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Description	

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Multioperator Teleoperation of Multirobot Systems with Time Delay: Part II—Testbed Description

Abstract

The Mechanical Engineering Laboratory (MEL)[1] has been developing coordinated control technologies for multi-telerobot cooperation in a common environment remotely controlled from multiple operators physically distant from each other. Previously, we learned about how the transmission delay over the network deteriorates the performance of telerobots through simulations. To overcome the operator's delayed visual perception arising from network throughput limitations, we have suggested several coordinated control aids at the local operator site. The testbed facilitates experiments with physical robots for validation beyond simulation. This paper mainly discusses the details of the testbed and investigates the use of an online predictive simulator to assist the operator in coping with time delay over the network. Practically, a common data relay station is suggested to reduce the travel distance of the master data over the network and enable multirobot predictive simulation at one's master station. Operators control their master to get their telerobot to cooperate with the counterpart telerobot using the predictive simulator as well as video image feedback. Specifically, exploiting the audio-visual resources of the simulator, operators can detect a priori the possibility of collision and coordinate conflicting motions between telerobots. We have demonstrated an object rearrangement task by two telerobots and two operators via an ethernet LAN that is subject to simulated delays and evaluated the validity of the online predictive simulator in Multioperator-Multirobot (MOMR) tele-cooperation.

1 Introduction

We have addressed the need for MOMR tele-cooperation in our previous work. The actions of remote telerobots not under the operator's control are not predictable, resulting in the possibility of collision in remote environments. This seriously affects operators' decision-making, and, accordingly, the performance of cooperating telerobots deteriorates. Thus, it is necessary to have additional information available irrespective of whether the network communication is impeded by time delay. Previously, to cope with the operator's delayed

1. On April 1, 2001, MEL merged into the National Institute of Advanced Industrial Science and Technology (AIST).

2. Currently with NHK Akita, Japan 010-8501.

visual perception arising from throughput limitations of the network, we experimented with local control aids for the operator to help safely steer remote telerobots in the presence of time delay. We have investigated the validity of this local strategy through various simulations in our virtual experimental testbed (Chong et al., 2000a).

To date, many works have reported on the control of telerobots over networks with time delay. Sheridan (1992) extensively reviewed relevant theories and technologies, primarily for the case of a single telerobot controlled by a single operator. In addition, Brady and Tarn (1998) proposed a new method for controlling telerobots over vast distances, where communication propagation delays exist. Recently, some efforts have been devoted to the teleoperation of multiple robots. Among them, Goldberg et al. (2000) built a collaborative system that permits a robot to be teleoperated by combining multiple operator inputs. Kheddar, Tzafestas, et al. (1997) and Kheddar, Coiffet, Kotoku, and Tanie (1997) demonstrated long-distance teleoperation with several robots in parallel from a single operator. Mitsuishi, Tanaka, and Tsuda (1998) addressed software design for a cooperative multioperator-multiobject teleoperating system. Suzuki et al. (1996) presented a human interface framework for teleoperation of multiple robots using the Web. But none considered communication delays between remote operators at a distance. Practically, to the authors' knowledge, MOMR telecooperation systems have not yet been built or even studied extensively. This is partly because a real system requires costly facilities providing a communication link between the local operator and remote task sites (Chong et al., 2000c). Another issue is the difficulty of coping with the delay in receiving information from the physically separated operator as well as the remote site.

We believe that experimental tests are crucial and have built a real testbed. In the testbed, as an extension of our previous simulations, we research cooperation of two telerobots with time delay remotely operated by two operators with large physical separation. To implement the throughput limitation of the network, an arbitrary communication time delay is simulated. Specifically, to assist operators suffering from the delayed

visual perception on telerobots not under their control, we bring in an online predictive simulator that provides operators with the worksite view in near realtime. This simulator also feeds another source of information to the operator, which signals a possible collision between two telerobots. Thus, the operator can coordinate motions of multiple telerobots in remote sites even if the other operator is physically at a distance and the network is subject to time delay. The validity of the use of predictive simulator is verified through real experiments in the testbed in which two telerobots in a common worksite are controlled cooperatively from two respective operators.

