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Test Bed Experiments for Various Telerobotic System Characteristics and Configurations

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ABSTRACT

Dexterous manipulation and grasping in telerobotic systems depends on the integration of high-performance sensors, displays, actuators and controls into systems in which careful consideration has been given to human perception and tolerance. Research underway at the Wisconsin Center for Space Automation and Robotics (WCSAR) has the objective of enhancing the performance of these systems and their components, and quantifying the effects of the many electrical, mechanical, control, and human factors that affect their performance. This will lead to a fundamental understanding of performance issues which will in turn allow designers to evaluate sensor, actuator, display, and control technologies with respect to generic measures of dexterous performance. As part of this effort, an experimental test bed has been developed which has telerobotic components with exceptionally high fidelity in master/slave operation. A Telerobotic Performance Analysis System has also been developed which allows performance to be determined for various system configurations and electro-mechanical characteristics. Both this performance analysis system and test bed experiments are described in this paper.

INTRODUCTION

Coupling human perceptual and cognitive capabilities to remote electro-mechanical robotic devices shields the human from physical harm. These telerobotic systems permit sustained time on tasks in hazardous or remote environs, reduce transit time to and from the remote site and its associated costs, and reduce or eliminate the engineering and logistic costs of life support systems (e.g. additional design and analysis costs, additional equipment to meet risk-reduction, need for redundant life support equipment, crew life-support and emergency procedure training costs, costs of launching larger payloads, etc.). Telerobotic systems permit the execution of tasks that exceed the performance capacity of fully automated robotic systems, and have demonstrated their worth and are in use in the nuclear industry and in deep-sea exploration and salvage operations. However, the current generation of telerobotic systems have not enjoyed broad commercial success because they are expensive to build and maintain, capable of performing only rudimentary manipulation tasks in a comparatively slow and clumsy manner (i.e. if they can accomplish the task, their performance times range between 8 and 500 times that of human performance), and demand highly trained operators to successfully accomplish assigned tasks. The sensory and perceptual requirements of the task, designed with the human in mind, can overwhelm the telerobot's sensory detection and processing capabilities, and manipulative requirements can exceed the kinematic or positional capacities of the remote manipulator [1].

Assessment of telerobotic system feasibility has been relegated to expensive and time-consuming field trials which often yield performance metrics which are of limited use in evaluating performance potential in dissimilar or alternative tasks. Performance tasks often are not well defined (e.g. manipulator positioning accuracy, force and torque, and operator perceptual requirements are not described), testing methods often are not described in sufficient detail to permit replication and performance comparisons among competitive telerobotic devices, and performance metrics often are of little utility to the engineering community which is interested in application or improvement in telerobotic devices.

Telerobotic devices vary significantly among each other in design and construction. Historically, developers have focused development efforts upon one, or at most a few, telerobotic subsystems using comparatively simple supporting apparatus ensembles to minimize total development time and development costs. For this reason, though the potential number of feasible combinations of alternative telerobotic subsystems is large, comparatively few implementations have been investigated. Merging a number of promising telemanipulation technologies often requires compromises in engineering design, and ultimately in system performance. The impact of any particular subsystem can be significantly influenced by the nature and performance of interrelated subsystems.

The degree to which an individual subsystem affects overall telerobotic device performance can be determined with accuracy only when considered conjointly with other subsystem designs. Telerobotic devices have been developed with either a specific set of tasks in mind, or a general goal of human capabilities. Once built, a prototype is typically subjected to a set of highly specific operational tests to determine performance feasibility. Regardless of test results, this approach requires that the developer undergo one field test after another to prove that the device is capable when other tasks are considered. Time and expense of field testing impedes marketing capability, and ultimately increases the cost of the device. Moreover, test methods are rarely described in sufficient detail to permit replication or comparison of findings, and performance measures (e.g. successful versus unsuccessful, total completion time, subjective estimates of performance difficulty) are not useful metrics to engineers concerned with efficiently improving the performance capacity of a telerobotic device.

