# Human-Machine Cooperative Telerobotics

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## Abstract

Radioactive tank waste remediation, decontamination and decommissioning (D&D) of contaminated DOE facilities, and other nuclear cleanup tasks require extensive remote handling technologies. The unstructured nature of these tasks and limitations of the current sensor and computer decision-making technologies prohibit the use of completely autonomous systems for remote manipulation. Teleoperated systems, in which humans are an integral part of the control, are used for performing these tasks. However, these systems are difficult to operate and make simple manipulation operations tedious and time consuming, and thus, greatly increase the costs and operator fatigue. Also, these systems are highly dependent on the human operator for safety. We are developing a methodology to incorporate sensor and model based computer assistance into human controlled teleoperator systems. In our approach, the human operator is retained at all phases of the operation, and is assisted, but never superseded, with sensor and model information only to the that it is accurate and useful. This form of machine assistance is accomplished by adjusting system parameters which are not under direct control by the operator, specifically, the mapping of positions and velocities between the master and slave and their impedance parameters. The degree of adjustment is weighted according to the accuracy of the environmental information, providing a novel way of incorporating sensor or model accuracy into teleoperated tasks. Experimental results from the application of this strategy in an impact task are presented.

## Introduction

Due to the increasing number of worksites which are hazardous or merely inaccessible, remote manipulation has become more and more important. Nuclear, underwater, and space applications exemplify a few of the dangerous environments in which work may be desired, while the recent interest in micromanipulation is an example of an inherently inaccessible environment. Unfortunately, the unstructured nature of many of the tasks of

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interest, as well as the limitations of the current sensor and computer decision-making technologies prohibit the use of completely autonomous systems for remote manipulation. Hence, teleoperated systems, in which humans are an integral part of the control, are most often used for performing these tasks. However, these systems are difficult to operate and make simple manipulation operations tedious and time consuming, and thus greatly increase the costs and operator fatigue. Also, these systems are highly dependent on the human operator for safety.

## Objective

This paper describes a new methodology to incorporate sensor and model based computer assistance into human controlled teleoperator systems. In our approach human operator input is enhanced but not superseded by the computer. This form of assistance is provided by adjusting system parameters that are not under direct control by the operator, such as impedance parameters and workspace mappings between the master and slave manipulators. The basic approach is to use available but incomplete and imperfect sensory and model data to assist the operator's motions, while the operator retains direct control of the manipulator. The amount and type of modification depends not only on the task but also on the accuracy of environmental information from the sensors or model. Since the operator always maintains direct control, fully intelligent computer decision making is not required. Note that the assistance is passive in the sense that the end-effector does not move unless provided a command from the human operator. Such a concept is different from (but can coexist with) traded control, where the human from time to time relinquishes control to the computer or shared control, where the human may act as a supervisor with respect to control of some variables and direct controller with respect to other variables [Sheridan, 1989]. Tasks which will benefit from this method include fine alignment of tools with precision tasks, impact control, obstacle avoidance, and force regulation assistance. These advancements will allow faster and more accurate task accomplishment in a wide variety of situations while retaining the best attributes of the human and computer control.

## Approach

### Background

Several types of systems and concepts have been defined in the area of remote manipulation technology [Sheridan, 1989]. The concept developed by Ray Goertz in the 1950's, in which a person's sensing and manipulation capability is extended to a remote location, is referred to as a teleoperator. His mechanisms were mechanical pantograph devices which allowed radioactive materials to be handled by operators outside of the “hot” area. Later, electrical servos replaced mechanical linkages and cameras replaced direct viewing, so that the operator could be arbitrarily far away. Usually the term teleoperator denotes systems in which the remote manipulator is directly and continuously controlled by the human operator. In these systems, the kinematic chain which is manipulated by the operator and may provide force feedback is referred to as the “master”, while the remote manipulator is referred to as the “slave”. Telerobotics is a more general term referring to human-machine cooperative teleoperation in which human and computer sensing and intelligence are used in conjunction to command the motion of a remote manipulator. The primary aspect of telerobotics which is emphasized in this project is the incorporation of machine intelligence and assistance into a teleoperator system.

Strategies in which human decisions are merged with computer assistance have been made possible by more complex forms of automatic control and sensor data fusion. One explicit attempt to combine human and machine control was made by Hayati and Venkataraman [Hayati, 89]. In this strategy, force and velocity commands from a master input device were combined with those from an automatic controller along each direction to be controlled. Backes [Backes, 92] presented a controller which superimposed various preprogrammed motions onto the command from the master, which could be initiated when desired. The idea of having a variety of preprogrammed control modes available was presented by Yokokohji et al. [Yokokohji, 93], allowing a better match between controller and task. To improve impact performance, an event-based controller which provided more automatic selection of controller parameters was used by Marth et al. [Marth, 94]. The same philosophy was used later by Guo et al. [Guo, 95] to allow semiautonomous obstacle avoidance in a teleoperated system. Elaborate virtual constraints have also been used to assist an operator in maneuvering a slave manipulator, including those by Joly and Andriot [Joly, 95] and Kosuge et al. [Kosuge, 95]. Teleoperation assistance has also been provided by integrating potential field effects and remote control of a manipulator [Aigner, 97].

