TONGUE-BASED ELECTROTACTILE FEEDBACK TO PERCEIVE OBJECTS GRASPED BY A ROBOTIC MANIPULATOR: PRELEIMINARY RESULTS

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Abstract - **A sensate robotic gripper was developed and interfaced to an electrotactile tongue stimulation system. The prototype system permits grasped object recognition by the user without visual sensory input. Modifications of an existing two finger robotic gripper included the addition of six conductive polymer force sensors mounted in a pentagonal (24mm diameter) pattern with the sixth sensor placed in the center. Shape information from the robot gripper in contact with a test object is relayed to the user via patterned electrotactile stimulation on a micro-fabricated flexible tongue array. A previously developed Tongue Display Unit (TDU) provides the electrotactile stimulation, which pattern maps information from the six sensors to discrete groupings of electrodes on the 12 x 12 matrix tongue array. Modification of an existing software program facilitated a tongue mapping closely resembling the spatial layout of the six force sensors. A preliminary human subject study was performed to demonstrate the accuracy of recognition when presented with one of four basic shapes. Results indicate sensor resolution and orientation influence performance, but even a limited configuration provides highly accurate shape recognition.**

Keywords - **electrotactile, tongue, robotics, perception, sensor, electrocutaneous, haptics, tactile.**

I. INTRODUCTION

There has been significant work in developing prostheses controlled by people with amputations or high-level quadriplegia. Tele-manipulation systems were initially developed for work in hazardous or inaccessible environments, e.g. the nuclear waste processing facilities and deep-sea exploration, where the human operator remotely controls a robot while viewing a video display of the end-effector. However, even the current systems are slow and clumsy, primarily due to the lack of appropriate sensory feedback to the operator. The tele-manipulation community has long recognized the inadequacy of strictly visual feedback, and the particular need for uniquely haptic information such as contact, grasp force, shear, and slip, which convey critical information about the state of the hand-object interaction [1]. Furthermore, the majority of existing haptic feedback systems (see e.g. [2] for a review) were designed to provide feedback to the operator's hands via special displays or gloves in order to stimulate the "normal" feedback channels the operator would utilize if directly handling an object. However, these approaches do not meet the specific tactile sensing and feedback needs for a useful robotic prosthesis.

Models of human manipulation and of fingerpad mechanics indicate that the shape of the finger deformation, distribution of force and pressure, and shape of the contact region facilitates grasp stability and successful manipulation [3]. For people with quadriplegia, however, ordinary haptic feedback for tele-operation is not possible because both sensation and motor control is lost below the level of the spinal cord injury. By using the tongue, tactile sensory deficiencies experienced by people with high-level quadriplegia may be overcome [4, 5]. Employing this new sensory feedback pathway would allow users to literally feel the objects that they are tele-manipulating. The study presented here utilizes the tongue as an alternate haptic channel by which sensory information regarding object shape can be relayed.

Although this system is intended for people with high-level quadriplegia, there are clearly numerous similar applications for the proposed technology, or at least the part of it that provides accurate tactile feedback through the tongue. Such a system could be coupled to various forms of robotic control, including the use of the hands to control the robot. Operators with normal motor control could incorporate hand feedback and tongue tactile stimulations to create an additional haptic channel. Many applications would benefit from a staff of robotic hands sure enough to entrust the handling of radioactive, biohazardous, or explosive materials. The prospect of tele-robotic systems that could enable human operators (potentially including persons with high quadriplegia who become expert in the use of the proposed technology for many life needs), sitting comfortably on Earth, to pick up and probe rocks on other planets, or feel the texture of object on the ocean floor, is exciting to space scientists and Navy planners [6].

The technology development studied here could potentially be used in such hands-free tele-manipulation environments. In addition, this study is one of the first experiments conducted to demonstrate the capacity of the tele-robot to convey shape information in the form of tongue electrotactile stimulations. The experimental apparatus (including robotic servo gripper, TDU, and interface control computer), in block diagram form, is shown in Fig. 1, below.