As an example, consider the case of haptic displays. There is little doubt concerning the utility of tactile feedback [2] as exemplified in Figure 1. There are few haptic displays, and no cutaneous display systems which are able to convey a complete sense of touch. Significant research and development efforts have been made in the area of psychophysics [3] (e.g. stimulus perceptual thresholds), and in displays designed to convey alphanumeric characters, or left-right up-down directional cues for vehicle operators. However, little is known about stimulus methods and strategies needed to convey perceptual information [4]. Questions concerning the design of haptic displays are manifold. For example, what stimulus tactor system (i.e. the form of stimulus, tactor size, spatial distribution, tactile and tactor force resolution, etc.) is acceptable given task constraints, mode of stimulation, and necessity of corroborating stimuli (i.e. postural, visual, and auditory feedback) for development of operationally relevant perceptions? Haptic displays must convey information without disrupting perception of master-controller force reflection (i.e. backward masking), keeping in mind operator tolerance and stimulus acceptance issues, and the problem of stimulus adaptation (i.e. requiring greater and greater stimulus intensities to achieve suprathreshold sensations). Significant future efforts will be required in designing haptic displays and assessing their performance in telerobotic systems. This will require test beds in which future displays can be exercised in telerobotic systems, and adequate tools with which to assess their performance and feasibility.

TELEROBOTIC PERFORMANCE ANALYSIS SYSTEM

Comprehensive analytic models, development and testing of

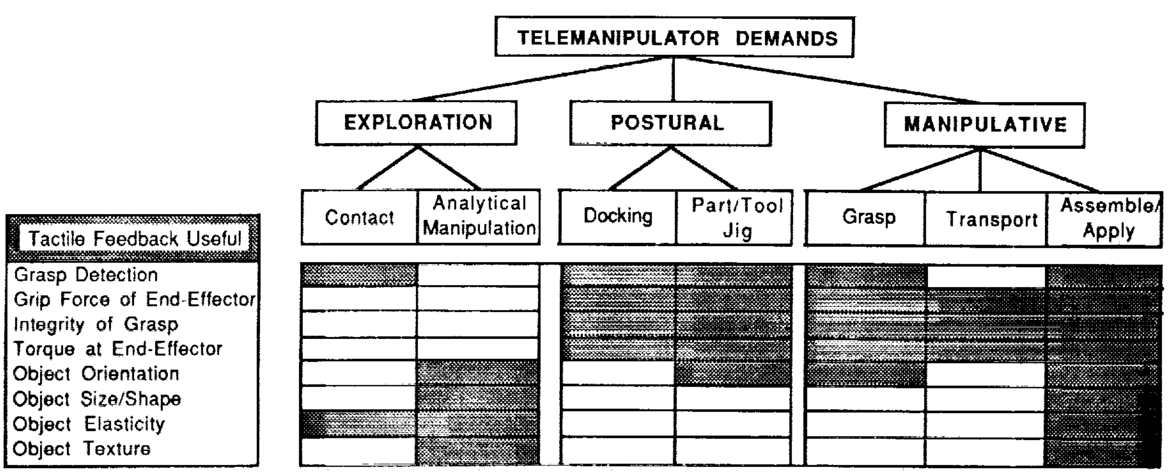

Figure 1. Scope of importance of tactile feedback in telemanipulation

multi-faceted prototypes, and enhancing our knowledge of the effect of interactions between subsystems upon overall system performance can help direct development of capable telerobotic systems that are not overly complex or expensive. In response to this need, WCSAR has undertaken a program to:

a) develop telerobotic work methods analysis procedures;
b) develop terminology used for describing telerobotic performance objectives; and
c) develop performance models and metrics used in describing device performance capabilities.

The industrial community has long accepted this practice, and uses methods engineering models for describing and analyzing human worker and machine performance in manufacturing environments. Using a standardized set of descriptors, task descriptions can be accurately conveyed to other engineers, task descriptions can be entered into computerized performance analysis models, and, thus, systematic comparisons can be made of task performance and cost across telerobotic devices developed within and among laboratories and vendors [5].

Following methods analysis, motor (e.g. Therblig sequence, indexes of difficulty for motor sequences, positioning tolerances, type and force of grasp, etc.), perceptual (e.g. task visual, aural, kinesthetic, and haptic detection demands), and cognitive (e.g. information processing, decision making, etc.) elements of a telerobotic task can be analyzed using a family of telerobotic performance prediction models. In addition to predicting performance feasibility for a telerobotic device of known physical performance characteristics, the models indicate which performance elements which are most troublesome, and what subsystems are most limiting of performance. With this knowledge, an analyst may change the methods of the task, or consider an alternative telerobotic design that is better in the face of performance and cost criteria. Figure 2 graphically shows the organization and process of the Telerobotic Performance Analysis System which is being developed.

