UNDERWATER TELEROBOTICS AND VIRTUAL REALITY: A NEW TECHNOLOGY PARTNERSHIP

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ABSTRACT

Despite major advances in autonomous vehicle technologies, human-controlled ROVs (remotely-operated vehicles) continue to fill an important role in underwater work. To perform effectively, however, the human operator requires meaningful cues for spatial orientation, good workspace visibility, and tight feedback about manipulator behavior. These needs can be hard to support in actual undersea operations. Telerobot designers for space missions have addressed these challenges by presenting a graphic, virtual reality model of the workspace to the operator, who then performs tasks on this representation of the actual work site. Real-time graphic modeling can (1) maintain a continuous, clear depiction of the workspace that is largely independent of communications bandwidth, (2) allow arbitrary shading and perspective of the workspace, (3) provide integrated navigation and orienting cues, and (4) support a rich, multi-sensory feedback environment.

The use of virtual reality technologies for operator interface design is being investigated at NCCOSC for undersea ROV applications. A general-purpose virtual reality testbed is described which involves a dedicated virtual reality system for underwater applications, together with a manipulator system and supporting software. The objectives of the testbed are to examine fundamental human performance and engineering issues connected with operating on a virtual workspace for real telerobotic tasks, and to benchmark emerging telerobotic technologies in a standardized test environment.

INTRODUCTION

The U.S. Navy performs a wide range of undersea missions including deep water search and recovery, mine detection and removal, ship servicing, sensor placement, and support for scientific research. For many missions, the choice of telerobotic systems over human divers is driven by operational requirements (e.g., water depth, environmental hazards, etc.) and by concern for human safety. Unfortunately, an ROV is almost never as effective as a human diver performing the same work. While human perception, decision-making, and manipulation are essential for most underwater tasks, constrained sensory feedback from the work site (via cable or acoustic links) limits the performance

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that can be currently achieved with telerobotic systems and provides a relatively poor substitute for direct human presence (e.g., Pepper, 1986).

There are many impediments to good operator feedback. TV cameras and other imaging sensors, for example, are usually mounted at fixed points on the remote vehicle, with restricted fields-of-view or adjustment ranges. Operator perspective on the environment is therefore tied to whatever "tunnel view" can be achieved through the sensors by vehicle positioning and self-contained lighting. Support references for navigating to the work site, orienting to the workspace (i.e., vehicle station-keeping), and manipulator operation are gathered through other devices and displays which the operator must mentally integrate into a single picture of the immediate environment. A representative operator station for performing these tasks is shown in Figure 1.

In addition, many tasks take place close to the ocean bottom, where sediment is stirred up by water currents or work activities. This further limits visibility of the workspace and reduces effectiveness by forcing divers or ROV operators to stop work until the sediment clears, i.e., a "move and wait" strategy.

Figure 1. Conventional telerobotic control station

Limited operator feedback and poor interface design constrain task productivity and extend task completion times. These effects, in turn, generate higher costs for surface support resources.

Mediated Telerobotics: the Virtual Reality Interface

Space telerobotic systems, being developed for satellite servicing missions, must support precise manipulation. This requires timely and accurate operator feedback about the remote work site, communicated with a limited-bandwidth, time-delayed channel (e.g., Sheridan, 1992). Designers of such systems have utilized graphical, predictive operator interfaces as a method for achieving the necessary feedback support with considerable success (e.g., Schenker, et al, 1991; Kim, 1993). The operator of such a telerobot acts on an artificial depiction of the work environment, while the computing subsystems process raw sensor information to ensure that the depiction is physically matched to the real environment. The operator can test and preview the effects of manipulator action in this surrogate environment before these actions are physically executed. Because most of the data processing occurs locally, i.e., at the operator station, the amount of command information that is actually sent to the telerobot site is minimized. This reduces the required bandwidth for communication with the remote vehicle.

Telerobotic interfaces are distinguished from the larger domain of virtual reality systems in that operator actions are ultimately realized in the physical world. Virtual reality is nevertheless an integral part of any telerobotic system, in that the operator is physically removed from the work setting and all actions are based on its representation (i.e., via the operator's displays. Virtual reality techniques have been successfully used to support real-time operator performance in a great many physical environments including aircraft piloting (e.g., Furness, 1986), data visualization (e.g., Fisher et. al., 1987), and manipulation of scaled physical objects (e.g., Brooks, 1988), as well as telerobotics (e.g., Tachi et. al., 1994).

