).

Figure 4. Index-Finger-Stroke

Procedure. The subject was tested individually in three phases. The subject sat at a table, and using her right arm extended forward with arm resting on table. For evaluation of the fabrics presented, with visual observation, the subject was instructed to stroke using her index finger making a fist with the other fingers (Figure 4.). As outlined briefly above, using the Repetory Grid model, the 10 fabrics were presented to the subject. The subject was then asked to select three fabrics at random (triads) and to continue to do this until at least 10 different combinations had been covered. The subject had to decide which two fabrics out of the three were most alike and provide adjectives (constructs) as to how they differed from the third fabric. Seeing the same fabric in different combinations (contrasts) allows one to notice other perceptions in terms of texture and emotion/moods that may not have been considered on initial evaluation of triad combinations. The experiment took place in a university studio environment. Classic FM was playing softly in the background to open up the emotions and relax the subject. This was turned off at a later stage without any comment. Subject tended to close eyes to concentrate on 'touching' the fabrics and experienced sleepy tendencies (winter time). As expected, colour tended to add to the emotional impact even though the focus was on 'touch'.

As outlined earlier, the constructs automatically split into two categories, which described 1. Fabric Surface, and 2. Emotional/Cognitive/Mood associations. This phase took approximately 1 hour. After tabling data, in the second phase, the subject was presented with the 10 fabrics again and asked to indicate, through the same touch and visual method, agreement with an individual fabric and a construct entering a "1", if the construct was not present, they indicated this with a "0". This took approximately 35 minutes depending on how many adjectives were originally given by the individual.

A Principal Component Analysis using SPSS was run and the Construct Groupings (Factors) evolved. On a separate day, for Phase 3 of the experiment, the subject was then asked to label each factor.

The purpose of the pilot experiment was to learn how subjects would describe stimuli when given no other guidelines except a request for adjectives, consequently providing a model to follow for the main experiment.

Results. Results are summarised in Table 1 below.

Table 1. Pilot Study Factors

| Fabric Surface		
Factor	**Construct Groups**	**Factor Label**
1	Resistant, soft, very soft, warm, quite warm, animal, deep pile, hairy	*Downy*
2	Changeable surface, high friction, uneven surface	*Irregular*
3	Quite silky	*Velvety*
4	Stretchy, non-rhythmic	*Flexible*
5	Spongy, grainy	*Yielding*
6	Bubbly, non-skin like	*Artificial*
7	Silky, non-gritty	*Smooth*
	Emotional/Cognitive/Moods	
1	Stimulating, very nice, caring, secure, luxurious, calming, content, sleepy	*Satisfied*
2	Teddy bears, warm	*Loving*
3	Comforting, babies, happy, non-painful, active	*Compassionate*
4	Relaxed	*Tranquil*
5	Sensual, disorganisation	*Blurred*

For "Emotional/Cognitive/Mood" relationships, there remained 3 constructs – Cosy, Efficient and Childish. However it is acceptable that Cosy and Childish is covered in Factor 2 and 3 and Efficient in Factor 1. The above data provides acceptable subjective results.

The main experiment, below, provides objective rather than subjective results through group analysis.

2.2 Group Study

Stimuli. 10 different fabrics (familiar), listed as follows, mounted flat on MDF wood measuring 2" x 3", taped down at two sides:

Figure 5. Fabrics for Group Study
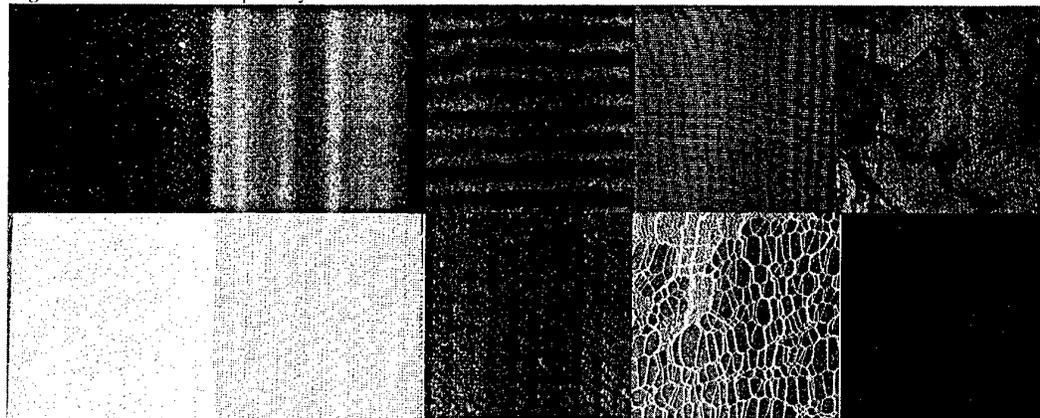
1. Denim *(100% Cotton)*
2. Fleece *(100% Polyester)*
3. Corduroy *(100% Cotton)*
4. Lycra *(83% Polyamide, 17% Elastane)*
5. Velvet *(100% Viscose/Silk)*
6. Satin Silk *(100% Silk)*
7. Irish Linen *(100% Cotton)*
8. Tweed *(100% Wool)*
9. Lace *(65% Polyamide, 35% Cotton)*
10. Leather