Although methods analysis and human performance used in industrial manual assembly operations are well established, new or revised models must be developed for telerobotic systems. Robust models of human performance are based upon intact humans whose perceptual-motor skills are not diminished as they are when coupled to a master-controller and given only limited subsets of sensory information.

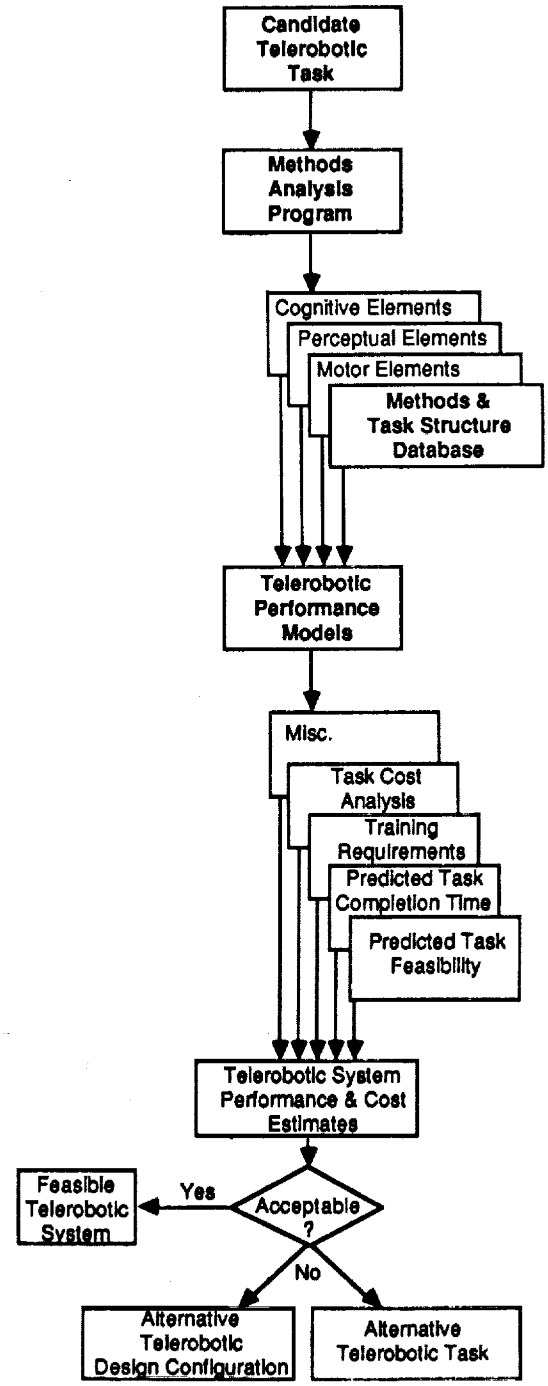

Figure 2. Telerobotics Performance Assessment System

Initially, we will employ motor, perceptual, and cognitive performance models which have demonstrated statistical robustness and operational validity industrial settings. The goals are to:

a) provide multi-variate design gradients to speed engineering development of telerobotic devices while minimizing data collection;
b) collect data using techniques which provide results which are acceptable to both basic science and engineering communities (i.e. performance findings are scientifically valid, yet metrics have engineering design relevance); and
c) provide on-line guidance to the experimenter regarding the design and implementation of an evolutionary, or "hill-climbing", experimental approach to determining the best mixture of telerobotic subsystems to meet a set of operational objectives.

DEMONSTRATIONS OF TELEROBOTIC PERFORMANCE ANALYSIS

For the purposes of demonstration, the Telerobotics Performance Analysis System will be used to drive the design, and to confirm the performance capabilities, of dexterous telemanipulation systems which provide simple yet compelling perceptions of remote touch. Clearly, there are a number of design variables which must be considered when designing and implementing an integrated end effector, master controller, and haptic display system. This engineering problem is of sufficient challenge to test the ability of the Telerobotics Performance Analysis System to conjointly evaluate several design variables simultaneously, and to expeditiously recommend valid design modifications following limited testing. The first phase of the demonstration will be based on a high fidelity, table-top master/slave gripper in which design variables can be independently modified and controlled. Perceptual-motor performance test findings will be used to direct experimentation and to provide multi-variate design gradients for use in guiding the next phase of the demonstration in which will employ a prototype manipulator (arm and hand), master controller, and haptic display complex in the WCSAR Telerobotics Test Bed. Results obtained will enable the engineering design of future more capable telemanipulator actuation, control, and display subsystems.