Virtual reality techniques can fuse real sensor data into an integrated depiction of the remote environment, and can enhance that depiction to support operator needs. Examples of such techniques include:

1. the ability to arbitrarily establish lighting and shadowing to support the best scene visibility. "Virtual lights" can be created and placed without regard for the constraints of physical equipment (Figure 2);

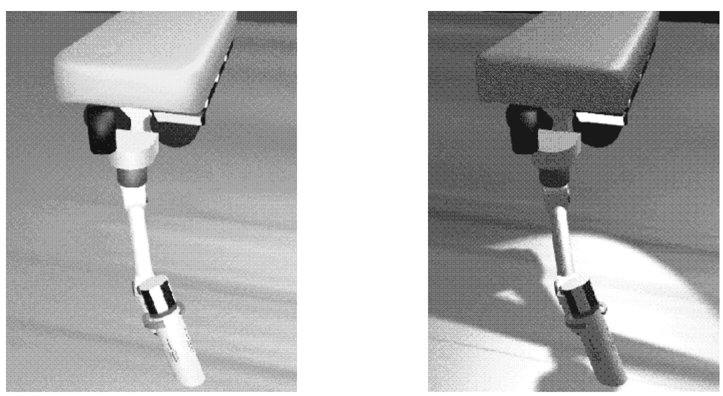

Figure 2. Virtual reality scene with and without arbitrary lighting and shading

2. the ability to establish arbitrary viewpoints of the work area (i.e., different viewing angles or distances, or multiple perspectives). Because all characteristics of the display are computer-generated, the operator controls "virtual sensors" that are independent of constraints at the work site, such as physical obstructions or visual interference by the manipulator itself (Figure 3). This can provide information about unseen features of the work space or unseen consequences of manipulation;

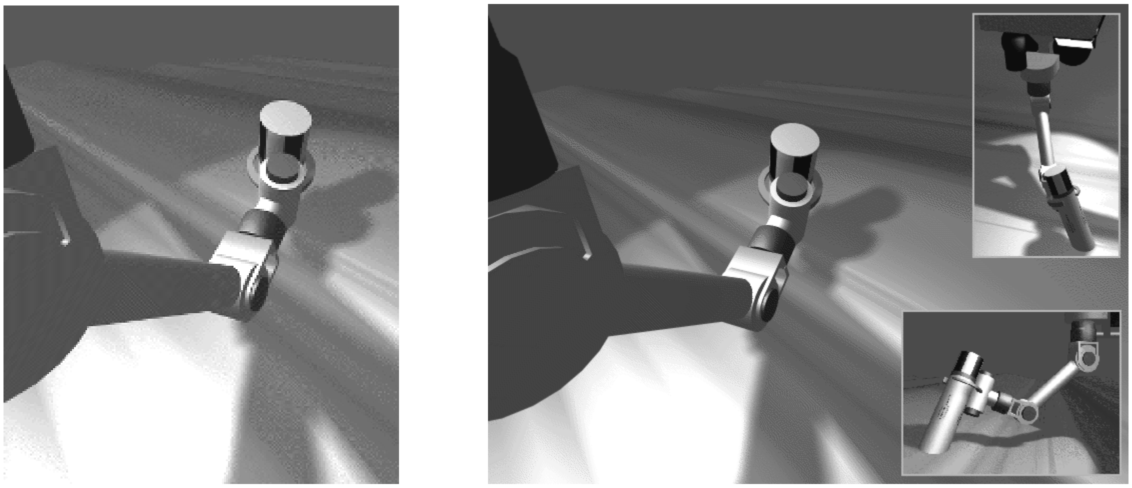

Figure 3. Multiple views of manipulator and work space combined in a single virtual reality interface

3. the ability to generate seamless, 360-degree views of the environment surrounding the work site, out to essentially arbitrary ranges. Such "virtual visibility" offers a large-scale context that can aid underwater navigation and search tasks, and can furnish a better sense of vehicle orientation in three-dimensions.

4. the capability to provide multi-sensory operator feedback, e.g., via integrated visual, auditory, and haptic displays. Human manipulation skills are almost entirely multi-sensory in nature and multi-sensory display has historically been a central thrust of virtual reality technology development (Burdea and Coiffet, 1994).

THE NCCOSC PROGRAM IN TELEROBOTICS AND VIRTUAL REALITY

The significant potential of virtual reality applications in telerobotic design is accompanied by an equally significant set of development issues requiring research and engineering attention. NCCOSC is addressing some of these issues by combining its experience with telerobot development (e.g., Shimamoto, 1993) and virtual reality systems (e.g., Murray, 1995) in a new research effort. The program focuses on benchmarking operator performance as a function of changes in virtual reality model characteristics. A unique, virtual reality-based testbed facility is being developed to support these investigations.