Subjects. 20 female 1st Year Fashion & Textile students aged 19-23, including two mature students aged between 30-40.

Procedure. The procedure was set out as in the Pilot experiment above; the environment was a university studio setting. For Phase 3 (labelling of factors), 4 of the students and the experimenter (5) sat down in a brainstorming session to provide labels for the 'Fabric Surface' factors that evolved. The experimenter gave labels for the Emotion/Cognitive/Mood responses.

Results. Five main factors were extracted, accounting for 87.2% of the variance. Items were allocated to factors if their correlation exceeded 0.75 for Factors 1 and 2 and 0.5 for 3-5.

Results are summarised in Table's 2-6, below.

Table 2. Group Study Factors

Fabric Surface		
Factor	**Construct Groups**	**Factor Label**
1 (34.5%)	+Coarse, +friction, +sandpaper, +thick	Rough
	-Silky, -very soft,	Downy
	+/-	*Animal*
2 (26.7%)	+Stiff, +very smooth, +waterproof, +furry	Coated Seabed
	-Breathable, -clean	Fresh
	+/-	*Protective*
3 (13.2%)	+Natural, +tingly, +spongy, +textured	*Mossy*
4	+Gaps, +rough, +not smooth	*Coarse*

(6.8%)		
5 (6.0%)	+Close weave, +slippery	Silky
	Emotional/Cognitive/Moods	
Factor	Construct Groups	Factor Label
1 (19.52%)	+By a fire, +country walks, +feminine, +hats, +warm, +winter	Sedate Warmth
2 (12.92%)	+1980's, +modern	Contemporary
	-Ancient, -nostalgic	Eternal Melancholy
+/-		Faded Familiarity
3 (10.48%)	+Comfort, -bikers, -masculine, -trousers	Male
4 (8.24%)	+Cycling shorts, +dance clothing, +leotards, +swimming	Energised
5 (6.67%)	+Rich, -summer shirts	Opulent Poise

[+ = positive correlation, - = negative correlation]

For "Fabric Surface", Factors 1 and 2 cover the most variance. Fabrics were therefore plotted as Factor 1 against Factor 2 as follows. This offers a somewhat contemporary and stringent approach in correlating Fabric Surface responses, but an unsettling approach in terms of emotion/cognitive/mood responses:

Table 3. Factor's 1 & 2 Allocation

Fabric Surface	
Factor 1: Animal	Factor 2: Protective
Denim	Fleece
Corduroy	Lycra
Velvet	Irish Linen
Silk	Leather*
Tweed	
Lace	
Emotion/Cognitive/Moods	
Factor 1: Sedate Warmth	Factor 2: Faded Familiarity
Fleece	Denim
Corduroy	Lycra
Silk	Velvet
Tweed	Irish Linen
Leather	Lace

* Leather could also come under Factor 1, but ultimately belongs in Factor 2.

Using all 5 factors, results are summarised as follows:

Table 4. Five-Factor Allocation

Fabric Surface Factors	Fabric Type
Animal	Corduroy, Leather
Protective	Fleece
Mossy	Tweed, Denim
Coarse	Lace
Silky	Lycra, Velvet, Satin Silk, Irish Linen
Emotion/Cognitive/Mood Factors	Fabric Type
Sedate Warmth	Fleece, Tweed
Faded Familiarity	Satin Silk, Lace,
Male	Corduroy, Leather
Energised	Lycra, Denim
Opulent Poise	Velvet, Irish Linen

Finally, if we merge both sets of factors together, we have the following summary:

Table 5. Combined Factors

Emotion/Cognitive/Mood	Fabric Surface
Sedate Warmth	Protective
Faded Familiarity	Coarse
Male	Animal
Energised	Mossy