Significant advancements have been made in the design and implementation of robotic end effectors. Three-digit and four-digit hand-like "tendon", gear, or direct-driven robotic end effectors have been developed in laboratories concerned with analysis and control of flexible hand-like grasping systems, and actuation and control strategies for multi-articulated grippers. Yet, many fundamental questions concerning end-effector geometry, degrees-of-constraint, actuation bandwidth, actuation and transmission strategies, etc. have not yet been answered satisfactorily. End effectors must resist damage in their operating environment and produce sufficient grasp force, manipulation bandwidth, and grasp compliance or stiffness to meet operational requirements. In addition to these design issues, there is uncertainty about the performance consequence of implementing greater end effector kinematic complexity (e.g. number of articulations within a digit, and number of digits), palmar and volar topology, and sensor integration.

Problems also must be overcome in the design and implementation of a dextrous end-effector master controller [6]. Ideally, the coupling between the controller and the operator's hand should be very stiff for the sake of good position and velocity perception and control. However, stiff coupling schemas result in rapid onset of localized hypoxia, localized muscle fatigue, discomfort, and tremor in the intrinsic muscles of the hand all of which limit operator tolerance and performance capacity. The bulk and limited degrees of freedom of a back-driven master hand-controller are also likely to restrict operator range of motion capability, and ultimately end effector dexterity. Deadspace, backlash, and friction in the master controller and end effector may significantly affect an operator's ability to perform or to recognize small displacements in the end effector.

In order to understand the effects of different forms of sensory feedback, and quantify how the performance of an operator is affected by changes in the electromechanical characteristics of a system, a high-fidelity, single degree-of-freedom, table-top master/slave gripper has been developed by WCSAR. With this system, the ability to test a number of different types of sensors providing high-performance force or tactile feedback to the operator is provided. In conjunction with various forms of sensory feedback, mechanical characteristics of the system such as compliance, mass, friction, backlash, and dynamic bandwidth can be altered, thereby providing a straightforward experimental system which allows Telerobotic Performance Analysis System to be used to quantify performance under various conditions.

The single degree-of-freedom master/slave gripper system was designed to be a nearly ideal electromechanical system. The master and slave devices are identical in design and construction. Figure 3 is a photograph of the system, and Figure 4 shows a layout sketch of one of the devices. Each device consists of two linear DC motors connected in parallel with a stroke of two inches (5 cm). A high-resolution linear encoder is provided for position feedback and velocity estimation. The devices have no backlash, and friction is minimal. Backlash was eliminated by using direct drive actuators and no gear reduction.

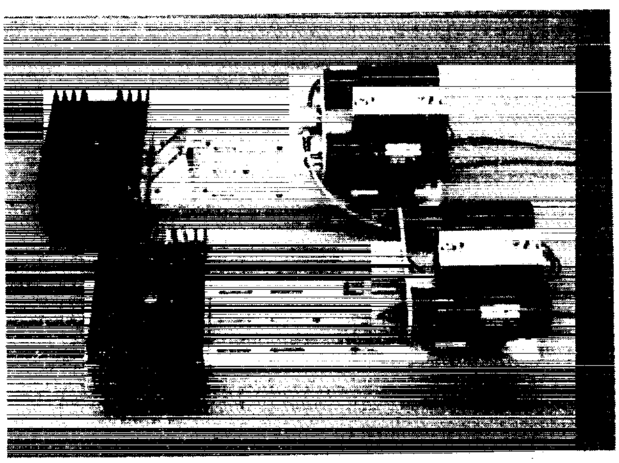

Figure 3. Single degree-of-freedom, table-top master/slave gripper

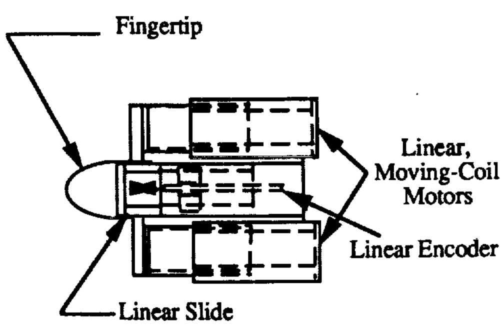

Figure 4. Mechanical detail of slave device (master is structurally identical)

Friction was minimized by using brushless motors and a precision linear slide. The slide is the sole source of mechanical friction with a friction force of less than 0.33 oz. (9.4 g). This is 0.25% of the maximum force which can be generated by the device, and 1/40th of the amount of friction in a typical gripping device. A mounting surface is provided to allow various sensors and displays to be tested with the system. The state-feedback bilateral controller used has active stiffness and damping as shown in Figure 5, and the configuration of the computer control system is shown in Figure 6.