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Abstract

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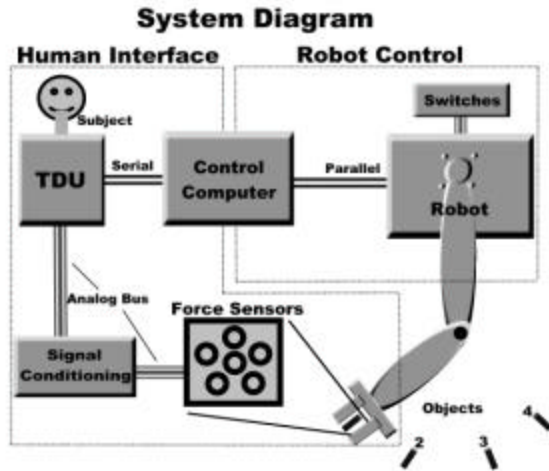4

System Diagram

Fig. 1. Experimental apparatus block diagram with outlined subsystems, Robot Control and Human Interface.

II. SYSTEM IMPLEMENTATION

Our overall goal was to demonstrate the feasibility of a novel sensate robotic gripper that could close the control loop in a human-telerobot manipulation task by providing tactile feedback of object shape information to the users tongue. To that end, we have developed a prototype system that affords a tactile interface between a robotic manipulator and a human subject. The interaction exists at the gripper face where six force sensors (Model #400, Interlink Electronics, Inc., Camarillo, CA) are attached and provide shape contact information in the form of 0-5 volt potential changes. These voltages are converted to electrotactile stimulations on the user's tongue by way of a Tongue Display Unit (TDU-ver. 1.1, Wicab, Inc., Madison, WI). The TDU is a programmable tactile pattern generator with tunable stimulation parameters accessed via a standard RS-232C serial link to a PC. The control scheme developed for this study is actually an open loop structure because the user does not maintain control over robotic manipulations. In addition, visual and auditory clues about the object being grasped were prevented so that this investigation could focus on the capacity of the robot system to accurately convey shape information to the subject via the tongue. Once this capability is demonstrated, the prototype may be expanded to allow closed loop robotic tele-manipulations. The block diagram in Fig. 1 shows the two interfacing subsystems.

A. *Robot Control*

For this study we modified a six-degree-of-freedom robot manipulator (Robix, Model RCS-6, Advanced Designs, Inc., Tucson, AZ). The electronic interface provided with the Robix facilitated access, via computer parallel port, to each of the DC joint servomotors, as well as seven external switch inputs. Using five of these inputs and skeletal software provided by the manufacturer, we created

a C++ language program that automated the control of robotic movements. Once initiated, this program responded to one of five external commands. Four pushbutton commands were linked to a unique set of movements, each aligning the manipulator with one of the predetermined object locations (labeled 1–4). The gripper then closes around the object, creating contact information corresponding to the locus of the sensor, and waits. Upon depression of a fifth pushbutton (labeled "Return"), the gripper releases the object and returns to its "Home" position. The robot control program was created as a graphical user interface (GUI) and presented as a basic window containing a pull-down "Options" menu. Within the menu were three choices, "Run," "Stop," and "Exit." Initialization of the robot commenced upon depression of the "Run" command and consequently enabled the pushbuttons for object manipulation control.

B. *Human Interface*

Realization of shape contact information is provided by six conductive polymer force sensors mounted on one face of the robotic gripper. Five sensors are located in a 24mm diameter pentagonal pattern, with the sixth located in the center. Each 7.75 mm diameter sensor has an interdigitated active sensing area of 5.08 mm, a thickness of 0.38 mm, and 30 mm dual trace leads. Since the active sensing area and trace leads are of similar thickness, a 'force concentrator' was added to the active area by applying a 3 mm x 3 mm x 1.3 mm (W x L x H) square of semi-compliant self-adhesive foam (3M, St. Paul, MN). This also helps to reduce the activation force dependence on sensor and/or shape surface height and consistency. To accommodate sensor dimensional requirements, two 16-gauge aluminum plates (Al 6061, 1@ 35 mm x 32 mm, 1@ 35 mm x 55 mm) were fabricated and fastened to the Robix gripper using double-sided adhesive tape (3M, St. Paul, MN). Fig. 2a shows the sensor attachment and spatial pattern on the aluminum plate.
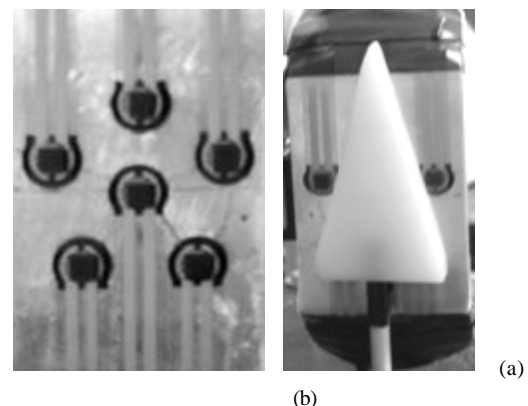

