Model-Based Supervisory Control in Telerobotics

Abstract

Model-based approaches can be used to confront several of the challenging performance issues in teleoperation. This paper describes a model-based supervisory control technique for telerobotics. A human–machine interface (HMI) was developed for online, interactive task segmentation and planning utilizing a world model of the telerobotic working environment (TRWE). The task model is transferred intermittently over a low bandwidth communication channel for interpretation, planning, and execution of the task segments through the autonomous control capabilities of a telerobot. For the purposes of outlining tasks, a human operator controls a simulation model to generate a "task sequence script" as a sequential list of desired sub-goals for a telerobot. A graphic user interface (GUI) facilitates the development of the task sequence script with viewing perspectives of the graphic display automatically selected as a function of the operational state and model parameters. Also, because the human operator is specifying discrete model set-points of the TRWE, and allowing the autonomous control capabilities of the telerobot to coordinate the actual trajectory between set-points, a provision is made to preview the proposed trajectory for approval or modification before execution. Preliminary results with a manipulator arm remotely controlled via the Internet demonstrate the utility of the model-based supervisory control technique.

1 Introduction

1.1 Model-Based Approaches in Teleoperation

Teleoperation has been traditionally applied for human control of remote machinery to perform tasks in dangerous or difficult-to-access environments, examples of which can be found in hazardous materials handling, space and underwater exploration, and, more recently, in the medical fields of endoscopy and microsurgery. In contrast to typical tasks performed by industrial robots and automated factory machinery, teleoperation tasks are usually nonrepetitive and often occur in partially known environments, and thus require human intelligence for flexibility in control and decision making. Model-based approaches have previously been used to confront several of the challenging performance-related difficulties in manually controlled teleoperation, examples of which include visual display issues, instability in control from transmission time delay, and remote manipulation of objects (Stark et al., 1987; Bejczy, 1991). Also, model-based approaches are an integral part of supervisory control techniques for extending the cognitive model of task goals from the human operator to the abstracted computer models for interpretation and execution by the telerobots (Sheridan, 1992). Furthermore, continual advancement of computer technology, especially with respect to human–computer interfacing and virtual
environments, bolsters the level and capabilities of real-time dynamic modeling and graphic simulations available as a tool in teleoperation.

1.1.1 Visual Displays. The need for spatial information of the remote task and the difficulties encountered with typically viewing a two-dimensional (2-D) representation of the three-dimensional (3-D) environment as video format on a flat monitor screen remains a significant issue in teleoperation. Monoscopic perspective displays alone cannot always suffice to represent 3-D spatial information. Careful investigations have shown that stereoscopic displays can provide for increased depth perception and performance benefits in teleoperation tasks (Chubb, 1964; Pepper, Smith, & Cole, 1981; Kim, Ellis, Tyler, Hannaford, & Stark, 1987a), but that careful calibration, proper optical alignment, and sufficient bandwidth are necessary for the effectiveness of such displays (Pepper, 1984; Liu, Tharp, French, Lai, & Stark, 1993). Proper viewing perspective and other monoscopic depth cues have also been investigated to help with visualization difficulties in teleoperation (Winey, 1981; Liu, Stark, & Hirose, 1991). In addition, model-based visual enhancements superimposed on the actual video feedback, such as a vertical line referenced to a horizontal grid, can significantly improve the relative depth perception of objects on monoscopic displays (Kim, Tendick, & Stark, 1987c).

1.1.2 Time Delay. Problems with control instability in teleoperation arise due to excessive time delay from communication between the local and remote sites, typically resulting in a "move-and-wait" strategy adopted by the human operator (Ferrell, 1965). Using a supervisory control strategy rather than manual control was shown as a possible way to circumvent the problem encountered with excessive time delay (Ferrell & Sheridan, 1967). In addition, the use of a local predictor in the form of a graphic model superimposed on the delayed video feedback was also demonstrated to help compensate for time delay (Noyes & Sheridan, 1984). This powerful technique has been further developed and tested as a robust strategy for time delay compensation (Hashimoto, Sheridan, & Noyes, 1986; Kim, Takeda, & Stark, 1988b). More recently the predictor display technique has been successfully implemented with state-of-the-art technology in the advanced teleoperation system developed at the Jet Propulsion Laboratory (Bejczy, Kim, & Venema, 1990) and also quite impressively for the towed submersible Argo at the Woods Hole Oceanographic Institution (Cheng & Sheridan, 1989).