Previously, we have experimented with using sensor data to adjust stiffness and damping of the slave to suit various task requirements [Dubey, 97]. These ideas prompted the investigation into the alteration of other human-independent parameters in a telerobotic system, specifically the position and velocity mapping parameters between the master and slave manipulators. Our concept of sensor assisted parameter variation for teleoperation assistance is illustrated in Figure 1. The operator uses an input device to control the motion of the manipulator. Information from sensors, such as force/torque, ultrasonic, range, and image processing, as well as available environmental models, will be collected. Assistance algorithms will then use this information to alter parameters, such as position and velocity mappings and dynamic parameters in impedance control implementations, on-line. The result is a passive form of assistance which leaves the operator in control of the motion of the manipulator, but assisted to the extent that the sensor and model information may be relied upon.

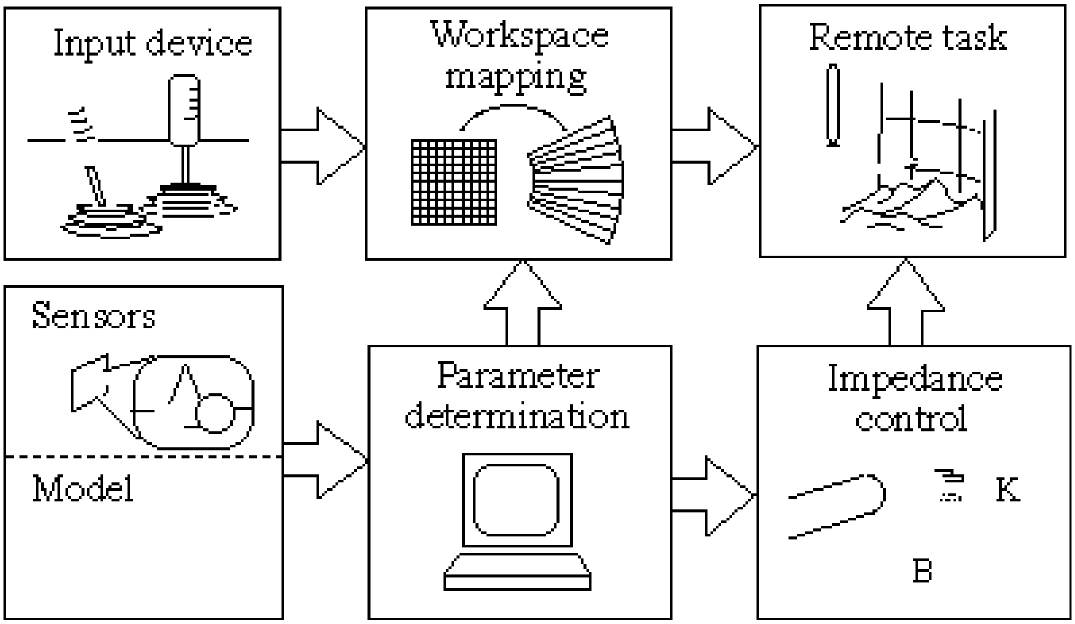

*Figure 1. Human-machine cooperative teleoperation concept*

## Variable Trajectory Mapping

The concept of using controllable position and velocity mapping between the master and slave to passively assist a telerobot operator is based on the philosophy that system parameters rather than direct commands from the operator should be altered on-line. Thus, computer control never supersedes the human's desired motion, but merely augments those which the computer deems to be appropriate or adjusts them to achieve some desired system dynamics. While velocity scaling has been used previously as a means to improve the workspace volume (by decreasing the master to slave velocity ratio) or motion resolution (by increasing the master to slave velocity ratio), it has typically been held constant. By exploring on-line variability of master-to-slave position and velocity mapping, a variety of advantages are available.

It is desired here to generalize this concept to include a wider array of position mappings and Jacobians, including those which vary and are nonlinear. One previously implemented example of a more elaborate form of position mapping was discussed by Sato et al. [Sato et al., 92]. In their case, a planar operating surface in the master workspace was mapped to a curved working plane in the slave's workspace with an isometric projection. This particular mapping made tracking along the curved environment easier for the operator to control. While the desired mapping between the master and slave workspaces in this situation was evident, many times it is the Jacobian which is constructed first rather than the position map.

## Sensor and Model Integration

One of the major contributions of this investigation is the integration of imperfect sensor or model data for teleoperation assistance. In general, this objective is accomplished by varying the master to slave Jacobian relative to the uncertainty in the environment parameters as supplied by the sensor or model. The mapping is adjusted such that the command from the operator is enhanced or diminished by the computer to the extent that it is believed to be accurate. Therefore, if the sensor or model data is highly reliable, input from the operator with which the computer agrees is greatly magnified. On the other hand, if the sensor or model data is inaccurate, the operator input is left almost unchanged. Note that this method is applicable to either model or sensor information, since data from both are used in the same way. If sensor accuracy parameters vary with environment conditions as they often do, data may be collected and analyzed on-line so that the proper mapping parameters may be updated. In addition, if models are being used, only the obstacles or tasks in the vicinity of the end-effector are of importance.

## Project Description

A real-time telerobotic controller is being developed to incorporate several types of sensory and model information for assisting the human operator through intelligent mapping of the master commands to the remote manipulator motion. It also adjusts the dynamics parameters of the remote manipulator based on the sensory and model inputs. In the first year, this controller will be implemented on a testbed consisting of a seven-degree-of-freedom Robotics Research Corporation manipulator and a six-degree-of-freedom force reflecting Kraft hand controller. The sensor suite consists of a vision system, laser range finder, force/torque sensors, and ultrasonic sensors. The $C^{++}$ code for the algorithm is being developed using ControlShell®, a real-time control software package, within a VME/VxWorks® environment, and will be compatible with the tank remediation and the D&D systems at ORNL.