(a)

(b)

Fig. 2. Thin film force sensors (Interlink Electronics, Inc.). (a) Basic layout on Aluminum robotic gripper plate. (b) Sensor activation for triangle shape.

Contact information from the sensors is modified by conditioning circuitry to produce a 0-5 volt output to the six analog channels on the TDU. The stimulation pattern generated by the TDU is output to a micro-fabricated flexible electrotactile tongue array consisting of 144 electrodes in a 12 x 12 matrix. The user may adjust the relative stimulation intensity with a manual control knob to allow for individual preference of suprathreshold stimulation levels.

A final software modification was made to provide users with a graphical feedback. Using an existing GUI, an image of the robotic gripper plate (see Fig. 2a) with six rectangles representing the actual sensor pattern is displayed. Data from the analog channels are digitally processed and shown as a varying color dependent upon the voltage magnitude. As a object is grasped, the graphical regions corresponding to those sensors in contact with it change from black (0 volts) to bright yellow (5 volts), depending on a linear transform of contact force magnitude (v_s), to stimulus intensity (v_i). The graphical representation of what the user should be feeling on their tongue (see Fig. 2b) provides a means of self-training, and affords error checking of the sensor-to-tactile display mapping function.

III. EXPERIMENTAL CONFIGURATION

An existing program was modified to provide an electrode stimulation pattern that spatially matched the sensors. Four electrodes were assigned to each sensor and are represented as gray areas in Fig. 3. The labels, "A1" through "A6", indicate the corresponding analog input channel. The stimulation pattern on the user's tongue therefore reflects the spatial information received by the TDU from the sensor array corresponding to the shape of the object grasped by the robot.

Our goal for the experiment, as previously stated, was to develop a system for the investigating the feasibility of conveying tele-robotic shape information via electrotactile stimulation on the tongue. To facilitate this goal, four different objects were chosen: a slender rod (9 mm x 46 mm); square (30 mm x 30 mm); triangle (24 mm base, 45 mm height); and open circle (32 mm OD, 12.5 mm ID). The size and shape of the objects were based on sensor resolution and each object provides unique, but not obvious, contact information. The shapes were machined from 6.4 mm thick high density polyethylene (HDPE).

The robot and objects were mounted on a rigid wooden platform (40 cm x 45 cm) to allow accurate and repeatable manipulations. The conditioning circuitry was placed on a stand above the robot, and other components including robot control pushbuttons, Robix electronic interface, TDU, and computer were located adjacent to the platform.
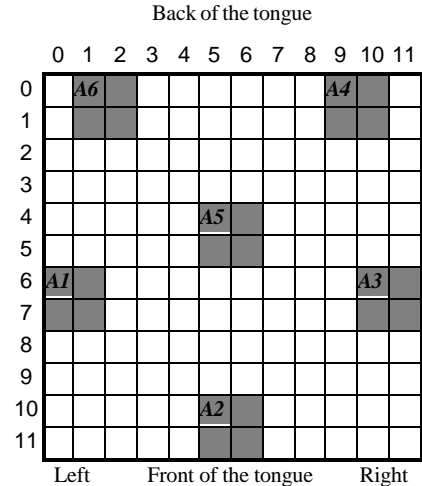

Fig. 3. Tongue display unit electrode mapping function (12x12 matrix). Dark regions indicate active electrodes. Labels indicate TDU associated analog input.