1.1.3 Force Feedback. To facilitate manipulation of remote objects, force feedback to the human operator has been incorporated in teleoperation systems research and design (Goertz & Thompson, 1954; Mosher & Wendel, 1960; Jacobsen, Iversen, Davis, Potter, & McLain, 1989). Bilateral force reflecting teleoperators with adjustable scaling of the kinesthetic coupling between master and slave have shown to be a robust control strategy for remote manipulation under a variety of conditions (Bejczy & Salisbury, 1980; Hannaford & Fiorini, 1988). To compensate for the inherent instability in time-delayed force feedback, model-based prediction of the force has been applied to the human operator's hand in combination with a visual predictor display of position (Buzan & Sheridan, 1989). Furthermore, cooperative control strategies, which share control between the human operator and telerobot computer controllers, provide flexibility in utilizing appropriate combinations of system resources for the given task (Hayati & Venkataraman, 1989) and have also shown to be effective for overcoming instabilities due to excessive time delay in force feedback (Kim, Hannaford, & Bejczy, 1992).

1.1.4 Supervisory Control in Telerobotics. Development of supervisory control systems in telerobotics has naturally relied upon model-based approaches for transferring the cognitive model of the task goals in the mind of the human operator to the computer models embedded in the telerobotics system for interpretation and execution of the task. An early supervisory control system for telerobotics involved the use of a master input device to teach a computer the movement and manipulation tasks for a telerobot manipulator (Brooks, 1979).
The predefined tasks could later be initiated relative to new coordinates with the human operator monitoring the execution. Even without time delay, the closed loop control of the task by the telerobot under human supervision was often faster and more precise than most manual control strategies, with exception of bilateral force-reflecting master–slave control where performance was slightly faster but prone to more errors. This technique was later extended to include an on-line computer simulation and graphics display with three teaching modes including the specification of a continuous robot trajectory, definition of discrete set-points with machine interpolation, and referenced symbolic goal specification, listed in order of increasing performance benefits (Yoerger, 1982).

The idea of a predictor display using a local feedforward model for time delay compensation was incorporated into a planning model for the human operator with time and space decoupling from the actual robot dynamics for faster planning of simple maneuvers and slower planning of complex ones (Conway, Volz, & Walker, 1987). Another telerobotics system incorporated the use of a computer mouse and graphic interface for the simulated moving of objects into new desired positions with the ability to “snap-to” reference targets, followed by the execution of the task by a 3 degrees-of-freedom (DOF) manipulator (Schneider & Cannon, 1989). A supervisory control technique utilizing computer graphic allows a human operator to specify end points in 3-space of straight line move segments with a mouse and then calculates trajectories using collision avoidance strategies (Park & Sheridan, 1991). A “teleprogramming” control strategy has been developed utilizing a simulation model that combines an interactive graphics display and real-time modeled kinesthetic feedback to automatically generate symbolic instructions on-line for a telerobot under time delay (Funda, Lindsay, & Paul, 1992). A “point-and-direct” technique allows a human operator to demonstrate required object grasping and placement locations for a telerobot using a virtual end effector superimposed on live video feedback of the remote workcell (Wang & Cannon, 1993).

1.2 Scope of Paper

This paper describes a supervisory control technique developed as part of an experimental platform to explore fundamental issues in model-based telerobotics. The focus will be the human–machine interface (HMI) for an on-line, interactive task segmentation and planning technique utilizing a world model of the telerobotic working environment (TRWE) with the interpretation, planning, and execution of the task segments through the autonomous control capabilities of the telerobots. An advanced graphic interface facilitates the development of a “task sequence script” as a sequential list of model states that define subgoals for a telerobot. In the current implementation, a human operator controls a simulation model to specify position set-points suitable for motion planning algorithms of the telerobot. The task sequence script is transferred intermittently to the TRWE for subsequent interpretation, planning, and execution of the task segments with the ability for the human operator to preview and modify the planned trajectories of the telerobot. A brief overview of the experimental system will be given, followed by an illustrative example of the model-based supervisory control technique, then results from preliminary experiments, and finally a discussion of the implementation of model-based supervisory control in telerobotics.

2 Experimental System Description

2.1 Overview of the Model-Based Telerobotics System

A video image of the telerobotic working environment (TRWE) and corresponding 3-D graphical model shows the two robots in the experimental set-up (Fig. 1): a stationary Mitsubishi RM-501 (M-robot) with a 5 DOF manipulator arm grasping a workpiece and a RadioShack Armatron (A-robot) with a 3 DOF nonholonomic mobile base and a 4 DOF manipulator arm. From a separate room in the laboratory, a human operator views video feedback of the TRWE and controls the robots either in a manual control mode or through inter-
action with a model of the TRWE in a supervisory control mode.