2   Bringing in Predictive Display in Tele-Cooperation

Existing networking facilities restrict the operator's timely access to information about telerobots in remote environments. Predictive display has been an oft-tried approach in dealing with communication time delay in teleoperation over the past decades. It typically provides operators with the immediate visualization of remote telerobot motions responding to their master control commands for which the real video image feedback is delayed (Kim & Bejczy, 1993). An important issue using predictive display in MOMR telecooperation is how to deliver real-time information of the counterpart operator's control command. Telerobot motions under another operator's control cannot be predicted locally in the operator sites. Another operator's telerobot motions are updated with one round-trip time delay whereas the operator's telerobot motions are predicted without time delay in the predictive display. Accordingly, there is one round-trip time mismatch between graphics update of two cooperating telerobots in the operator site.

To overcome this difficulty, we have already proposed several coordination strategies through simulations in our previous virtual testbed (Chong et al., 2000a). Likewise, the predictive simulator has been employed to detect collision between telerobots and fine-tune their motions towards the task goal when the network is im-

peded by communication time delays (Chong et al., 2000b). This work addresses an experimental investigation on the possible use of a predictive simulator in MOMR tele-cooperation. The master commands are sent to the remote site via the operator's predictive simulator. In MOMR tele-cooperation, the delay in receiving the information on the counterpart telerobot from the remote site requires the operator to transmit the same master control commands simultaneously to the predictive simulator in the counterpart operator site. To enable the operators to facilitate this data travel, a common data relay station is suggested between the operators on the network. A priori models of remote environments are necessary to have this local predictive simulator available. For this, an interactive modeling tool based on an on-board sensor has been recently developed to build a reliable 3-D model as quickly as possible (Even, Fournier, & Gelin, 2000).

3 Experimental Testbed

This section details the tele-cooperation testbed we built at MEL. Tsukuba, Japan. It consists of two master control stations and one common task site interconnected through a fast ethernet LAN. (See figure 1.) A pair of operators controls their respective master systems to safely steer telerobots towards cooperation over the network without collision.

3.1 Master Control Station

Figure 2 illustrates the master control station. It consists of a prototype master system built by Toshiba R&D Center and an online predictive graphics simulator that runs on a Unix-based operating system (Pentium II PC at 450 MHz, running Linux). Real video camera images from the task site are displayed in another PC client (Pentium III at 667 MHz, running Windows) which has access to the video broadcasting server.

3.1.1 Master System. The six-DOF master system is small, lightweight, and has feedback force-

reflection capability. (See figure 3.) This general-purpose device employs the twin pantograph mechanism for its positional three axes. If its handle is guided by the operator hand, the resultant master position will follow a similar path on a reduced scale. Also, the gimbal-like mechanism permits the master handle to rotate freely in any direction. This arrangement is effective to decrease the computational burden in coordinate transformations in dissimilar master-slave teleoperation systems. Please refer to table 1 for detailed specifications. Several types of sensory information are incorporated in a real-time controller developed within a QNX environment. (QNX is a real-time operating system for PCs.)

We have implemented different operating modes such as the position-to-position, position-to-velocity, and force-to-velocity modes. Basically, position-to-position control mode is exploited over a limited motion range, in which the master position is interpreted as a telerobot end-effector position command through coordinate transformations. The displacement from the initial position drives the telerobot to move on an appropriate scale. When the master position reaches its limit, it is returned to a nominal position to generate further displacement with this retrieving displacement nullified. To overcome the limitation of the master's workspace and make the operation continuous and smooth, rate control approaches are also implemented. The current master position is interpreted as an end effector velocity command of the telerobot. Similarly, force can be interpreted as an end effector velocity of the telerobot. Note that, in the force-to-velocity mode, the master position is controlled with high stiffness gains, and the reaction force is generated at the master when the operator tries to move it. In this case, however, the telerobot force is not reflected to the operator hand. These modes have tradeoffs and can be implemented according to task conditions.