Opulent Poise	Silky
Fabric	**Combined Factors**
Denim	Energised – Mossy
Lycra	Energised – Mossy
Fleece	Sedate Warmth – Protective
Corduroy	Sedate Warmth – Protective
Leather	Male – Animal
Velvet	Opulent Poise – Silky
Satin Silk	Opulent Poise – Silky
Irish Linen	Opulent Poise – Silky
Tweed	Faded Familiarity – Coarse
Lace	Faded Familiarity – Coarse

This study evaluated fabric responses and suggests that the characteristic "feel" of a given fabric depends on a particular combination of variables involving both a fabric surface and its emotion/cognitive/mood associations. If we label them separately for example categorising a fabric under a fabric surface factor only, the fabric type can differ in the emotional response. In consideration of the variables that make up a factor, by combining the factors a solution can be reached in terms of discriminative fabric perceptions.

If we then rework them in terms of words associated with the 'wearing' of these textures, i.e. the emotional self:

Table 6. Fabric vs. Factor vs. Self

Fabric	**Combined Factors**	**Emotion/Self**
Denim	Energised – Mossy	Happy, young, confident, impulsive
Lycra	Energised – Mossy	Happy, young, impulsive, nervous
Fleece	Sedate Warmth – Protective	Happy, content, satisfied, reserved,
Corduroy	Sedate Warmth – Protective	Happy, content, reflective
Leather	Male – Animal	Fear, Anger, Surprise, passionate, impulsive, strength
Velvet	Opulent Poise – Silky	Happy, loving, sensual, sleek, sophisticated, extravagant, reflective, spiritual
Satin Silk	Opulent Poise – Silky	Happy, loving, sensual, reflective, sleek, sophisticated, open
Irish Linen	Opulent Poise – Silky	Happy, sensitive, reflective, spiritual, moralistic
Tweed	Faded Familiarity – Coarse	Content, reserved, isolated, moralistic, eccentric
Lace	Faded Familiarity – Coarse	Sad, sensitive/sentimental, uneasy, shy, insecure, confused, isolated, nervous

In the visual response given by students, outlined below in two examples, the relationship between fabric and the self, as above, is evident.

3. Visual Response

Mood Board Exercise. Based on the above experience, students were given a brief to select their own choice of fabric to work from and create a visual response to. The mood boards were to selectively reflect some of their responses to the physical evaluation of the fabric they selected. (These research/ideas boards are used by designers to develop design philosophies.) On completion they were then asked to label their boards with a word or words that encapsulate a visual conclusion. It should be noted that a majority of the students were previously unfamiliar with using or working with computers prior to this module. They were given 2 weeks (6 hour total module time) to complete it. It shows a variable response to different fabric qualities and on the basis of individual choice, choices they made based on curiosity or that they may relate to. It proved a positive experience in terms of introducing virtual technologies to a group that work in a particularly tactile or hands-on manner. Two examples are given below:

Figure 6. Childhood Summers
Soft, light, cool, breathable, childhood, summer, fun, nostalgic, sweets, pretty, feminine, light, home-made, homely, mothers, chintz, comfortable clothes, 1950's, kitsch, afternoon tea, games, 'my old dresses'.

Figure 7. Slithery Lizzie
Cold, tightly woven, smooth, small grooves, slithery, wet and slippy, skin shiny, leather boots, frogs, lizards, crocodiles, sleek, sexy, punk, prostitute.

In the first story, 'Childhood Summers', the colour (pink and white), fabric type (100% Cotton) and weight (light) of the fabric, builds a visual story and a representation of a friendly character and whimsical environment. She looks delighted and in her light-hearted garden of innocence, domesticated and moralistic nostalgia. In the story of 'Slithery Lizzie' the slippery coated rigid fabric and texture has been used to create a possibly hostile character of the night that is as manipulative and corrupt, evil or just as strong, sassy, and free as a wild crocodile or snake. Yet she is also timid, mischievous and cute as a small frog.

An example of this seasons (summer) visual and oral texture messaging is as follows: *'Who can resist clothes that look like they've been stolen from your little sister's wardrobe? ... What grown-up girl doesn't yearn to don dreamy dressing-up-box clothes that their great-grandmothers might once have worn .... What did you do in the war mummy? something more whimsical for those 'let's pretend' moments ... Right now, fashion is a real giggle'.* See Figure 8, below [13]

Figure 8. 'What did you do in the war mummy? ... A real giggle (1980's kid)'

4. Handle

In terms of the ergonomic criteria for a suitable haptic device, four handle methods shown below show fabric properties evaluated by handle type. As suggested earlier, the multiple finger pinch and the touch-stroke are the most relevant. [3] However, using just the index finger has also proved acceptable.