A schematic representation of the experimental system relates the various components of the human–machine interface (HMI) and the TRWE (Fig. 2). The TRWE consists of the robotics hardware, video cameras, and a computer workstation (Silicon Graphics Personal Iris) as well as the physical workspace and objects. Two color camcorders are mounted as approximately orthogonal side views and a third monochrome CCD camera is mounted overhead to provide a top view of the workspace. The video signal from the overhead camera is also digitized into the local computer to sense position feedback for autonomous control of the A-robot. A model-based technique for image processing and control, inspired from the scanpath theory of human vision, is implemented as part of the experimental investigations (Stark, Mills, Nguyen, & Ngo, 1988; Noton & Stark, 1971).

The HMI consists of the displays, control input devices, and another computer workstation (Silicon Graphics Indigo2 Extreme). The three camera views of the TRWE are transmitted by video cable to the HMI and displayed on three 10-in. B/W video monitors. A selector switch relays one of the camera views to a 27-in. color TV (Sony). A pair of 2 DOF joysticks are used to manually control the telerobots and interact with a computer model of the TRWE. A keyboard and computer mouse are used to configure the control interface. Separate but interacting computer models residing at both the HMI and TRWE allow the specification of task goals by the human operator and the interpretation and execution by the telerobots. Communication between the workstations at the two sites is through the Internet via UNIX TCP/IP sockets.

### 2.2 Model of the TRWE

Geometric, kinematic, and dynamic knowledge of the telerobots, workspace objects, and task environment is used for the basis of the content, geometry, and dynamics that define the computer model of the TRWE.
(Ellis, 1991). This basis is then used to define the necessary forms of the model for display and control. An interactive simulation model is used for training and practice prior to performing teleoperation tasks with expensive hardware. A feedback model updated by sensed information transmitted from the TRWE is used as a supplemental viewing aid to the video. The simulation model is also used in a supervisory control mode to outline tasks for the telerobots as a sequence of desired model set-points. Feedforward models updated by algorithmic path planning at the TRWE are used for previews of proposed trajectories for approval or modification by the human operator.

### 2.3 3-D Graphic Model

Polygonal approximations of the telerobots and modeled workspace objects are animated and displayed using routines supported by Graphics Library (GL) for the Silicon Graphics workstations. Depending upon the current mode of control and operational state, a combination of the varied forms of the model of the TRWE is selected to form the current graphic model to be communicated to the human operator. The feedback model of the TRWE in Figure 1 is drawn using solid model geometry with lighting and shading algorithms. Also note the addition of visual enhancements in the form of vertical reference lines extending from the end effectors of the telerobots to a horizontal grid at the support plane. Previous studies have shown the benefit of such visual enhancements for positioning tasks in telerobotics (Kim, Ellis, Tyler, & Stark, 1985).

### 2.4 Graphic User Interface (GUI)

A graphic user interface (GUI) with pop-up menus for system configuration, two viewports for the graphic model, and an input panel for quick access to commands is displayed on a high-resolution (1280 x 1024 pixels) color monitor (Fig. 3). The use of multiple viewports for the graphic model aids perception of the 3-D spatial layout from the monocular 2-D display. Also, a scrolling text window in the lower portion of the screen (not shown in the figure) outputs system messages for the
human operator and becomes an immediate record of on-line interaction and operation. In addition to the wide industry acceptance of GUIs and their familiarity among computer users (Beckert, 1990), studies have shown the advantages of a GUI with a computer mouse over a user interface with menu selection and function keys in terms of task completion times (Rauterberg, 1992).

Pop-up menus facilitate setting the configuration of the HMI. In addition to establishing communication with the TRWE, initializing the telerobots, and choosing the operational control modes, the human operator activates the pop-up menus to define attributes of the model. Predefined geometric databases are imported to initialize the workspace model for the task. Several drawing styles are available and can be used to help distinguish the various aspects of the graphic model. In Figure 3, the solid model of the M-robot represents the feedback position, while the wireframe models (with hidden line removal) represent a desired goal position set by the human operator and a feedforward preview of the proposed trajectory as calculated by an algorithm at the TRWE. Graphic models of the telerobots as stick figures are also an option. Visual enhancements such as a vertical reference line or coordinate axes attached to the end effector of a telerobot model, as well as target reference axes on modeled workspace objects, can be added to the graphic display.