The master system has access to the predictive simulator through an ethernet LAN. As an interprocess connector between the master controller that runs in QNX and the predictive simulator in Linux, a pair of cooperating sockets manages the communication via shared memory. The interface is made by two programs: a client and a server. Specifically, to transmit master com-
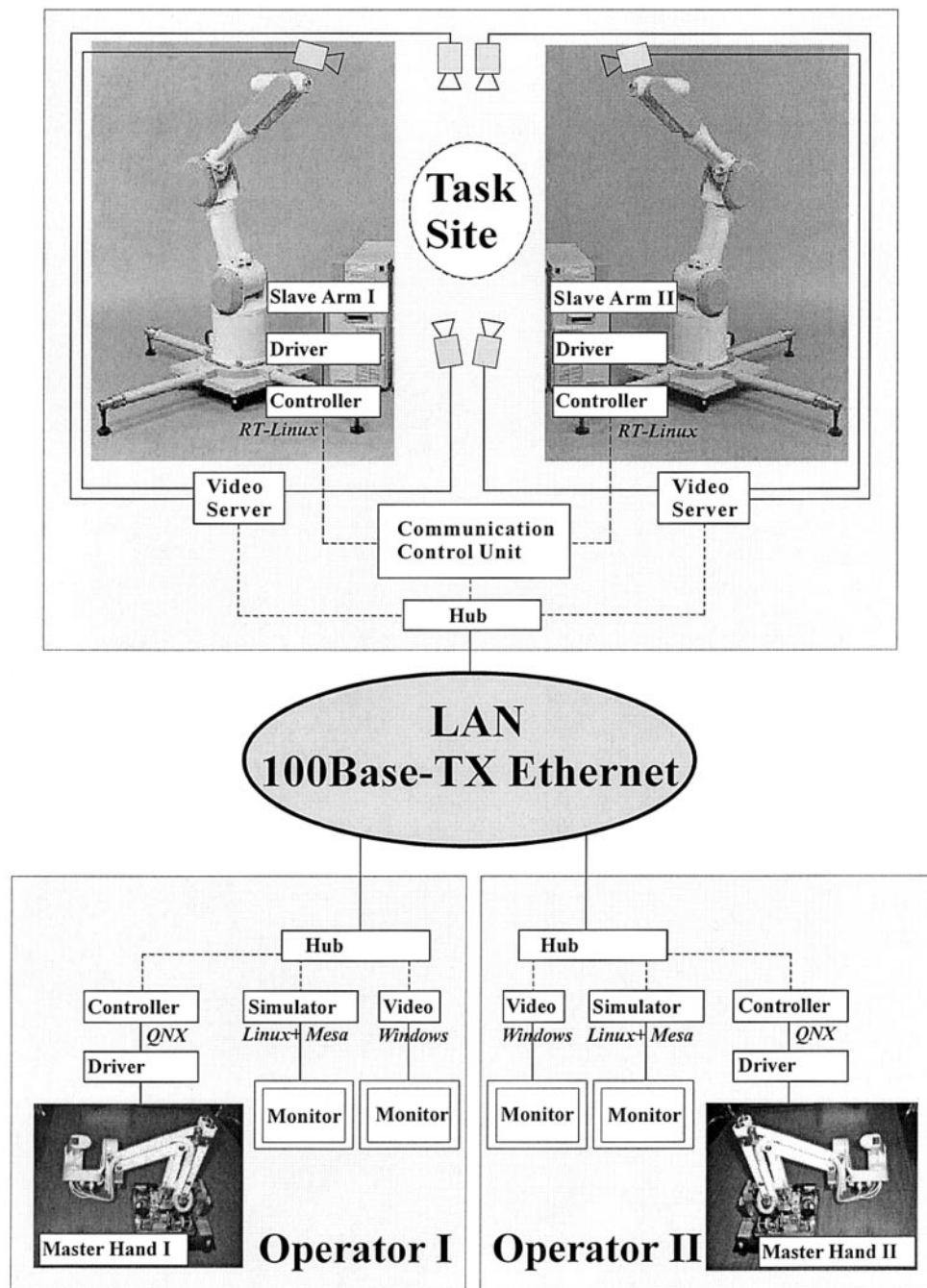
Figure 1. *An experimental tele-cooperation testbed at MEL.*

mands to the simulator, the servo control programs in the master controller first writes the sensory information (that is, angle, velocity, force/torque, error status, and time) in the shared memory, and then the client sends this to the predictive simulator every 10 ms. In the predictive simulator, the server receives transmitted data

Figure 2. *Local master control station.*

Figure 3. *Master device at the operator site.*

and writes it on the shared memory. The simulator program finally reads the master data and has its graphics model respond to the operator's control commands as intended.