Figure 9. Handle Techniques

1. Touch-Stroke   2. Rotating Cupped   3. Multiple Finger   4. Two Handed Rotation
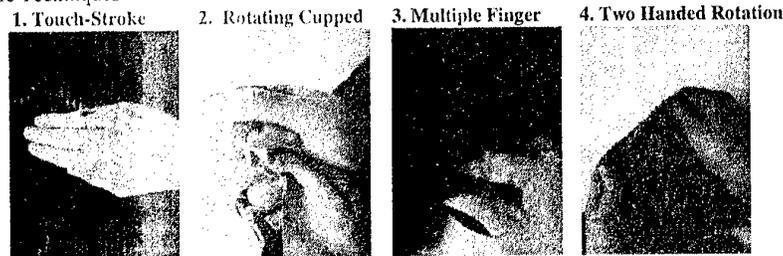
Table 7. Handle Techniques

	Handle Technique	Properties Evaluated
1	Touch-stroke	Surface quality (texture), temperature
2	Rotating Cupped Action	Stiffness, weight, temperature, comfort, overall texture, creasing
3	Multiple Finger Pinch: Rotating between the Fingers action with one hand (thumb and 1 or 2 fingers)	Texture, stiffness, temperature, fabric structure, both sides of a fabric, friction, stretch (force-feedback)
4	Two Handed Rotation Action	Stretch, sheerness

5. Conclusions

This research introduces the delightful aspects of fabric perception through an examination of visual, touch and emotional/cognitive/mood impact. The evaluation of this multi-modal, cognitive and emotional experience, examined together, offers a reality model in the development of a vocabulary, 'oral and aesthetic texture', that could be implemented in the development of control variables for interactive communication within a virtual environment. Combined with previous work where evaluation was based on existing sensory evaluation techniques, [14] [15] both scalable and detailed analysis of fabric surface and its properties coupled with humane assessment of fabric perceptions can be established that can be used to refine haptic technology for the fashion and textiles and clothing arena.

'The hypothesis is developed that brains are designed around reward and punishment-evaluation systems, because this is the way that genes can build a complex system that will produce appropriate but flexible behaviour to increase fitness ... The reason that both emotion and motivation are treated [considered together] is that both involve rewards and punishments as the fundamental solution of the brain for interfacing sensory systems to action-selection and execution systems. [16] The amygdala and the orbitofrontal cortex are areas in the brain associated with emotion and motivation, stimulated by for example sensory stimuli and cognitive processing of language, memory and association. Functions of emotion are involved in the following responses: autonomic, behavioural, motivational, communication, social bonding, cognitive evaluation – events and memories, and in the storage of memories. [16] These responses are associated with clothing as with most stimuli, however, with the wearing and selection of clothing, a closer understanding to the relationship of the self can be examined.

The next phase of this research that will therefore involve evaluating and measuring psychological and neural responses to clothing and fashion, i.e. fabric in context. It is anticipated that the research, as well as providing the necessary data for translation in a virtual sense, could also provide insight into medical disorders associated with these systems in the brain.

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7. Acknowledgements

force magnitude paralleled the actual force.

Although the fit was not perfect, these preliminary results clearly validate the use of bio-mechanical models of the arm to analyze the interaction force recorded during imposed motions. Future work with a larger set of stimuli might be necessary to assess whether more complex models should be considered.

Acknowledgments

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Haptic transmission over IP networks:
image perception in response to increasing latency

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Abstract

Computer haptics is increasingly becoming available for use within human machine dialogues as display capabilities improve and their cost falls. The next obvious development is for haptics to be included within multimodal applications running over networks using Internet protocols (IP). Clearly, in order to engineer networks to carry haptic information in an efficient and cost-effective manner, it is necessary to quantify how the characteristics of the transmission path impact on the user perceptions of haptic image quality.

This paper will report the results of experimentation with our haptic network simulation into the impact network latency on the user perception for quality of transmission of a haptic image. And, it will briefly discuss the implications this research may have for the transmission of haptics over IP networks and QoS measurement.

1. Introduction

Quality of service (QoS) models and assessment methods exist for visual and auditory transmission. These will need to be combined with haptics, and other new types of sensory information emerging onto public networks, to provide QoS tools for assessing the capability of networks to carry multimodal information.