The types of assistance expected to be offered by our technology include optimal trade-offs in workspace volume and motion resolution, avoidance of hard impacts, assistance in tool alignment with precision tasks while preserving the operator's ability to finely adjust the position, obstacle avoidance, and automatic adjustment of dynamics parameters to optimally suit current working conditions. Comparison studies will be developed between standard teleoperation and the proposed computer assisted teleoperation to verify advantages with respect to task efficiency, operator fatigue, and safety. Specific mock-up experiments will be developed based on the task needs in tank-waste cleanup and D&D and the potentially available sensors.

In the second year, we will test the computer assisted teleoperation on the simulator for the Modified Light-Duty Utility Arm (MLDUA) at ORNL, and then implement the control algorithm on the actual hardware, provided the simulation results are positive. We will also implement the new controller on the Dual Arm Work Module (DAWM) at ORNL and verify operability in D&D activities by field testing the system.

### Technology Development

As an example of the application of the variable trajectory mapping concept and its integration of sensor accuracy parameters, a task in which an approach and impact of the end effector with a surface was performed. If contact with a surface is to be made, it is desirable to move quickly in free space, while minimizing the probability of a hard impact. In keeping with the philosophy of teleoperation assistance developed in this paper, the burden on the operator to achieve this goal will be alleviated by adjusting the relationship between the master and slave velocities during the approach. Information about the distance from the surface derived from a hand-mounted laser range finder along with the uncertainty in this measurement will be used to determine the proper velocity scaling function. Similarly, information about the surface location in the form of an inaccurate model could be integrated in the same way. While investigations such as those by Li [Li, 96] and Kitagaki and Uchiyama [Kitigaki, 94] have proposed excellent methods of determining optimal approach velocity to make contact, these methods were intended for autonomous robotics. The method derived below is meant as an example of how sensor inaccuracy may be used to modify teleoperated control of a remote manipulator as a safeguard against hard impact.

The objective of this task is to approach and make smooth contact with a surface. Information from an imperfect sensor (or imperfect model) is used to estimate the location of the surface. The master is used to command the slave to approach the surface and make contact with it. Master and slave velocities are related with a Jacobian J, which in the one-dimensional case may be represented by function s(x). In order to derive a conservative estimate of the desired scaling, a maximum master velocity will be assumed and related to the desired approach velocity to obtain the desired scaling function s(x).

### Theoretical Development

Assume that the sensor data from the laser range finder has a probability distribution around the actual wall position given by a Gaussian curve. Therefore, given a sensor reading, the actual location of the wall may be expressed as a random variable with standard deviation $\sigma$ and mean location $\mu$. Note that in the development of the theory, although $\sigma$ is most often referred to as the sensor uncertainty, it actually represents the uncertainty in the manipulator's relative position and thus also includes other factors such as the position controller and calibration accuracy. Thus, the probability density p(x) of the wall location may be given as

$$p(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{1}$$

where x is an inertially fixed coordinate and $\mu$ is defined in this coordinate system. In actuality, the accuracy of this data may be increased by subsequent measurements, and depends on such factors as environmental reflectivity, ambient lighting, and distance. However, for this example, it will be assumed that the distribution p(x) remains constant.

If the distance sensor is highly reliable, i.e., its standard deviation $\sigma$ is small, a desired approach velocity may be formulated. (Recall that in practice, this velocity will be related to the maximum expected master velocity to generate a velocity scaling function.) A smooth transition from the nominal free space velocity to the maximum allowable impact velocity may be derived by fitting a third-order spline between these two values over the region of deceleration. The velocity curve used for a reliable sensor is then given by the following equation,

$$v_s(x) = -2\frac{v_{nom} - v_{\min}}{\delta^3}(x - x_1)^3 + 3\frac{v_{nom} - v_{\min}}{\delta^2}(x - x_1)^2 + v_{\min} \qquad (2)$$

for $x_1 < x < x_1 + \delta$

where $\delta$ is the distance over which the manipulator will decelerate, $v_s(x)$ is the desired approach velocity, $v_{min}$ is the allowable impact velocity, $v_{nom}$ is the nominal slave free space velocity, x is the distance from the wall, and $x_1$ is the distance from the wall where $v_{min}$ must be reached. The value of $x_1$ is determined by the inaccuracy in the wall's estimated position, so that a confidence level may be placed on the probability of impact at speed $v_{min}$. Thus, if $x_1$ corresponds to the $3\sigma$ distance from the wall, there is a 99.5% probability that the impact velocity will be less than $v_{min}$. The resulting velocity and wall location probability density are shown in Figure 2. Since the spline was calculated in space rather than time, the acceleration is not a constant over this interval. However, the deceleration distance $\delta$ may be chosen to place a limit on the magnitude of the deceleration which will be required.

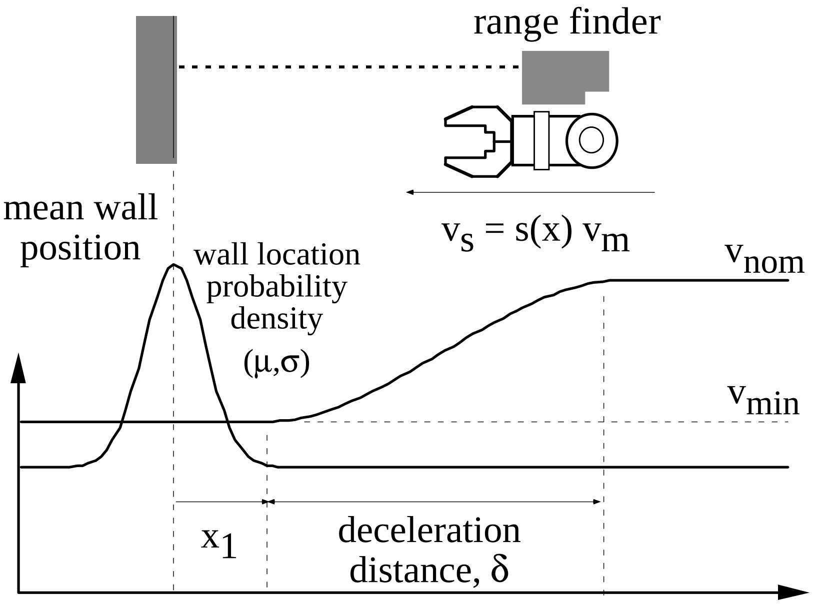

*Figure 2: Scaling function for approach*

This curve is then converted into a scaling function by using the ratio of the maximum expected master velocity and the desired free space velocity as the nominal free space scaling, as follows:

$$s_s(x) = \frac{v_s}{v_{mmax}} \qquad (3)$$

where $v_{mmax}$ is maximum expected master velocity. Thus, if the master is moved at its maximum velocity constantly, this scaling curve will produce a slave velocity as expressed by Equation 2.

If the distance sensor is unreliable (or absent) there can be no improvements to the human input, and thus the scaling function for this situation should be a constant. For situations in which the sensor is less than perfect but can still provide some assistance, Equation 2 may be weighted to provide a compromise scaling function according to the following :

$$s(x) = w(\sigma)(s_{nom}) + (1 - w(\sigma))(s_s(x)) \tag{4}$$

where $s_{nom}$ is the nominal free space scaling, and $w(\sigma)$ is the weighting between the human and computer, which will be derived next.

The standard deviation $\sigma$ of the sensor may be interpreted to correspond to the desired weighting, so that if it is small, a higher weighting is desired on the sensor's effect. Likewise, if $\sigma$ is large, the sensor should have less effect on the velocity curve. The weighting expressed as a function of $\sigma$ must then map its [0,_) interval into a [0,1] interval. A function $w(\sigma)$ which achieves this objective is

$$w(\sigma) = \frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left(\frac{\sigma - \sigma_h}{\sqrt{2}\Sigma}\right) \tag{5}$$

The parameter $\sigma_h$ is the accuracy of the human's assessment of the wall position. Thus, when $\sigma = \sigma_h$ , the weighting on the sensor influence is 50%. While base-mounted cameras have the ability to provide good information to the human about the distance and reduce the value of that parameter, a hand-mounted camera would provide few distance cues. In such a situation, weighting would be shifted more heavily to the sensor. The parameter $\Sigma$ may be adjusted to select how rapid is the change between heavy weighting on the human and heavy weighting on the computer influence.

The result of combining Equations 2-5 is a set of scaling curves over the approach distance parameterized according to the sensor accuracy. Figure 3 illustrates the variation in these curves with respect to sensor accuracy.

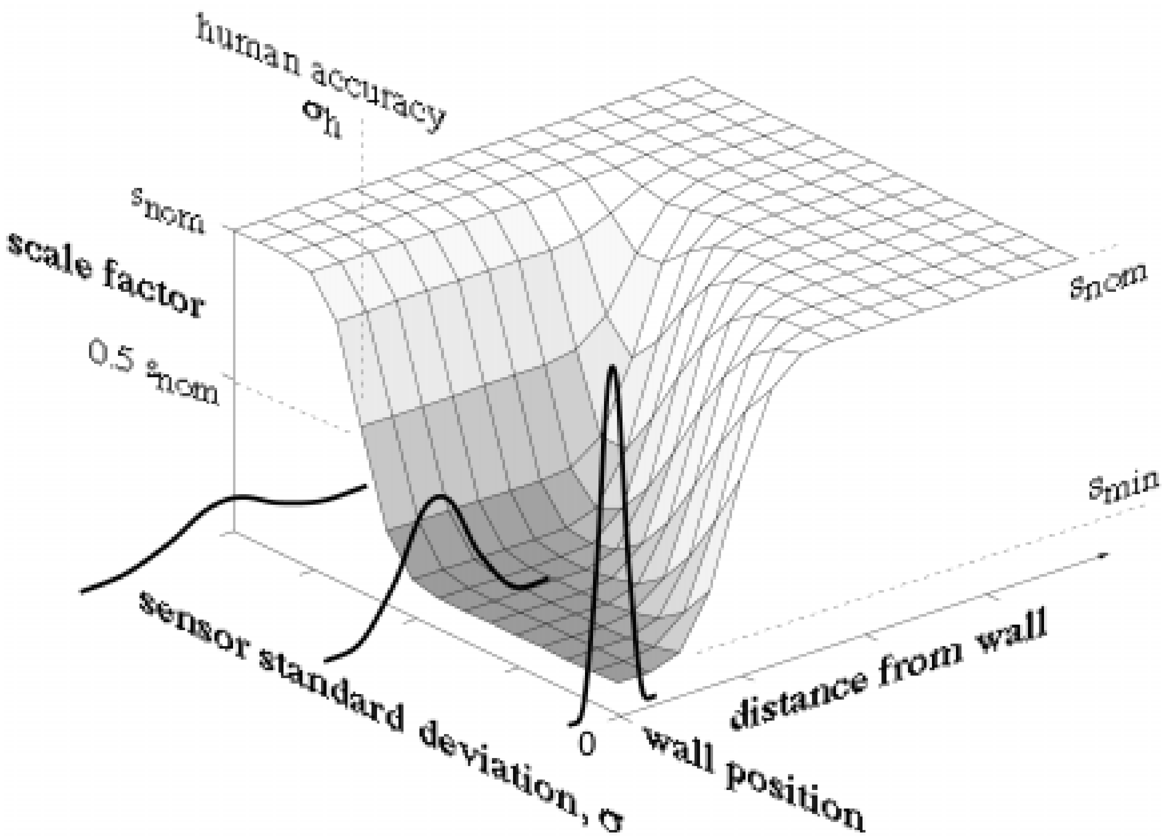

*Figure 3. Scaling curves as a function of sensor data standard deviation and distance to wall*