3.1.2 Graphics Simulator.

We developed a predictive graphics simulator using Mesa, a 3-D graphics library with an API very similar to that of OpenGL. It helps the operator visually verify his or her telerobot motions without time delay. Operators can set the viewing of the predictive simulator so that they may observe some different angles of concern or hidden angles that the cameras at the remote site cannot cover. We can change the viewing of the simulator during the operation, if need be. Mesa was originally designed for Unix/X11 systems. Specifically, one needs an ANSI C compiler and the X development environment. In this work, 3-D graphics models of the two telerobots and the task environment are constructed for simulation. Additionally, we installed a graphics accelerator, the 3dfx Voodoo3 3000 AGP, to aid in the generation of real-time graphics. This card works with Linux via 3dfx's glide library. The graphics image of telerobots is controlled by the same master control law that controls the real telerobot.

3.2 Transmission Control

A 100Base-TX ethernet and a dual-speed ethernet hub are used to transmit data among two master con-
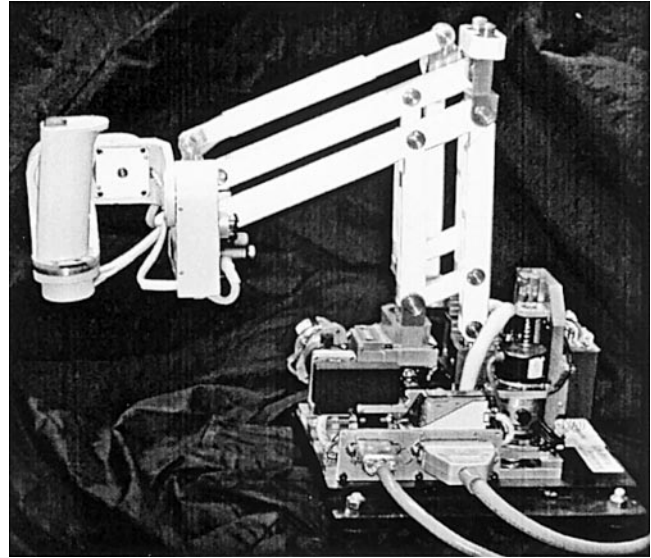
trol stations and two telerobots at a remote site. Let's assume that the master commands from the two operator stations first reach a common relay station and are forwarded to respective telerobot controllers and the counterpart operator station. We developed a communication control program in the control tower station (Sun UltraSPARC 170; hereafter, CTS) on the network to get all the communication among master stations and the task site connected or disconnected, which is facilitated by socket links. Likewise, the CTS also stores data in a buffer, which enables the communication over the LAN to simulate different time delays. Specifically, the CTS receives the master commands via operators' predictive simulators (such as robot joint configuration data) and directly relays it to the respective predictive simulators in the counterpart operator sites. On the other hand, the CTS relays the same data to the real telerobot with time delay by storing the data in a ring buffer until the specified delay timer expires.

3.3 Video Camera and Broadcasting Server

Local operators can have a better understanding of the remote task site if multicamera views are incorpo-

Table 1. *Specifications of the Master Device*

Axis	1	2	3	4	5	6
Motor	Sanyo R301-011E	Sanyo R301-011E	Sanyo R301-011E	Inland QT-1207C	Inland QT-1204B	HDS RH-5A 5502
Motion limit	±25 mm	±25 mm	±38 mm	+60°/−60°	+80°/−40°	+60°/−60°
Reduction	Timing belt	Timing belt	Timing belt	Spur gear	Spur gear	Harmonic drive
Ratio	1.5	1.5	1.5	200/9	200/9	80
	Ball screw lead 3 mm	Ball screw lead 3 mm	Ball screw lead 3 mm			
	Pantograph 1/4	Pantograph 1/4	Pantograph 1/3			
Driver	TITECH V2	TITECH V2	TITECH V2	TITECH V2	TITECH V2	TITECH V2
Brake	None	None	None	None	None	None
Encoder	2500 ppr	2500 ppr	2500 ppr	2000 ppr	2000 ppr	360 ppr
Force sensor	$487\mu\varepsilon$ 2.3 Kg$_f$	$478\mu\varepsilon$ 2.3 Kg$_f$	$431\mu\varepsilon$ 2.3 Kg$_f$			
Torque sensor				$838\mu\varepsilon$ 6.7 Kg$_f$ cm	$838\mu\varepsilon$ 6.7 Kg$_f$ cm	$1622\mu\varepsilon$ 6.7 Kg$_f$ cm