Research testbed facility

The NCCOSC test bed facility consists of a virtual environment interface and control system, a Western Space and Marine, Inc. MK-37 remote manipulator (typical of many systems used for underwater work) and a hardware/software architecture designed to support both in-house and collaborative research efforts.

The hub of the research facility consists of the Virtual Environment for Undersea Telepresence (VEUTel), a system developed by Innovation Associates, Inc. (Schebor, 1994) under a Small Business Innovation Research (SBIR) project. VEUTel (Figure 4) is a virtual reality interface system designed expressly for control of a remote underwater telerobot. VEUTel features:

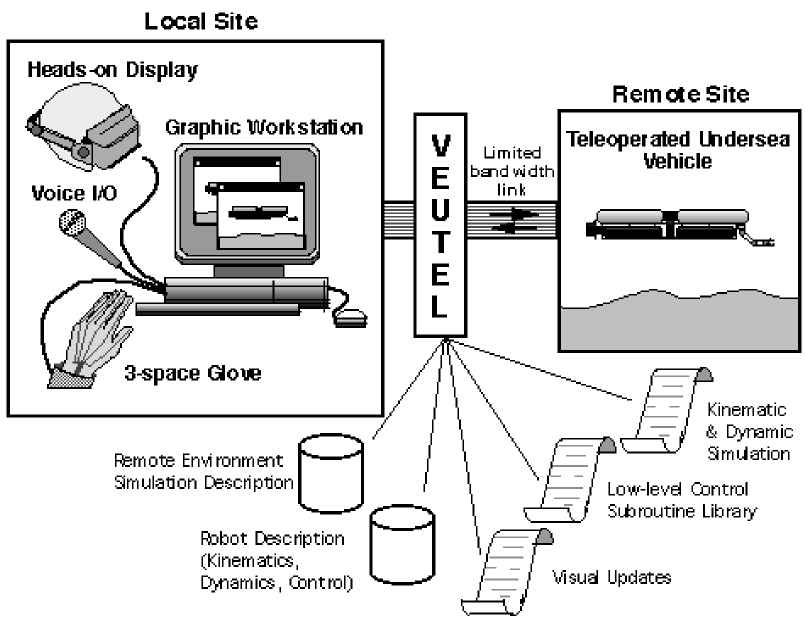

Figure 4. VEUTel system components and architecture

1. an advanced three-dimensional, stereoscopic display of the remote telerobotic work space. The display can be implemented on a conventional flat-panel (CRT) display or on a head-slaved helmet-mounted display (HMD);

2. dynamic creation and updating of the virtual reality model using an integrated, vision-based tracking system at the remote vehicle to measure and correct deviations between the simulated and real environments;

3. an advanced human-machine interface employing an intuitive, virtual reality interface with multi-modal user interaction. The interface supports complete sensor and manipulator control through a conventional telerobot master system, through a computer-linked glove, and through voice command. All controls and system status data are integrated into the virtual environment itself, so the operator can access any required information in a single, immersive display;

4. a flexible, object-oriented software architecture to generate remote scene environments and objects, and to accommodate alternate hardware

configurations (e.g., alternative manipulators, arms, or control dynamics). Such flexibility will support the integration of tactile sensors into later phases of the research program without major changes to other VEUTel components.

Research program

The NCCOSC research program seeks to develop data bases of operator performance as functions of interface characteristics. This is achieved in phases, by first measuring performance of basic operator actions, and then moving to more complex, operationally-relevant tasks. Visual interface features are examined first, followed by other forms of operator feedback, particularly haptic displays.

Operator performance benchmarks are generated through a standardized battery of perceptual-motor tasks. The test battery involves a series of very elemental actions (e.g., move, rotate, grasp, turn, etc.), which are individually measured and modeled for time and accuracy. Performance prediction for a complex task can then be done analytically, by breaking the complex task down into its constituent elemental actions and adding together the appropriate model data. The technique has an extensive history in human work performance measurement and its use as a human-machine performance tool has been advocated elsewhere (e.g., Pepper and Kaomea, 1988). Advantages of this approach are: (1) the test battery can be applied across different telerobot and display configurations for system comparisons, (2) the use of elemental actions can help to identify specific engineering deficiencies in the human-machine system (e.g., backlash in the manipulator arm for linear movements of different lengths), and (3) predictions of "real world" performance can be made for novel tasks that may never have been performed before.

NCCOSC is located adjacent to several U.S. Navy communities that use ROVs and manned submersibles for underwater work. Volunteer operators from these communities will be used to generate the performance data bases for the perceptual-motor task series. Tests are conducted using direct vision as the baseline, i.e., where the operator can directly view the work space. The test battery is repeated using a set of virtual reality depictions with differing characteristics (e.g., with and without control of scene perspective, with and without control of light and shade, etc.). Because the physical work space and the virtual reality depiction are both implemented in the laboratory, model accuracy and performance measurement can be precisely controlled.