Pop-up menus also provide access to a number of extensions to the displays and controls. For increased depth perception and telepresence, the graphic model can be optionally displayed using stereoscopic viewing devices including a pair of field sequential liquid crystal lenses (StereoGraphics CrystalEyes) or a custom built head-mounted display (HMD) used in previous research in the laboratory (Kim, Liu, Matsunaga, & Stark, 1988a; Liu et al., 1991). The human operator selectively chooses from various robot control strategies including joint angle control (JAC) versus end effector control (EEC) and position control versus rate control, as appropriate, depending upon the requirements of the task (Kim, Tendick, Ellis, & Stark, 1987b; Hirose, Myoi, Liu, & Stark, 1990; Takeda, Kim, & Stark, 1989). Various input devices are also available, including a 6 DOF SpaceBall or a VPL Dataglove with an integrated Polhemus 6 DOF electromagnetic tracking system for EEC of a manipulator arm.

A GUI input panel provides quick access to frequently used symbolic commands. The input panel was created using Forms Library and development software (Overmars, 1993). Separate subpanels with virtual push buttons function to set the control mode for each telerobot.
and to execute symbolic commands for model-based supervisory control. A 2-D positioner sets parameters for the viewing perspectives of the graphic model and a group of sliders adjust software gains for the input devices.

3 Model-Based Task Segmentation

3.1 Navigation and Placement Task

This section illustrates the model-based supervisory control technique for a navigation and placement task with the M-robot. The three video camera views at the TRWE show the initial configuration for the navigation and placement task (Fig. 4—upper left, upper right, lower left). The M-robot is grasping a long cylindrical workpiece, which is to be inserted vertically into the shorter cylindrical tube across the workspace. To perform this task, the human operator must guide the telerobot and workpiece through a complex environment, avoiding collision with workspace obstacles. A graphic representation of the model of the TRWE shows the M-robot in the desired goal position for the navigation and placement task (Fig. 4—lower right).

3.2 Generating the Task Sequence Script

The human operator interactively coordinates tasks for a telerobot by controlling a local simulation model to generate a task sequence script that will be transferred intermittently to the workstation at the TRWE by request of the human operator for interpretation, planning, and execution. This requires that the model of the TRWE be extended in the dimension of time on a non-continuous scale. Here this is accomplished through a sequential list of model nodes, or discrete set-points in time of the desired state of the telerobot. The idea is to define a sequence of subgoals that outlines a task and then utilize the available autonomous control capabilities at the TRWE to plan and execute the task. In this example, the human operator uses a joystick to manually control a simulation model of the M-robot and grasped workpiece to define position set-points as trajectory nodes of the task sequence script.

The input panel of the GUI allows quick specification of the control mode for the M-robot and facilitates the development and execution of the task sequence script (Fig. 5). In supervisory control mode, the human operator depresses a virtual push button with a mouse click to define the current position of the simulation model as a trajectory node in the task sequence script with the ability to later add, insert, edit, or delete trajectory nodes. A counter with indexing buttons is used to cycle through the task sequence script and specify the current trajectory node under control, as indicated by the digit to the right of the decimal point in the counter. By selecting “show script,” the list of defined trajectory nodes is displayed for an outline perspective of the task sequence script (Fig. 6—left). Otherwise, only the current trajectory node under control is displayed (Fig. 6—right), thus reducing the complexity of the graphic model.

The human operator also specifies a list of options for each trajectory node, including a request to pause before execution, a time specification for execution, and a preview request of the proposed trajectory to the next node in the task sequence script (which also activates a pause request). The task sequence script is transferred remotely by depressing “send TSS.” Following execution of a move to a trajectory node, the workstation at the TRWE returns system status and position information to update the feedback model at the HMI workstation. The digit to the left of the decimal point in the counter tracks the execution of the task sequence script by the M-robot and indicates the latest trajectory node to be reached.

The M-robot stops execution if a “set pause” has been defined in the task sequence script for the next trajectory node, and the workstation at the TRWE transfers the planned trajectory if a “set preview” has been defined. In addition to pause and preview requests within the task sequence script, the human operator may also at any time request a pause in execution as well as a preview using the “pause” and “preview” buttons. A highlighted “pause” button indicates “wait for supervisory approval” and the human operator resumes execution by depress-
Figure 4. Views from the three video cameras at the TRWE show the initial configuration for the navigation and placement task. The task is to guide the M-robot with grasped workpiece across the workspace while avoiding collisions and to insert the rod vertically into the cylindrical tube. A graphic model representation of the TRWE shows the M-robot in the desired goal position for the navigation and placement task.

tion by request of the human operator using the “send TSS” button.