rated. For this, we mounted video cameras on the ceiling and the side wall in the task site, in addition to the ones attached on the top of the gripper of each robot. (See figure 4.) To send the camera images to the local operator site, we used a video broadcasting server (MegaFusion eWatch MD-100) that enables real-time streaming of video images over the Internet. (See figure 5. Please refer to table 2 for detailed specifications.) For the communication interface, the server has 10Base-T and RS-232C ports and can access the LAN/Internet through a hub, a router, a terminal adapter, or a modem. The camera's pan, tilt, and zoom functions can be controlled by the server's standard or user-developed HTML contents through a serial interface, which allows one to zoom in on details and monitor large areas from different angles. However, even if possible, the frequent change of the camera functions during the operation will not improve the operator performance. It might deteriorate in most cases. The server can connect up to four NTSC video cameras and up to ten clients. The client in the local operator site should have access to the video server through the network. Through incorpora-
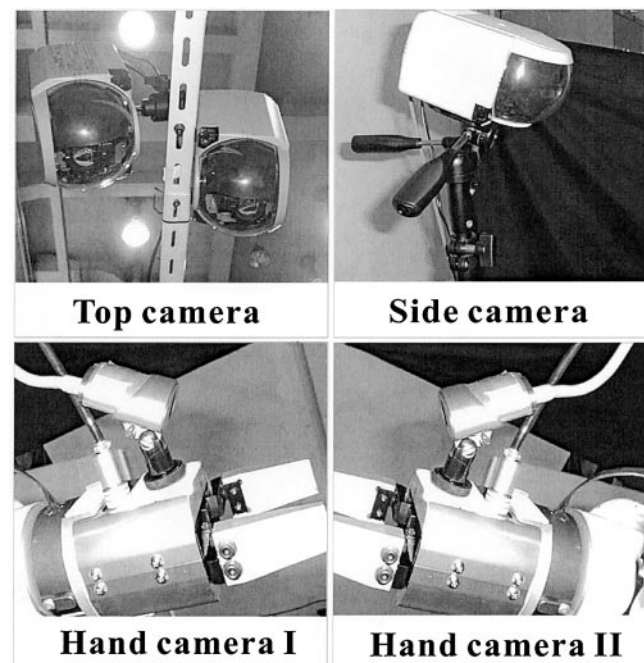
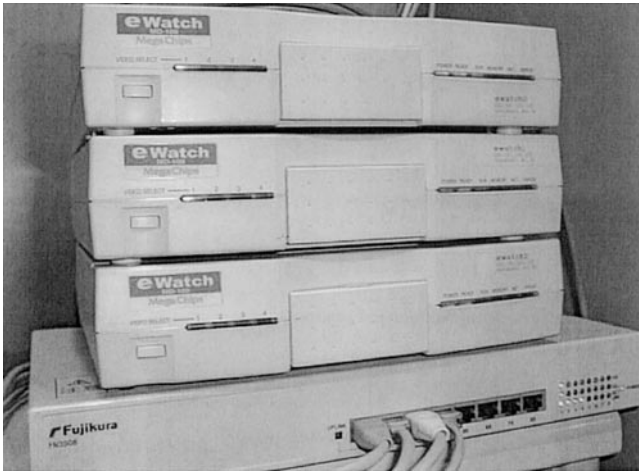**Figure 4.** *Video cameras at the work site.*

Figure 5. *Video server and dual-speed ethernet hub.*

tion of the server's plug-in software into Web browsers such as Internet Explorer or Netscape Communicator, the server's video images can be viewed from the clients over the network. (See figure 6.)