## Accomplishments

### Experimental Hardware Platform

The telerobotic system used as the platform for our research consists of a seven-degree-of-freedom Robotics Research Corporation (RRC) manipulator controlled with a six-degree-of-freedom Kraft master hand controller, shown in Figure 4. The controlling software has been developed with the ControlShell® programming tool on a VxWorks® real-time operating system. The implemented block diagram is shown in Figure 5, where the shaded blocks represent the impedance parameters and velocity mappings which are assumed to be adjustable by the human-machine cooperative control algorithms. A Sick Optic-Electronic DME2000 laser range finder was mounted on the end-effector of the manipulator to provide distance information to a table surface, and a $JR^3$ force/torque sensor provided force information at the hand. The task to be performed involved an approach of the end-effector to the surface so that contact was made. No instructions were given as to the magnitude of the force to be maintained once contact was made, but a minimum impact force and time to approach were desired. The manipulator was started above the surface far enough to encompass the entire deceleration phase of the scaling equation, but close enough so as not to require indexing to reach the surface.

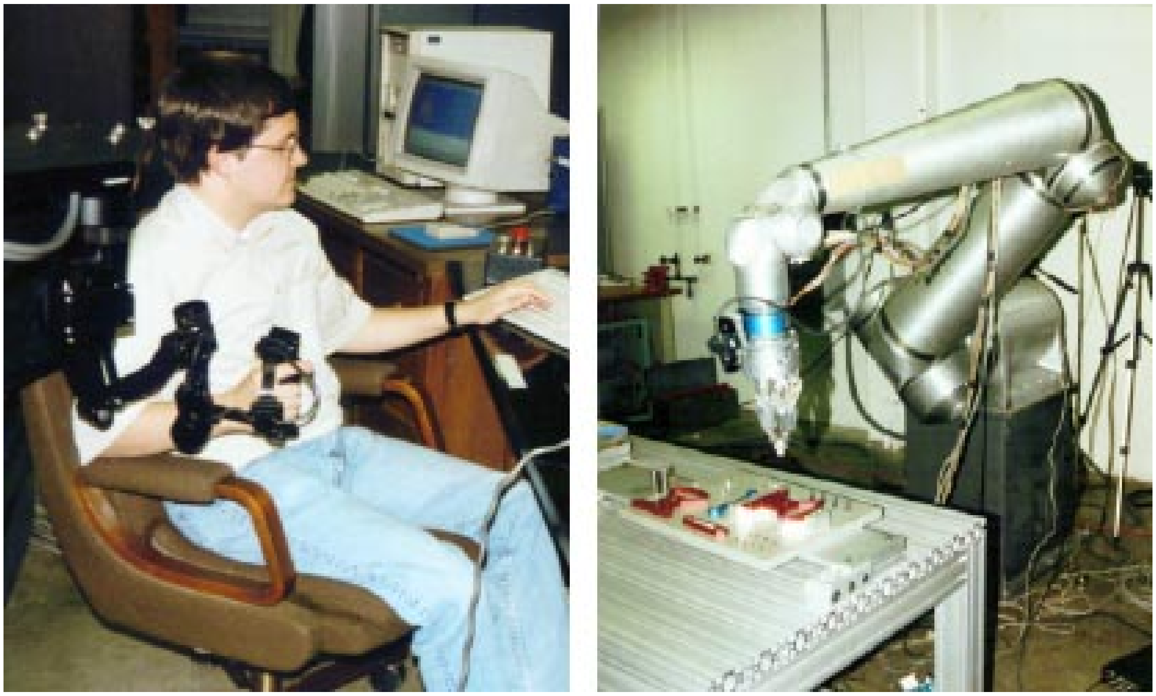

*Figure 4. Kraft master controller and 7-DoF RRC manipulator*

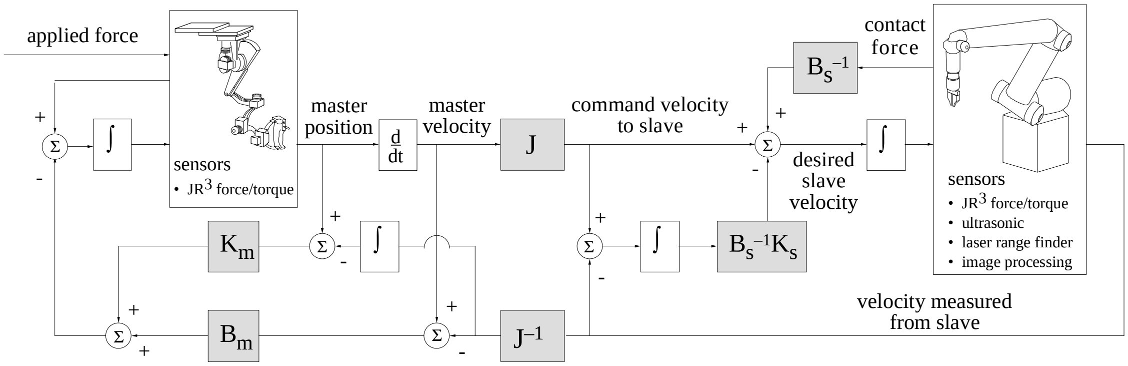

*Figure 5. System block diagram*

Accuracy of the measurement of the manipulator's relative position with the surface was evaluated first. The end-effector mounted laser range finder was positioned above a surface and distance measurements were collected. Two surfaces were used to represent an accurate measurement and a poor measurement: a smooth white surface, and a rough black surface. The measurements were then subtracted from the manipulator position to cancel out motion caused by inaccuracy in the positioning controller. The standard deviation $\sigma$ of the resulting set of measurements is shown in Table 1. As expected, the standard deviation was greater at greater distances from the surface and greater for the rough, black surface. For the experiments discussed below, however, a constant average standard deviation for each situation was used.