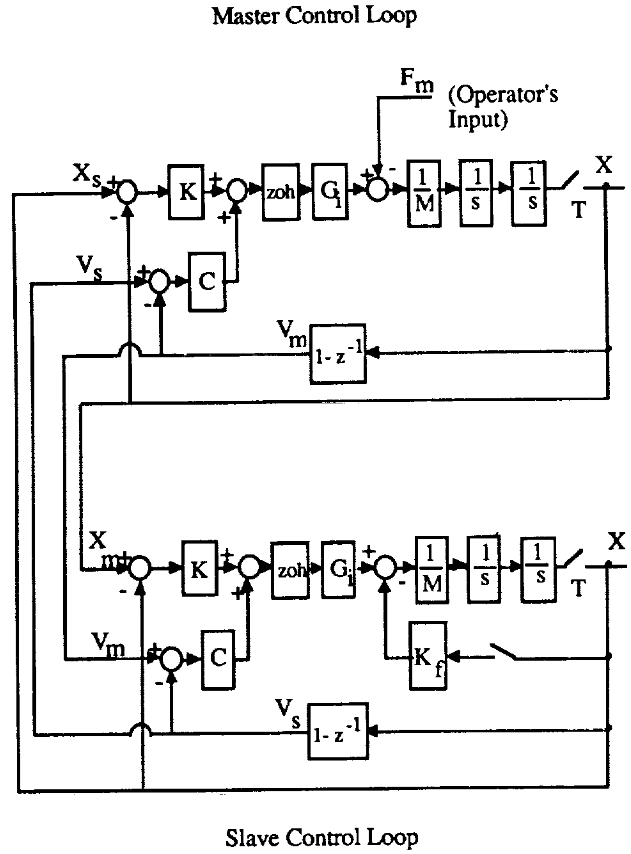

Figure 5. State-feedback bilateral control system with active stiffness and damping

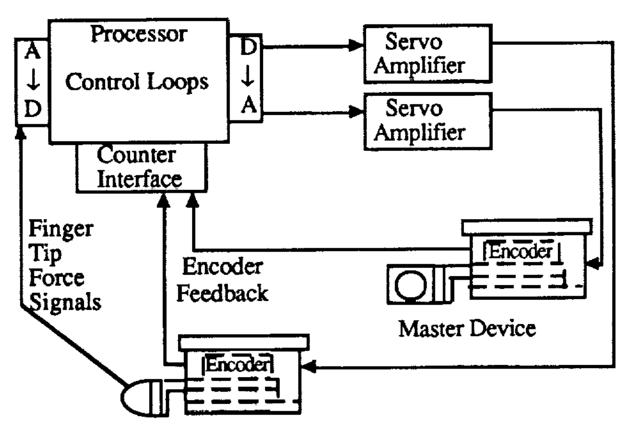

Figure 6. Computer control configuration for master/slave gripper

Initial experiments with this system involve the measurement of an operator's grasp control performance. The system is configured using only the master device as illustrated in Figure 7, and is controlled using the position controller shown in Figure 8. The human subject attempts to maintain a constant force level on the actuator while a multi-frequency sinusoidal position command, X_{com}, is commanded to the actuator. The multi-frequency sinusoidal input is an effective continuous random input acting as a disturbance input to the system. Forces the human subject provides are sensed with a force sensor attached to the mounting surface of the actuator system. The performance measure is the difference between the actual measured forces the human subject applies to the actuator and the reference or mean force level that is intended to be maintained. The parameters that are presently being studied are the stiffness term, K, and the damping term, C. Friction and mass will be studied in the next phase of the experiment, and backlash will then be added in a subsequent phase of experimentation with master/slave operation. The results will be analyzed using the Telerobotic Performance Analysis System, will provide a baseline to determine what the performance tradeoffs are as a function of the above parameters.