Existing video broadcasting technologies have unavoidable delays such as source compression delay at the video server and image reconstruction delay at the clients (in addition to the network transmission delays). The video image input in our server can be compressed at up to thirty frames/second when only one camera channel is input. The compression speed decreases to approximately two frames/second with four camera inputs. This compression speed is not changed according to the resolution of input image. However, the network traffic and the performance of the client PC will affect the broadcasting and decompression speed, which results in an increase of total time to completion of video transmission. Specifically, a Windows PC with a Pentium II processor at 333 MHz or higher processor clock speed is recommended for the client. In experiments using the network with time delay, the client PC presents the operator with delayed video images.

3.4 Telerobots and Task Environment

Two seven-DOF robots (PA-10, Mitsubishi Heavy Industries Ltd.) are positioned on opposite sides of a common working table. (See figure 7.) These robots have a 950 mm arm length and a 10 Kg_f payload capacity. Different-shaped and different-colored acrylic plastic plates with a vertical handle are initially scattered on the table and are to be properly fitted into their specified places. Due to the limitation of the robot's workspace, some plates are out of reach of one robot. Similarly, some grasped plates cannot reach their proper places. Thus, delivering plates within the reach of the counterpart robot is a major requisite for this task. Thus, even though two robots are controlled independently by their respective operators, cooperation between the two robots is essential to perform this task successfully.

4 Use of Relay Station and Simulator Resources Against Collision

4.1 Data Relay Station

The actions of the telerobot under another operator's control is impossible to predict in the presence of delay. Thus, operators usually send a very limited position/velocity command and keep their telerobot away from the other telerobot. Another option is to use the joint position data sent from the remote controllers. These data can be incorporated in a local graphics simulator to provide the operator with a virtual predictive enhancement. This will reduce the delay in receiving the information on the counterpart telerobot beyond what we can achieve using the existing video transmission techniques.
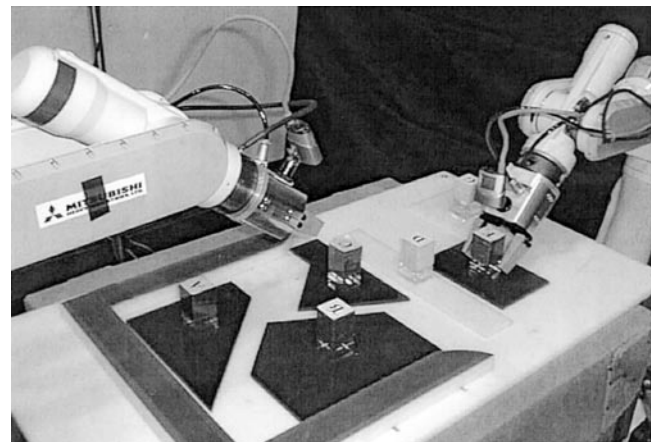
Here we suggest a common data relay station (the CTS in subsection 3.2) between local operators on the network. To overcome the delay in receiving the data of another telerobot from the remote site, it is necessary to have an additional source of data about the robot. This requires the operators to send their master control commands simultaneously to the counterpart operator site and to the remote site. For this, the master command data from local operator stations are centralized in a common relay station on the network and are forwarded to respective target telerobot controllers. This relay station also passes the data to the counterpart master station. Thus, the relay station receives the master data and

Table 2. *Specifications of the Video Server*

Video inputs: 4 ch.	NTSC/EIA via BNC connectors
	640×480/240, 320×480/240
Video outputs	NTSC/EIA via BNC connector
Video encoding	RVC, JPEG
	Max. 30 fps for 1 ch., Max. 2 fps for 4 ch.
Video recording memory	10 MB
Audio inputs: 1 ch.	Microphone via jack 3.5ϕ
	Line via RCA connector
Audio outputs: 1 ch.	Headphone via jack 3.5ϕ
	Line via RCA connector
Audio encoding	G723.1 (CELP): 6.3 K bps
	G726 (ADPCM): 32 K bps
Size	207D × 242W × 58H mm
Power supply	AC 100V ± 10%

Figure 6. *Four remote site views in the client monitor.*

Figure 7. *Telerobots and work environment.*

distributes them to the controllers at the remote site and the local simulators at the master stations at the same time. Practically, they communicate with each other using a TCP/IP socket connection via shared memory. This will minimize the travel distance of the master data because the data can reach the counterpart master station not via the remote site. Thus, the local simulator's predictive visualization of the operator's master control data can be extended to that of the counterpart operator without having to wait for data from the remote site. (See figure 8.) Also, we can have extra information, such as the orientation of the gripper and the current safety margin displayed in the graphics simulator.