For the transmission of visual and auditory information a key constraint that impacts on image quality is the bandwidth available for the transmission. However, for an experimental haptic transmission system we developed – this linked two Phantom display units via an IP network to enable two way communication between them – we found bandwidth to be a minor issue. The major factor that governed the image quality in our haptic transmission was the latency of the network over which it was running.

Latency is the time taken within a network for the round trip of a packet of information to a destination and back to the source. With our simple haptic transmission system we saw instability and communication break down when network latency increased. To investigate this further, and to enable us to develop strategies to control or manage the impact of latency on haptic IP transmission, we built a simple haptic network simulator that allowed us to control the latency within a simulated haptic transmission path.

One end of our network simulation was a virtual Phantom haptic display which could have a virtual object placed in front of it. A real Phantom was then used to feel the remote virtual object through the simulated network by communicating with the virtual Phantom. The latency of the network between the real and virtual Phantoms was varied to investigate the impact on the user perception of the transmission quality.

The latency range used in the experiment was 0 to 40 milliseconds in 10 millisecond steps. This roughly covered the range found when we used the "Ping" network tool to check the Internet latency from our laboratory to a small selection of UK Universities where computer haptics research is currently taking place. Since we may need to engage in haptic communication over these network routes in future studies they were used to set the latency range for our experiment.

2. Methodology and procedure

An experimental control program was written in LabView and C++ to control the presentation of an image presented to a participant with a Phantom haptic display. The image simulated an object that had been sent from a remote Phantom over an Internet link with a controlled level of latency and a little simple damping. Each participant carried out a simple object discrimination task.

For a level of latency a participant was asked to determine if the image being presented by a Phantom was a cube or sphere. After each object presentation the subject adjusted an on screen cursor with a mouse to provide an image quality judgement on a rating scale.

The rating scale was one developed for use in transmission performance testing (ITU 1998) and has been used for on-screen presentation in audiovisual quality assessments (Hands 2001). The participants were

also asked to indicate whether the image quality was acceptable before going on to the next object presentation.

Each subject received 5 levels of latency (0, 10, 20, 30 and 40 milliseconds) for both a sphere and cube recognition task and repeated 5 times. The presentation order of the treatment combinations was randomised.

There were 16 participants who were BT employees working in the Adstral Park site near Ipswich.

3. Results

The experimental control program recorded measurements of the user interaction with the virtual objects. This enabled both objective measures of the participants performance to be taken as well as the quality of service ratings that the participant provided.

Statistical testing of the rating scale score with a 2 way repeated measures ANOVA indicated that there was a significant difference in user perception of image quality as a result of increasing latency $F_{(4, 60)} = 34.9$, $p < 0.0001$ There was also a difference between the object shape $F_{(1, 15)} = 26.909$, $p = 0.0001$, and a significant interaction between shape and latency $F_{(4, 60)} = 14.908$, $p < 0.0001$

The average acceptability score was also tested with a 2 way repeated ANOVA. Again latency was statistically significant ($F_{(4, 60)} = 21.164$, $p < 0.0001$), but there was not a significant result for object shape or the interaction.

Testing the participant's recognition times did not provide any statistically significant results. Neither was their any statistically significant differences in the accuracy with which participants were able to identify whether an object was a sphere or a cube.

4. Discussion

As latency increased in this experiment the users perception of the quality of the haptic image was reduced. This was not a simple linear relationship with increasing latency. The reduction in perceived quality interacted with the type of object being displayed. For the sphere degradation was not as large as for the cube as the latency increased see fig 1.

Fig. 1 Interaction Bar Plot for Average Quality of Service Effect: Shape * Latency

Clearly, this type of quality measurement is going to be task dependent. Any task used will need to be representative of the eventual use of the transmission path.

Traditionally in communications networks the major concern has been with the bandwidth limitations. With increasing use of new forms of sensory information being used over networks it will be necessary for network providers to offer a quality of service that is both economic and effective for the consumer. If latency cannot be avoided then it will be necessary to develop methods for transmitting haptics that are robust with respect to latency (Wilson et al 1999).

5. Conclusions

A better understanding of human communication with computer haptic simulations, and interactions with other sensory modalities, will indicate where it may be possible to make engineering trade offs to manage down or remove the impact of latency on the customers perceptions. There is much work that needs to be done to enable robust reliable real time haptic communication to take place over public IP networks with a reasonable quality of performance when latency is present.

6. References

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7. Acknowledgements

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