The second phase of the NCCOSC program involves testing with a set of operational tasks, defined by the Navy operators, under the same series of display conditions. Empirical performance with these more complex tasks will be compared to predicted performance from the modeling technique described earlier. If the results are in sufficient agreement, then two objectives will be achieved: (1) the use of standardized tasks as a benchmarking method will be validated. If such validation is obtained, then the methods can be applied across other telerobotic applications and systems, providing a reliable general-purpose tool for performance characterization and prediction, and (2) the relative contribution of different visual display features (e.g., perspective control, lighting control, etc.) to performance support can be evaluated by measuring the sensitivity of task performance to the presence or absence of these features. Such data can be used to model different telerobotic systems and tasks.

Research collaboration

NCCOSC expects to introduce haptic feedback and other multi-sensory displays into its research program through collaboration with other laboratories, where studies of haptic performance are already in place (e.g., Cutkosky et. al., 1992). Most human activities are multi-sensory in nature, and additional feedback modes can supplement the visual sense in important ways. Haptic feedback is a logical first choice for multi-sensory investigations in that the sense of touch and feel may provide the primary means for updating the underwater world model used for the virtual reality interface, especially if the location, orientation, or condition of the work space is not precisely known or if imaging sensors (e.g., video cameras, ultrasound, laser, etc.) cannot provide sufficient information. It has been demonstrated, for example, that a visual model of an unknown object can be built up solely by registering the physical locations of contact events from a telerobot end effector (e.g., Driels et al, 1992; Fyler, 1981).

The VEUTel architecture of the NCCOSC research testbed can be easily reconfigured to add haptic feedback, although the motor performance test battery used for visual displays will require extensions to include such task-relevant characteristics as slip detection and grip force. The fundamental testing concept is similar, however, for both visual and haptic feedback modes.

Further approaches to operator support

Generating an immersive, virtual reality scene for telerobotic operations is not difficult. Ensuring that the scene correctly represents the physical world, however, and that operations on that world are updated in a timely fashion is a formidable challenge. Moving a remote manipulator in the absence of accurate feedback can be both inefficient and dangerous. It falls to investigations such as those described here to determine exactly how accurate the virtual reality scene needs to be, and how rapidly it must be updated. Once such (probably task-dependent) data are developed, however, many interesting support tools can be added to the operator's display to assist performance.

Using an alternate application of virtual reality, the displayed scene might rely on raw imaging with graphical overlays to provide enhancements for recognizing task-critical elements of the work space. This approach has been taken in space applications studies for satellite repair missions (e.g., Bejczy et. al., 1990; Kim, 1993). It provides the operator with immediate recognition of a problem when the raw (although possibly degraded or time-late) scene image and its graphical overlay do not match. To the extent that the raw image must be updated, communication bandwidth requirements increase. With the use of high bandwidth fiber-optic data links in most current ROV systems, however, this is not a severe penalty. The performance gain comes from the design of the graphical overlays, which can contain special highlighting information to guide operator procedures, provide interactive decision support to the operator, or offer hazard warnings.

In addition to providing a clear view of the underwater work scene, a virtual reality interface can add elements to the image as necessary, to guide a desired operator behavior. “Virtual landmarks” or navigation grids, for example, with horizon lines or highlighted depictions of bottom terrain (from existing data bases or real-time mapping of the sea floor) could help the operator to navigate and orient to the work site. On a smaller scale, visual or haptic markers could be inserted into the environment as guides for a specific manipulator path, to help the operator locate particular regions of an object, or as barriers, to help the operator avoid certain sensitive or dangerous regions of the work site (e.g., Rosenberg, 1992; Sayers and Paul, 1994). The underlying theme of these virtual reality applications is that the relation between the real and artificial worlds need not be a one-to-one mapping; information can also be modified or enhanced to obtain a desired operator performance.

Summary

NCCOSC is beginning a new program in ROV operator interface development that focuses on immersive, virtual reality methods for system control. The program is distinguished from similar efforts in its use of a reconfigurable test bed (VEUTel) and a standardized benchmarking method for performance measurement. The objectives of the NCCOSC effort are to develop and demonstrate the utility of a virtual reality interface, to develop time and accuracy performance data for a core set of elemental actions as functions of virtual reality display features (e.g., perspective, scale, light and shadow, multiple views, etc.), and to define a model of human information processing that relates these display features to skilled task performance.

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