IV. SUBJECT EVALUATION AND RESULTS

A human subject study aimed at quantifying the accuracy of shape recognition with only tongue electro-stimulations was conducted (i.e. no visual feedback). Five adult subjects familiar with electrotactile stimulation participated in this experiment. Each subject was first shown the apparatus including the robot, the four possible shapes, TDU, and graphical display. Subjects were trained in TDU operation, and on the sensor-to-electrode spatial mapping using the graphical display so that they could see and feel each test shape (see Fig. 2b).

Once subjects could identify each of the four objects without the aid of visual or verbal feedback when randomly presented, a blindfold was administered, and two blocks of 12 randomized trials (equal representation) were performed. When an object stimulus was presented, subjects were given control of the stimulus intensity, and had unlimited decision time. Data was recorded as a Boolean 1 or 0 indicating correct or incorrect shape identification, respectively. If the decision was incorrect, the "perceived" shape was also recorded for analysis. The overall results of response from the 5 subjects (120 trials, total) are presented in a confusion matrix (Table 1). On average, subjects required approximately 9.3 minutes (SD = 3.1 min.) to complete the first block of 12 trials, and approximately 6.3 minutes for the second block (SD = 1.1 min.). Generally, subjects did not have significantly fewer errors in the second block. This phenomenon promotes the idea that users of a closed loop electrotactile tele-manipulation system will learn to process substitute sensory information to the point where tasks are perceived as unconscious extensions of the body.

TABLE 1
CONFUSION MATRIX FOR OVERALL SUBJECT PERCEPTION
(PERCENT CORRECT)

Actual Stimulus	Perceived Shape			
	ROD	CIRCLE	TRIANGLE	SQUARE
ROD	0.967	0	0.033	0
CIRCLE	0	0.933	0.067	0
TRIANGLE	0	0	0.967	0.033
SQUARE	0	0.167	0.033	0.80

V. DISCUSSION

The results of our study show that, overall, subjects were quite able to correctly identify the four test shapes using only electrotactile stimulation on the tongue, despite the low spatial resolution of the sensor array. In particular, high recognition accuracy was attained for both the slender rod and triangle. While somewhat lower, the circle and square recognition rates were also very promising. Some perceptual difficulty is evident in five of the 120 trials wherein subjects confused the square for the circle (Table 1). Of the five subjects, one scored perfectly and another identified only one shape out of 24 trials incorrectly.

Subject misperception of a square as a circle is interesting in that the only difference between the two shapes is the presence of sensory information from the central force sensor. We speculate that this error stems from lateral masking effects, where adjacent and surrounding sensory stimulation inhibits a centrally located stimulus, making it more difficult to detect on the tactile display [7].

Another factor that may contribute to the misperceptions is that each sensor is fed through an independent conditioning circuit and, due to variations in electrical components and limited tuning capabilities, the voltage gains may be unequal. In addition, the force exerted by the Robix gripper is not always uniformly distributed. Confusion would be introduced if object stimuli from sensor voltages were not within a known tolerance of one another. This in fact, is a probable cause for some of the single occurrences of false recognition. Subjects remarked that at times certain stimulus areas on the tongue seemed weaker than others and as a result had some difficulty identifying the object. A future iteration of this experiment would benefit from the use of a rigid DC servomotor where parallel gripper plates could be maintained throughout the robot's entire gripping range. Subjects also reported the existence of a stray stimulus associated with analog input A2 (see Fig. 2). The location of this errant electrode was near the intersection of column and row 10. When input A2 received sensory information (e.g. the triangle shape), the presence of a stimulus somewhat near A3 may have caused difficulty for the subjects. Further analysis is scheduled for solving this problem.

VI. CONCLUSION

A sensate robotic gripper and tongue electrotactile stimulation interface has been developed and tested. The system is intended to allow object recognition by the user without visual sensory input. Results from a preliminary human subject study demonstrated the effectiveness and accuracy of object identification when presented with multiple random instances of four simple test shapes held by a robotic gripper. However, this study is only the first step toward realizing a fully functional sensate gripper capable of relaying contact information for complex objects and orientations. We expect that future increases in sensor resolution will enhance performance, but even the limited configuration developed here provided highly accurate shape recognition.

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