In defining the trajectory nodes of the task sequence script, the human operator controls only a kinematic model of the M-robot and is not constrained by the robot dynamics (speed of movement) or the workspace obstacles. By decoupling the space/time constraints of the telerobot in simulation as well as removing physical constraints, the human operator can define the trajectory nodes and develop the overall task sequence script as fast
(or slow) as the simulation and human neuromotor control system will allow. Also, the human operator has the freedom of “going through” obstacles to more quickly reach a goal with the simulation model, an event likely to be physically impossible and/or potentially dangerous with actual hardware. This reemphasizes that the human operator is specifying a sequence of discrete trajectory nodes to define the task sequence script, and not the actual trajectory between nodes. Also, the number and choice of trajectory nodes are highly dependent upon the task and autonomous capabilities of the telerobot.

3.3 Viewpoint Control

A major advantage of the graphic display is the ability to arbitrarily orient the viewing perspective and more easily visualize the spatial layout of the model of the TRWE. A manual viewpoint control algorithm using joysticks or the keyboard allows the human operator to rotate about the entire workspace or just about a specified telerobot model, zoom along the viewing vector, and also simulate camera rotation in the pan and tilt directions. Alternatively, a mouse press in a 2-D positioner panel specifies the azimuth and incidence angles of a graphic viewpoint perspective at a constant radial distance in the upper hemisphere centered with respect to either the workspace or a particular telerobot model. Also, a number of preset viewpoints are accessed using function keys, such as front, rear, side, and top views of the workspace or telerobot model.

To decrease the workload of the human operator, the viewpoints are selected automatically as a function of the parameters of the model and the current state of control, and can be readjusted manually if so desired (i.e., if an obstacle is in the line of sight). For example, after receiving a trajectory preview from the TRWE, a pair of nearly orthogonal views centered on the trajectory preview is displayed automatically. Similarly, when initiating control of the simulation model to define a trajectory node, a pair of views centered on the simulation model is calculated as a function of the robot kinematics and automatically selected for display to the human operator. The viewing perspectives can be later updated to the position of the simulation model with a function key defined on the keyboard.

To generate the viewpoints for a specified telerobot model, the forward kinematic map is solved to yield the position and orientation of the end effector, as well as the position of each joint in the kinematic chain. The position of the end effector defines the local origin for the subsequent viewpoints and the orientation of the end effector is used as reference axes to determine the direction of the viewing vectors. For the automatically selected viewpoints, approximately front and side orthogonal views are generated in the upper hemisphere centered at the end effector and at a set radius. The viewing vectors are pitched 18° upward from the plane parallel to the base support for an elevated view. A pair of front and side views for a single trajectory node show the flexibility of the model for visual clarification of the spatial layout of the TRWE (Fig. 7).

3.4 Preview of the Planned Trajectory

In defining the task sequence script, the human operator is specifying a sequence of desired positions of the M-robot and not the path between two subsequent
positions. The TRWE workstation calculates the path, or dynamic trajectory between set-points, which is to be followed by the M-robot controller in executing the movement. If requested by the human operator, the planned trajectory can be transferred from the TRWE workstation and displayed for inspection and possible modifications before execution.

A sophisticated path planner for the M-robot with the ability to calculate collision free trajectories in the midst of modeled obstacles is not yet implemented due to limitations of programming time. The TRWE workstation simply calculates the standard trajectory of the M-robot controller box, which linearly interpolates each joint angle from the current position to goal position without regard to possible collisions with objects in the path. The dynamic trajectory is determined by the joint with the largest angle to traverse. This joint follows a velocity profile determined by the maximum operating speed of the M-robot (approximately 400 mm/sec) and the remaining joints follow a synchronized velocity profile so that the time of starting and stopping is simultaneous for all joint angles.

Two successive trajectory nodes in a task sequence script define a segment in which the M-robot must clear an obstacle during a rotation movement of the waist (Fig. 8—upper left). As a cautionary measure, the human operator sets a preview request for this trajectory node as part of the task sequence script. When the task sequence script is transferred to the TRWE and the M-robot has completed the script up to the previous trajectory node, the TRWE workstation pauses execution and transfers the planned trajectory between the current M-robot position and the next trajectory node (Fig. 8—upper right).