4.2 Audiovisual Aids for Collision Avoidance

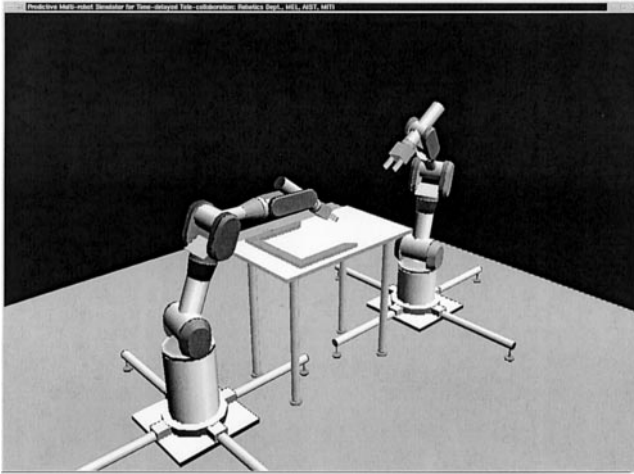In this work, we bring in the multi-telerobot predictive simulator with audiovisual resources to avoid

Figure 8. *Two-telerobot predictive simulator.*

Table 3. *Subjects Used in the Experiments*

Group	A		B	
Sex	M	M	M	M
Age	35	25	36	26

operator is immediately informed from the changing colors which link is likely to collide at the moment. Thus, even if the operator is observing another video feedback image, she can respond to the warning signals and revise current control commands to avoid collision.

5 Demonstration of Pick and Place

5.1 Methods

A pick-and-place demonstration was performed in the real testbed. This demonstration was basically similar to the previous experiments using the computer graphics models in our virtual testbed. We had six objects scattered on the working table. The operators controlled their telerobot and collaborated with the counterpart operator in arranging the objects, and the operators were informed which object should be positioned where. Each object had a different color and shape and was distinguished by an alphabet character on top of the vertical handle. The usefulness of the proposed approach can be evaluated using a measure such as the total time required for completing the task. We compared this measure with changing network delays, and we also investigated how the predictive simulator works in collision detection without delay. Two pairs of subjects performed the operation solely with multicamera views. The same pairs also performed the same trials with the predictive simulator in addition to multicamera views. Prior to the real trials, we made each subject perform practical trials to minimize effects due to learning during the experiments. Table 3 shows the subjects used in the experiments. Each of the pairs made a total of forty trials. Specifically, they made ten trials with video feedback only and video feedback plus predictive simulator aid cases. They repeated the same trials with no

collision between two cooperating telerobots in a remote environment. When transmitting the master control commands to the remote site, operators are not able to simultaneously observe all camera views as well as the predictive simulator. According to the first author's experience, human operators should concentrate on the one specific view that is of the most concern at the moment. Moreover, due to the network delay, the operator cannot detect collisions in time from the video image feedback. In this experiment, online collision detection is performed in the predictive simulator. Provided that the minimum distance between two telerobot graphics images is less than an allowable limit, it should be considered that collision is likely to happen. Here the allowable limit is determined according to the possible motion ranges of the counterpart telerobot throughout the time delay in receiving the master commands from its operator site. This delay is not significant in many cases and also can be handled with the coordinated control aids proposed in our previous experiments using virtual simulation models. If the minimum distance approaches the predetermined limit distance, prior to collision, the simulator signals to the operator using its audiovisual resources. Practically, we installed short sound clips in WAV and AU formats in the simulator. We play these audio files and change the default colors in the simulator until the safety margin is restored. The

Table 4. *Task Completion Time in Two-Telerobot Cooperation.*

Time Delay Subject group	0 sec.		1 sec.	
	Video only	Video plus simulator	Video only	Video plus simulator
A	245 sec.	215 sec.	270 sec.	231 sec.
B	200 sec.	180 sec.	289 sec.	211 sec.

time delay and a 1 sec. time delay. The order of trials was chosen randomly.