| Smooth white surface | | | |
|---|---|---|---|
| distance (in) | 19.8 | 30.0 | 40.0 |
| σ (in) | 0.025 | 0.033 | 0.038 |
| Rough black surface | | | |
| distance (in) | 19.2 | 29.5 | 40.4 |
| σ (in) | 0.171 | 0.269 | 0.435 |

Table 1. Standard deviations of measurements for surfaces tested

**Experiments**

Three sets of experiments were done: one in which an average σ from the white surface was used to represent a good sensor, one in which an average σ from the black surface was used to represent an average sensor, and one in which it was assumed that no sensor was available. A position-dependent scaling equation s(x) function was then constructed for each of the first two situations according to Equations 2-5. For the good sensor, the accuracy of the distance measurement dictated that the scaling equation would be essentially identical to Equation 2. The parameters chosen in this equation were $\delta = 4$ in and $x_1 = 0.1$ in (approximately $3\sigma$ distance from the sensed wall surface). Rather than use velocity magnitudes of the master and slave to deduce desired scaling, maximum (free-space) and minimum (impact) scaling values were chosen as 3 and 0.05, respectively. Thus, the following equation was used to determine the scaling factor:

$$s(x) = \begin{cases} 3 & x \geq 4.1 \\ -.0922(x-0.1)^3 + 0.553(x-0.1)^2 + 0.5 & 0.1 < x < 4.1 \\ 0.05 & x \leq 0.1 \end{cases} \tag{10}$$

Similarly, parameters chosen for the case of the average sensor were $\delta = 4$ in and $x_1 = 1$ in (approximately $3\sigma$ distance from the sensed wall surface). A maximum scaling of 3 was used for this situation; however, a minimum scaling of 0.2 was used to reflect the fact that from Equation 5, the minimum desired scaling of 0.05 would be slightly weighted toward human control as well. Thus, the resulting scaling equation was used:

$$s(x) = \begin{cases} 3 & x \geq 5 \\ -.0875(x-1)^3 + 0.525(x-1)^2 + 0.2 & 1 < x < 5 \\ 0.2 & x \leq 1 \end{cases} \tag{11}$$

For the situation with no sensor assistance, a constant scaling of 1 was used.

The slave was placed at the same initial location for all three experiments. Then the master was brought toward the table with the intention of making smooth contact. The position of the master and slave, each measured in its own base coordinates, and the force measured by the sensor along the line of approach, was recorded. The results for all three situations are depicted in Figures 6-8. Several runs of each situation were attempted, with typical results presented. The rapid automatic deceleration of the slave is evident in the first two figures at a time of 1 sec, illustrating the effect of the variably scaled

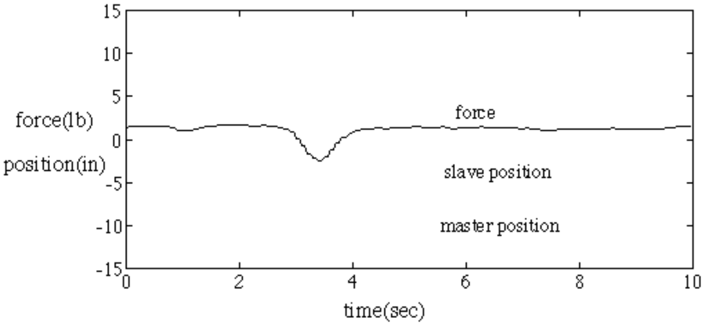

*Figure 6. Teleoperated surface approach and contact, with variable scaling and good sensor*

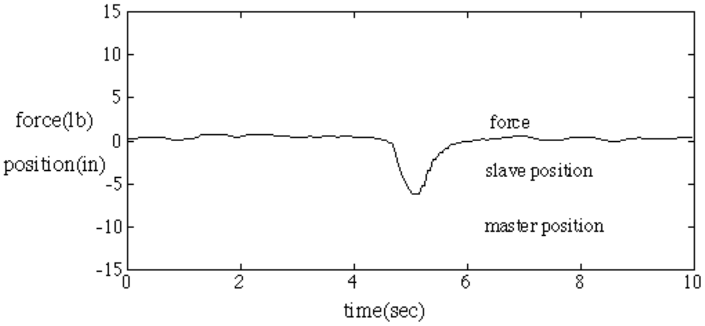

*Figure 7. Teleoperated surface approach and contact, with variable scaling and average sensor*