After visual inspection of the trajectory preview, the human operator confirms that the planned trajectory clears the modeled obstacle and resumes execution of the task sequence script. If unsatisfied with the planned trajectory, the human operator can edit the trajectory node and modify the task sequence script. A trajectory pre-
view reveals a node that requires modification before execution (Fig. 8—lower left) while another shows predicted completion of the navigation and placement task with the assistance of the model (Fig. 8—lower right).

4 Utility of Model-Based Supervisory Control

The navigation and placement task as illustrated in Section 3 was used to obtain preliminary results comparing the model-based supervisory control and manual control modes. In both modes, video feedback from the three cameras at the TRWE was viewed using the three small B/W monitors, with a selector switch to display one of the views on the large-screen color TV. A variable gain, 2 DOF joystick was used as a rate control device to manipulate the M-robot or a simulation model in either joint angle control (JAC) or end effector control (EEC) mode. A function key was defined on the computer keyboard to switch between JAC and EEC and a 3-way switch on the joystick was used to select the individual joint angles or coordinate axes under control.

In model-based supervisory control mode, a feedback model of the TRWE was displayed for additional visualization of the remote site. Also, the simulation model and GUI were used to define trajectory nodes, generate the task sequence script, command execution, and approve or modify trajectory previews of the M-robot. The high-resolution color monitor with double viewport option displayed the graphic model and interface panels for control. In manual control mode, input commands through the joysticks for the M-robot were interpreted and transmitted to the TRWE with video feedback only. Latency of the joystick input through the A/D board was less than 25 msec, transmission delay through the Internet was less than 75 msec, and latency of the output to the M-robot controller was less than 50 msec.

An experienced human operator, familiar with the HMI and control modes from system development, but untested with the given task setting, was used as a subject. Over the period of 1 week, the subject performed 15 pairs of trials of the navigation and placement task using both the manual and supervisory control modes, alternating the control modes in random order for each successive trial. The subject was instructed to complete
Figure 8. Two successive trajectory nodes define a segment of a task sequence script in which the M-robot must clear an obstacle during a rotation movement of the waist (upper left). The corresponding trajectory preview visually verifies the predicted success of the planned path between the model set-points (upper right). A separate preview reveals a trajectory node that requires modification (lower left) while another preview shows predicted success of the navigation and placement task (lower right).
the task as rapidly as possible while avoiding all collisions of the telerobot and grasped workpiece with the other objects. Time of completion for the task and number of collision errors were recorded as primary measures of task performance. The output of system messages was logged in a diary for an official transcript of each task trial.

Figure 9 shows the learning curves comparing the model-based supervisory control mode with the manual control mode for this experienced subject performing the navigation and placement task over a period of 1 week. Initially the subject failed to complete the task with manual control due to excessive collision errors with the workspace obstacles. Using the model-based approach to visually clarify the spatial layout of the TRWE and carefully plan the trajectory nodes for the M-robot, the subject was able to successfully complete the task without error for the initial two trials.

As the subject became familiar with the task, time of completion for both control modes reduced, stabilizing at approximately 6 min for model-based supervisory control and fluctuating with a higher variance near 7 min for manual control. The frequency of collision errors also reduced for manual control, but the subject still remained prone to collision errors throughout the experiment, due to the difficulty in visualizing the task with video feedback only. The number of collision errors remained low throughout the trials for model-based supervisory control, at a frequency of 0.2 errors/trial.

These results are the training data for a single experienced subject performing a previously unpracticed task. Further testing is required before definite conclusions can be drawn. However, this pilot experiment does demonstrate the utility of the model-based supervisory control technique, even for a task with negligible time delay and with a very simplistic path planning technique for the telerobot.

5 Summary and Discussion
5.1 Multiple Modes of Model-Based Supervisory Control

The approach of model-based supervisory control in telerobotics provides a matrix of possible interactions
ranging from manual control of remote machinery by
the human operator, to shared control between the
human supervisor and remote intelligence, to full au-
tonomous control by the telerobots. This multiplicity of
information loops and levels that provides a spectrum of
control modes in telerobotics has been previously out-
lined (Sheridan, 1992) and will be represented here with
respect to the present research as a block diagram (Fig.
10). Even though our experimental system hardware is
relatively simple, we have exploited quite a few of these
possible interactions.

5.1.1 Manually Controlled Teleoperation. The
outer loop in the block diagram represents manual con-
trol of the remote machinery by the human operator.
Using appropriate input devices, the human operator
drives the actuators of the telerobots whose output is
sensed and displayed to the human operator to close the
control loop. The inputs and outputs can be generalized
as flow (velocity) and effort (force) and can also be trans-
formed for scaled manipulation.