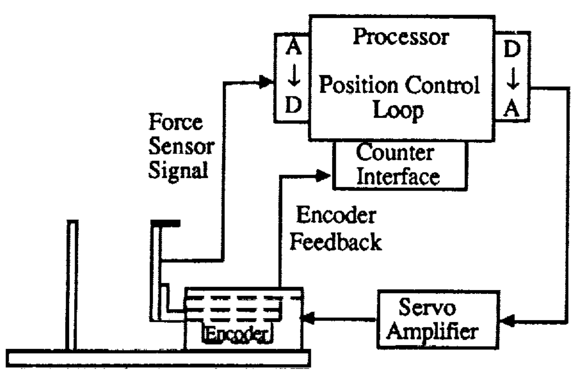

Figure 7. Computer control configuration for initial experiments

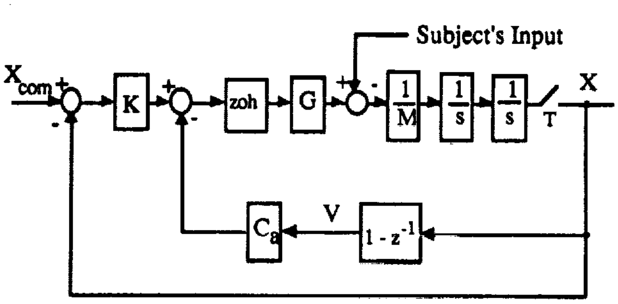

Figure 8. Position control loop for initial experiments

In the present experiment, the system is nearly an ideal linear, second-order system. The stiffness term, K, and the damping term, C, control the placement of the poles in the characteristic equation of the system and can be varied since they are constants in the software of the control system. The system is linear until physical limits are reached. The maximum power limit of the system limits the acceleration of the actuator to 2050 in/sec^2. The maximum natural frequency of the system is limited by a mechanical resonance at 115 Hz. Closed-loop natural frequencies of 35 Hz can be easily obtained, and both natural frequency and damping ratio can be experimentally over a wide range. As and example, a frequency response plot of the system with the natural frequency set at 14 Hz and the damping ratio set at 0.68 is given in Figure 9. Figure 10 is a position versus time plot for a position step input command for the system with this natural frequency and damping ratio.

Figure 9. Position loop frequency response showing magnitude ratio response

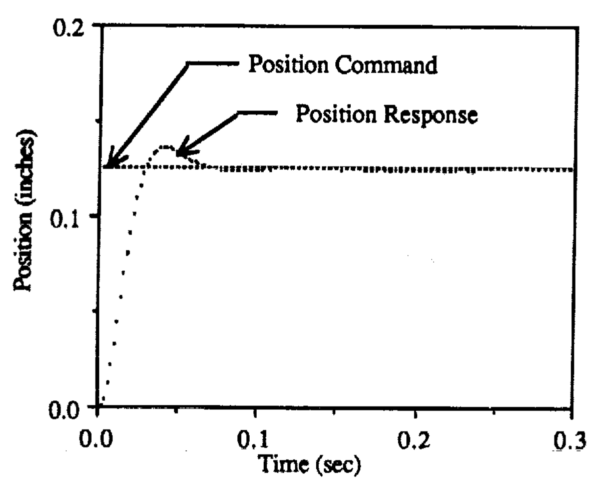

Figure 10. Time response to step input in position command

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The goal of these experiments is to establish what physical parameters (i.e stiffness, damping, mass, friction etc.) and characteristics (i.e. types of sensory feedback, haptic display, etc.) are required for a teleoperated system to perform tasks which are characterized by a given an index of difficulty rating [7]. A rating of telerobotic components and technologies based on a task complexity or difficulty index will help to establish least cost approaches to teleoperator development. For example, haptic display technologies assessed using the Telerobotic Performance Analysis System can be rated using results of the form shown in Figure 11.

CONCLUSION

The improvement of dexterous manipulation and grasping capabilities in telerobotic systems will depend on the development and integration of high-performance sensors, displays, actuators, and controls into systems in which careful consideration has been given to human perception and tolerance. One of WCSAR's objectives is the development of these advanced component technologies for use in telerobotic systems for space. As part of this effort, The WCSAR Telerobotics Test Bed [8] has been established in which these technologies can be verified and integrated into telerobotic systems. The layout of the test bed is shown in Figure 12. One of the major systems in the test bed is a telerobotic manipulator with a high-fidelity master/slave hand. The master/slave arm portion of the system consists of a Cincinnati Milacron T^3-726 electric-drive robot and a non-kinematic replica master arm which was designed at WCSAR. The original controller of the robot has been replaced with a new, higher-performance controller designed at WCSAR which is capable of being flexibly programmed in a number of telerobotic operating modes.