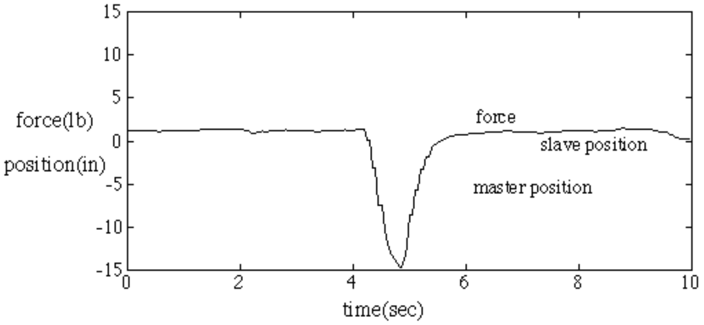

*Figure 8. Teleoperated surface approach and contact, with constant scaling*

constant velocity of the master. It may be seen that the time, as well as the initial force of impact, is reduced when the algorithm for a good sensor is used. The task of making contact is accomplished over a period of about 2 seconds in Figure 6 and about 4 seconds in Figure 7. Figure 8 shows the same experiment with a constant one-to-one scaling between the master and slave. Notice that even though the operator slowed down during the final part of the approach, there was still a larger initial force than that seen in the previous two figures. The forces seen in these figures are primarily due to the fact that time delay in the system cause the operator to react late in stopping the manipulator. Since the first oscillation in the force seen in these figures after contact is made depends on the depth to which the commanded position penetrates the surface, a late reaction results in higher initial forces. Thus, if the motion has been scaled down by the time the manipulator reaches the surface, a late reaction has less severe consequences. One factor which could not be quantified by these results was the security the operator felt in performing the experiment with variable scaling. When it could be assured that the impact velocity would be limited, the operator could move the master much faster throughout the approach and contact task and thereby reduce the approach time.

In these experiments, the operator's gaze was perpendicular to the line of approach of the manipulator to the surface. In this arrangement, the human's assessment of the manipulator's relative distance from the surface was fairly good, and some improvements could be effected with careful attention to the situation. However, in a situation where the view comes from a hand-mounted camera, it can be very difficult for the operator to estimate the remaining distance to the wall and the advantage of sensor assisted teleoperation is even more evident. The sensor would be given more weight to reflect the larger $\sigma_h$ in Equation 5, and thus the impact velocity and minimum scaling would be correspondingly reduced.

## Benefits

The new technology for teleoperation is expected to help the tank waste remediation, D&D, and other nuclear cleanup tasks in the following ways:

- Increased efficiency and lower costs: Several tasks such as grasping of the sluicer and other tools by the Modified Light Duty Utility Arm (MLDUA), maintaining desired distance from tank walls (Figure 9), precise positioning of the water jet, etc., could be done much faster. Similarly, a variety of D&D tasks such as drilling, sawing, unbolting, etc., could be done with increased efficiency. For example, avoiding saw binding and maintaining proper blade depth for teleoperated aluminum reactor vessel cutting task done at CP5 should benefit from the proposed technology.

- Improved safety: Sensor assistance would result in safer teleoperation due to obstacle avoidance (Figure 10 and 11) and reduction in impact forces during contact. For example, the likelihood of collision of MLDUA with Hose Management Arm (HMA) or the tank wall can be reduced significantly. Also, computer assistance can be important while scarifying the walls due to extreme fog in the tank.

- Lower operator fatigue: The proposed system would assist the operators in performing tasks with significant reduction in fatigue.