5.1.2 Feedforward Model for Predictive
Display. The input action of the human operator as sent
remotely for manual control also drives a local feedfor-
ward model of the TRWE using the known dynamics of
the telerobots and controllers. Such a feedforward model
is used for a predictive display in the case of teleopera-
tion under excessive time delay.

5.1.3 Feedback Model for Additional Visual
Information. Information from the sensed parameters
of the TRWE updates a feedback model for additional
visualization of the remote site. This information is dis-
played to the human operator using 3-D computer
graphics to provide flexibility of viewing perspective.

5.1.4 Simulation and Training. The local model
of the TRWE is used for real-time simulation of teleopera-
tion tasks. In addition to providing experimental test
beds for various concepts and issues in teleoperation,
such simulation models are valuable for training human
operators before manually controlling the actual telerob-
otic hardware.

5.1.5 Interactive Task Segmentation and
Planning. The human operator controls a local simula-
tion model of the TRWE to outline tasks for the telerob-
tots. This is accomplished here through the definition of
discrete model set-points, or trajectory nodes, to gener-
ate the task sequence script that is transferred to the re-

ote this information to the human operator. Viewing perspec-
tives of the 3-D graphic representation of the model of
the TRWE are calculated as a function of the forward
kinematics of a specified telerobot model.

5.1.7 Acceptance/Modifications of Display
Viewpoints. If desired, the human operator can manu-
ally adjust the automatically selected viewpoints. A view-
point control routine provides the ability to modify the
current viewpoint with a joystick, keyboard, or GUI input panel.

5.1.8 Algorithmic Planning of the Multisegmented Task. The remote intelligence interprets the task outline received from the HMI and plans accordingly to execute the task. Using the task sequence script generated by the human operator as an outline of position subgoals, the workstation at the TRWE calculates the trajectories between the specified trajectory nodes.

5.1.9 Preview of the Planned Model at the TRWE. If requested by the human operator, the calculated plans at the TRWE are transferred to the HMI and previewed using the model. The proposed segment trajectories as determined by the TRWE workstation are transferred to the HMI workstation and displayed using a 3-D graphic representation.

5.1.10 Approval/Modification of the Proposed Plan. Through inspection of the preview, the human operator acts as a supervisor to accept or modify the proposed plan. The human operator can modify the proposed segment trajectories by editing the trajectory nodes and, once satisfied, resumes execution of the task sequence script.

5.1.11 Autonomous Control of the Telerobots. Remote feedback loops are closed to autonomously control the telerobots and execute the calculated plans. Speed and precision of movement of the segment trajectories by autonomous control exceed that capable by the human operator in manual control.

5.1.12 Monitor Task Execution. During execution of the calculated plans, the human operator acts as a supervisory monitor of the telerobots under autonomous control. If necessary, the human operator can abort execution of the segment trajectory and enter the manual control mode.

5.1.13 Configuration of the Telerobotic System. The human operator interactively sets the various model parameters and control modes to configure the telerobotic system as desired. In the current implementation this is achieved through the use of pop-up menus with the computer mouse and input panels, as well as symbolic keyboard input.

5.2 Directions for Future Investigations

Decades of previous research have shown that model-based approaches can certainly assist the human operator in teleoperation tasks. Visual aids in the form of a separate graphic model with arbitrary viewpoint or as visual enhancements superimposed on transmitted video images facilitate spatial perception of the remote site. Local feedforward models driven with control commands from the human operator and used as predictor displays have been shown to help compensate for manual control with excessive time delays. In addition to providing a valuable training tool for human operators, interactive simulation models can be used on-line as an integral part of a supervisory control command language.

Yet questions remain regarding the assumptions imposed and limitations of the model. The use of a model requires a priori knowledge of the telerobots and remote workspace (which is not always available) and must also be able to adapt to a dynamically changing environment through on-line model updates. Furthermore, models are only approximate representations of a physical process. What if the model is incomplete, or inaccurate and potentially misleading to the human operator? Also, complex interactions with the environment and dexterous manipulation tasks require increasingly sophisticated models.