5.2 Results and Discussion

Table 4 shows the results of overall trials. The task completion time means the average over ten repeated trials, and the time delay is the one-way transmission delay of command signal between the master stations and the corresponding telerobot controllers. When the operation was conducted solely based on the fixed multicamera views, operators faced several serious difficulties as follows: (i) The video image feedback delay caused an unexpected collision between two telerobots. (ii) The video camera did not show the overall configuration of telerobots, which might lead to singular positions. (iii) The limited scope of video camera coverage allowed the counterpart robot to instantly show up and make the operator nervous. (iv) Telerobots sometimes partly occluded their counterpart robot. This forced the operator to watch another video feedback. Without the predictive simulator, task completion time increased about 11% and 14% for the pairs of subjects A and B, respectively, even though the CTS simulated no time delay. It was observed that items (ii) through (iv) were likely to impede the operation irrespective of network delays. Operators often lost their sense of direction for an instant due to an abrupt revision of master commands and/or the change of video in those cases.

If the operators have a visual enhancement and another source of information available from the predictive simulator, they could control their telerobot to keep an adequate safety margin all the way through the task. The simulator also signals to the operator when a collision is expected and/or the telerobot comes in contact with the working table. Operators did not face the situation in which they had to alter master control commands instantly, if they listen for the sound. In addition, from the simulator's overall view of the telerobots and the working table, operators quickly make a decision about the direction they should move their telerobot and confidently move there at a relatively high speed. Thus, the task completion time was reduced for both pairs of subjects about 10% to 27% as shown in table 4. One troublesome aspect in this approach we also should point out is that there is some mismatch between the real world and the graphics models. Thus, we need to have effective calibration of the simulator to have higher-fidelity prediction available (Kim, 1996; Oyama, Tsunemoto, Tachi, & Inoue, 1993).

It is also possible that the virtual force would be incorporated in the predictive simulator when contact is made because force reflection to the operator hand can improve the task performance. Very recently, for ground teleoperation of a space robot, reflected force was successfully used to improve the performance of the operator despite time delay (Peñin, Matsumoto, & Wakabayashi, 2000). Also, an algorithm has been implemented based on virtual springs in force-feedback teleoperation to keep a Stewart platform inside the useful workspace (Rubio, Avello, & Florez, 2000). To further this approach, we will have the virtual force reflected to the operator's hand directly from the predictive simulator in addition to existing audiovisual resources. This will help the operator have more-realistic virtual environments

that are tolerant of network delays and accordingly enhance the operation performance.

6 Conclusion

A multirobot remote tele-cooperation technology is proposed for multiple operators with large physical separation in the presence of time delay over the network. We have built an experimental testbed at MEL in which pick-and-place demonstrations were conducted with two pairs of subjects and two telerobots over an ethernet LAN subject to simulated delays. To assist the operator suffering from delayed visual perception of the telerobot under another operator's control, we brought in an online predictive graphics simulator. For this, a common data relay station was suggested between local operators to facilitate their master data transmission over the network. Practically, master data was forwarded via the relay station to the counterpart master site and this enabled the prediction of both telerobots at one's master station. Thanks to the simulator's variable angles in addition to fixed multicamera views, the operator could reduce the task planning time and make the operation smooth. Moreover, the overall configuration of the telerobot was monitored in the simulator to avoid singular configurations, while the video cameras zoomed in on the points of interest.

The current results show that the use of a predictive simulator facilitates fast, collision-free MOMR tele-cooperation over networks with time delay. Exploiting audiovisual resources of the simulator, the operators improved their performance, especially in task completion time. Operators could control their telerobot more confidently without having to consider collisions with another telerobot controlled from a distance because the simulator would signal collision beforehand in an audiovisual way. Additional supplementary information such as contact force reflection will be incorporated in our following work. It would be difficult to say that multirobot tele-cooperation can be completed solely with the help of a predictive simulator, but the simulator may give useful information to supplement delayed

multicamera views and guide the operator through network delays.

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