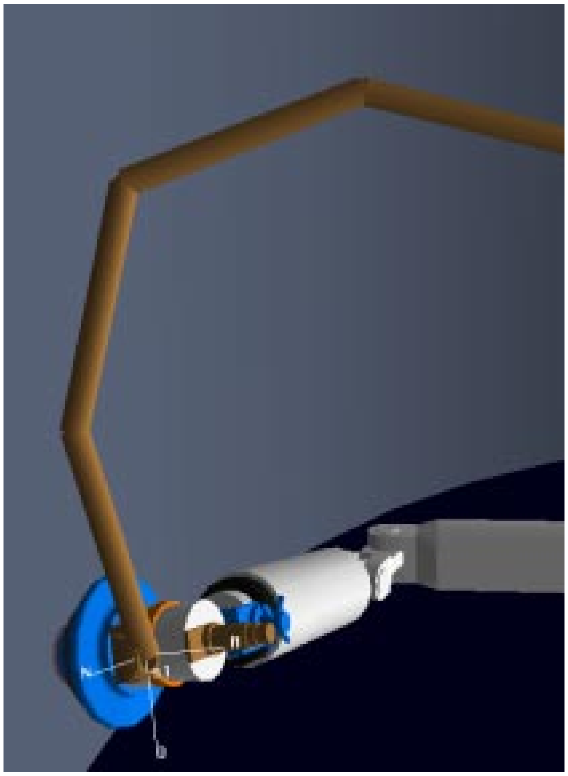

*Figure 9. Proximity maintenance with the tank wall*

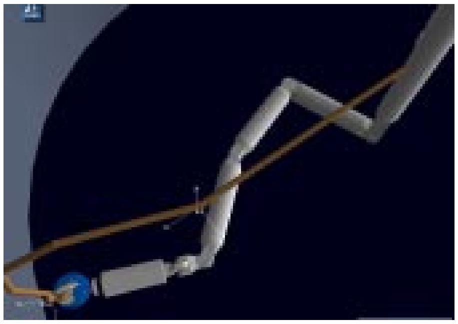

*Figure 10. Collision between HMA and MLDUA*

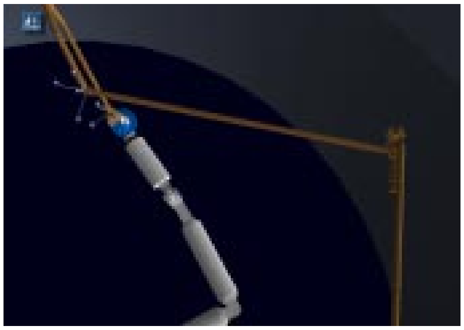

*Figure 11. Collision between HMA and tank wall*

## Future Activities

The concept of variation in human-independent parameters to assist in difficult teleoperation tasks is one which may be extended in a variety of ways to aid several types of tasks. Initially the application to impact mitigation will be extended to two dimensions to effectively enforce guarded moves around obstacles. Once it is noted that an obstacle is in the workspace, by sensor or model information, scaling will be reduced to disallow a hard contact with the object. In two dimensions, however, there is the option of changing the scaling in the commanded direction as well as the direction itself. By altering the direction of the command slightly near an obstacle, it may be completely avoided, and any contact whatsoever between it and the end-effector will be avoided. The development of the theoretical background for this concept will be aided by the viewpoint of mapping the workspace of the master into the workspace of the slave. Another modality using the concept of variability in position and velocity mapping will allow faster alignment with precision tasks by the end-effector. If a desired position is known, albeit inaccurately, motion will be scaled up when the end-effector is commanded to move in the direction toward the goal, and likewise motion will be scaled down when the end-effector moves away. Thus, the intended effect is that the gross alignment takes place much more quickly, while high resolution motion at the goal by the human operator is still allowed to make adjustments beyond the capability of the computer and sensors alone. The commanded direction from the end-effector may be altered or not as well, depending on the results of trial experiments. A similar concept will be used to assist in force regulation in teleoperation. In a system such as ours which is impedance controlled, the impinging force on the end-effector is determined by the depth to which the manipulator is commanded below the surface and the stiffness of the control. By using the same directionally dependent scaling as described for the object alignment, the command point may be assisted in reaching a desired position below the surface, implicitly regulating the force. By adjusting the regions which the special scaling algorithm is in effect, assistance in force regulation may be afforded without prohibiting the operator from leaving the surface when desired. A final application which will be implemented involves the assistance in tool alignment. The use of certain tools such as drills and saws naturally benefits from teleoperation in which certain motions are constrained; however, if the control is not precise, binding can occur, requiring fine adjustments of the motion. By greatly reducing the scaling along directions which these tools should not move, the motion is effectively constrained, while still allowing for fine adjustments by a human operator. Furthermore, the scaling need only be in effect near the surface which is being operated on, so that large motion may be made in free space to initially position the tool.

## Contract Information

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FETC Contracting Officer's Representative (COR):
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## Schedule

Base contract start date: September 1, 1997

- Controller development and implementation (9/97 – 4/98)
- Experiments and testing (5/98 - 8/98)

Options A & B begin on Sept 1, 1998

Implementation and testing on MLDUA (option A) and DAWM (option B)

Contract end date: February 28, 1999.

## References

[1] T. B. Sheridan. Telerobotics. *Automatica*, 25(4):487-507,1989.

[2] S. Hayati and S. T. Venkataraman. Design and implementation of a robot control system with traded and shared control capability. In *Proceedings of the 1989 Int. Conf. on Rob. and Aut.*, pages 1310-131, Scottsdale, AZ, May 1989.

[3] P. G. Backes. Multi-sensor based impedance control for task execution. In *Proceedings of the 1992 IEEE Int. Conf. on Rob. and Aut.*, pages 1245-1250, Nice, France, May 1992.

[4] Y. Yokokohji, A. Ogawa, H. Hasunuma, and T. Yoshikawa. Operation modes for cooperating with autonomous functions in intelligent teleoperation systems. In *Proceedings of the 1993 Int. Conf. on Rob. and Aut.*, volume 3, pages 510-515, Atlanta, GA, May 1993.

[5] G. T. Marth, T.-J. Tarn, and A. K. Bejczy. An event based approach to impact control: Theory and experiments. In *Proceedings of the 1994 Int. Conf. on Rob. and Aut.*, pages 918-923, San Diego, CA, May 1994.

[6] C. Guo, T.-J. Tarn, N. Xi, and A. K. Bejczy. Fusion of human and machine intelligence for telerobotic systems. In *Proceedings of the 1995 Int. Conf. on Rob. and Aut.*, pages 3110-3115, Nagoya, Japan, May 1995.

[7] L. D. Joly and C. Andriot. Imposing motion constraints to a force reflecting telerobot through real-time simulation of a virutual mechanism. In *Proceedings of the 1994 Int. Conf. on Rob. and Aut.*, pages 357-362, San Diego, CA, May 1994.

[8] K. Kosuge, K. Takeo, and T. Fukuda. Unified approach for teleoperation of virtual and real environment – manipulation based on reference dynamics –. In *Proceedings of the 1995 Int. Conf. on Rob. and Aut.*, pages 938-943, Nagoya, Japan, May 1995.

[9] P. Aigner and B. McCarragher. Human integration into robot control utilising potential fields. In *Proceedings of the 1997 Int. Conf. on Rob. and Aut.*, pages 291-296, Albuquerque, NM, Apr. 1997.

[10] R. V. Dubey, T. F. Chan, and S. E. Everett. Variable damping impedance control of a bilateral telerobotic system. *IEEE Control Systems*, pages 37-45, Feb. 1997.

[11] K. Sato, M. Kimura, and A. Abe. Intelligent manipulator system with nonsymmetric and rdundant master-slave. *Journal of Robotic Systems*, 9(2):281-290, 1992.

[12] Y. F. Li. A sensor-based robot transition control strategy. *Int. J. of Rob. Res.*, 15(2):128-136, Apr. 1996.

[13] K. Kitigaki and M. Uchiyama. Optimal approach velocity of an end-effector to the environment. *Advanced Robotics*, 8(2):123-137, 1994.