5.2.1 Model Initialization and Development.

Knowledge of the geometry, kinematics, and dynamics of a telerobot should be available through the development of a teleoperation system; however, knowledge of the environment and task will have to be generated where feasible. In the current system implementation, locations of objects, and task models are known a priori
and generated off-line. Ideally, a model-based telerobotics system would incorporate a modeling program, such as a standard CAD package or virtual world developer, to facilitate the generation of a model database for on-line access. Also, a combination of autonomous model-based active sensing and vision at the remote site with assistance by the human operator is currently being explored for on-line model additions and updates.

5.2.2 Detail and Accuracy of the Model. An understanding of the detail and accuracy of the model are crucial to the effectiveness of control performance. The human operator must be cognitively aware of the nature and capabilities of both the local model of the TRWE for interaction and visualization and the remote model for properly guiding the autonomous control capabilities of the telerobots. Also, tolerances for discrepancies between the model and real environment must be accounted for through error detection and recovery techniques (Funda et al., 1992). Model calibrations and recalibrations, and also camera calibrations are required to ensure adequacy of model accuracy, especially when using sophisticated graphic overlays on video (Kim, 1994). However, when the models drift from calibration and the error goes undetected, what limitations and difficulties are imposed on the human operator in the reliance of such models?

5.2.3 Task and Model Complexity. Increasing levels of task sophistication and complexity require increasing levels of model development and detail at both the HMI and TRWE. This is particularly true for instilling autonomous capabilities into telerobots beyond the current path planning and trajectory control. Reflexive behaviors such as obstacle avoidance and remote compliance during manipulator contact with objects would utilize feedback loops closed at the TRWE. Also, a more sophisticated path planning technique with the ability to circumvent obstacles would rely heavily upon modeled knowledge of the TRWE (Lozano-Perez, 1987).

Model complexity is also reflected in the level of fidelity and realism of interactive simulations, which attempt to mimic the remote environment through a synthetic experience, especially with the incorporation of models for kinesthetic feedback through contact and object manipulation. Even in the case of manual control without the use of computer models, where emphasis is placed on the controls, actuators, sensors, and displays for the extension of human manipulation and sensing capabilities, the internal cognitive model of the human operator must be suited for the complexity of the task.

For the model-based supervisory control technique described in this paper, interaction with the simulation model to define trajectory nodes did not rely on model realism, rather on the human operator's ability to effectively control the model to define goals that were well suited for the autonomous control capabilities of the telerobot. Thus, it is interesting to consider the possible forms of the model of the TRWE that exist at different levels and abstractions throughout a supervisory control system for telerobotics. Furthermore, the distribution and connections between the various forms of the model embedded in a supervisory control system are adapted to the different capabilities of the telerobot and the human operator.

6 Conclusions

An experimental telerobotic system has been developed to investigate the advantages and issues in model-based supervisory control, building upon the foundations of previous research in this area. Separate but interacting computer models of the telerobotic working environment (TRWE) are employed at the local and remote sites for specification of the task by the human operator and the subsequent interpretation, planning, and execution utilizing the autonomous control capabilities of the telerobots. The approach is illustrated for a navigation and placement task with a 5 DOF manipulator arm where difficulty in visual representation with static video cameras and close spacing of work space obstacles lead to multiple errors (object collisions) and long completion times with manual control.

A human–machine interface (HMI) using computer graphics allows a human operator to specify a sequential list of discrete model set-points, or trajectory nodes, that define a “task sequence script” for a telerobot. An inter-
active simulation model of the TRWE is used to specify the model trajectory nodes, independently of the actual dynamic and physical constraints of the TRWE in both space and time. An automatic viewpoint selection algorithm facilitates control of the graphic presentation of the model with the ability for the human operator to manually adjust the viewing perspective. When satisfied, the human operator initiates transfer of the task sequence script to the workstation at the TRWE for execution.

The workstation at the TRWE calculates the planned trajectory between the current telerobot position and the next specified model trajectory nodes in the task sequence script. The human operator has the ability to request a preview of this planned trajectory for approval or modification. When satisfied through visual inspection of the preview, the human operator resumes execution of the task sequence script. The telerobot then executes the planned trajectory under autonomous control with speed and precision. Thus, the approach of model-based supervisory control in telerobotics provides a platform of various levels of responsibility and control in teleoperation tasks that attempts to maximize the abilities of the higher level intelligence provided by the human operator and the lower level control functions of the telerobots.

Results from preliminary experiments with a navigation and placement task of a 5 DOF manipulator arm teleoperated through the Internet have demonstrated the utility of the model-based supervisory control technique. Further investigations are necessary to help answer questions regarding the assumptions and limitations involved in utilizing a model of the TRWE for assistance in the control of remote machinery.

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