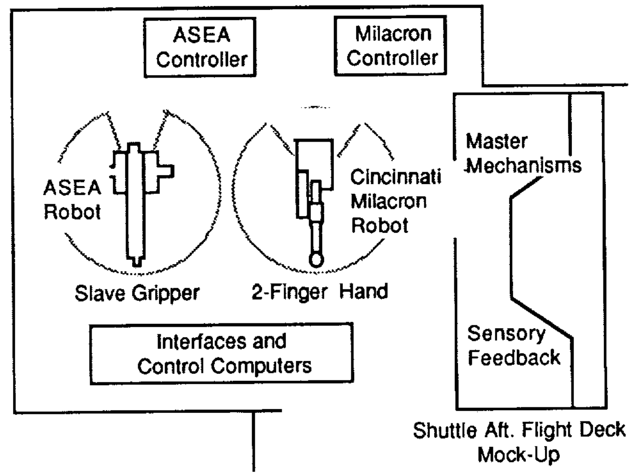

Figure 12. WCSAR Telerobotics Test Bed

The performance of the single degree-of-freedom master/slave gripper described in the previous section has indicated a possible advantage of telemanipulation systems with reduced degrees of freedom but improved electromechanical characteristics and haptic displays over current multiple degree-of-freedom systems. A high-fidelity, two-fingered, master/slave hand therefore has been designed and is currently being tested at WCSAR. The hand consists of a thumb and index finger on the master controller, and a replica of these digits on the slave gripper with corresponding degrees of freedom. The two degrees of freedom are independently controlled by the operator in performing dexterous manipulations. Together with the original arm subsystem, this hand subsystem will allow the assessment of more complex tasks and larger integrated systems with the Telerobotic

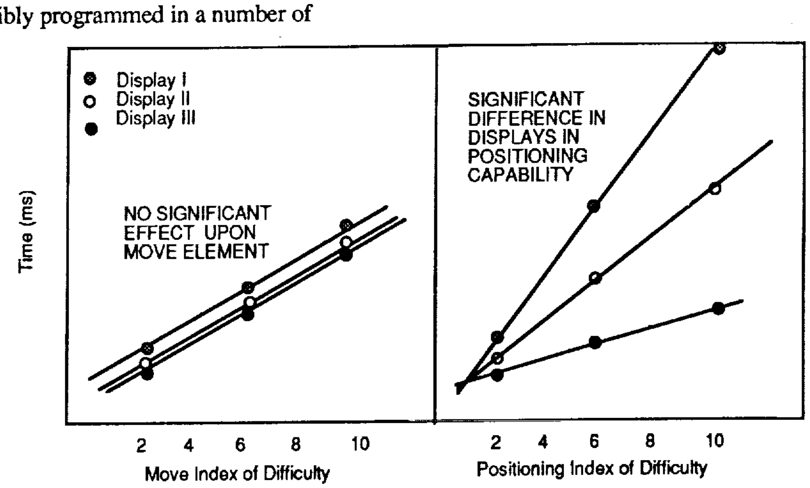

Figure 11. Example of Results from the Telerobotic Performance Analysis System

Performance Analysis System. The hand includes a direct-drive force-reflection system, with minimal friction and zero backlash. The system therefore is capable of supporting high-fidelity telemanipulation with advanced tactile sensors and haptic displays. This combination will be assessed in order to evaluate performance of tasks with high-fidelity telemanipulation and limited degrees of freedom as compared to telemanipulation with many degrees of freedom but low-fidelity.

In conclusion, we are developing the Telerobotic Performance Analysis System to speed engineering development of telerobotic devices, and to provide on-line guidance to the designer in determining the best mixture of telerobotic system components for given operational objectives. Moreover, standardization of telerobotic performance analysis procedures, terminology, performance models, and metrics used in describing device performance capabilities shall assist the scientific and engineering community in its efforts to develop commercially successful telerobotic devices.

ACKNOWLEDGMENTS

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