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Multioperator Teleoperation of Multirobot Systems with Time Delay: Part I—Aids for Collision-Free Control

Abstract

In this paper, various coordinated control schemes are explored in Multioperator-Multirobot (MOMR) teleoperation through a communication network with time delay. Over the past decades, problems and several notable results have been reported mainly in the Single-Operator–Single-Robot (SOSR) teleoperation system. Recently, the need for cooperation has rapidly emerged in many possible applications such as plant maintenance, construction, and surgery, because multirobot cooperation would have a significant advantage over a single robot in such cases. Thus, there is a growing interest in the control of multirobot systems in remote teleoperation, too. However, the time delay over the network would pose a more difficult problem to MOMR teleoperation systems and seriously affect their performance. In this work, our recent efforts devoted to the coordinated control of the MOMR teleoperation is described. First, we build a virtual experimental test bed to investigate the cooperation between two telerobots in remote environments. Then, different coordinated control aids are proposed to cope with collisions arising from delayed visual feedback from the remote location. To verify the validity of the proposed schemes, we perform extensive simulations of various planar rearrangement tasks employing local and remote graphics simulators over an ethernet LAN subject to a simulated communication delay.

1 Introduction

Recent advances in telerobotic systems allow us to replace humans for many hazardous environments and tasks such as space, undersea, and military operations as well as nuclear and toxic waste cleanup. Over the past decades, several notable results have been reported in teleoperation to cope with its inherent time delay. Thus, the current on-site work that usually requires a lot of travel could be replaced by remote teleoperation over the network. Recently, the need for cooperation has rapidly emerged in many possible applications such as plant maintenance, construction, and surgery, because multirobot cooperation would have a significant advantage over a single robot in such cases. Therefore, it is expected that MOMR teleoperation will be applicable to various remote operations and play a significant role as an alternative to support the coming society in which the working population decreases.

The control of telerobots at the remote site is commonly visualized through round-trip time delays to the local operator site. In that case, predictive display overlay can be superposed on the camera image feedback from the remote site to tackle time delays. In contrast, in MOMR teleoperation, a local operator site might be at a physical distance from another operator site. As a result, the telerobot not under the operator's control would not be predictable in the operator site. The lack of proper coordination causes remote multiple telerobots to be exposed to the danger of collision. This makes remote cooperation through teleoperation hardly feasible. In this paper, thus, we propose different coordinated control aids to overcome the throughput limitation of the low-bandwidth network in the presence of large physical separation between two operators (Chong et al., 2000).

Many research works have been reported in both teleoperation and telerobotics. Sheridan (1992) has made an excellent and extensive survey of literature on those fields. Recently, Matsumaru et al. (1999) proposed the task-based data exchange for teleoperation systems through an ISDN to overcome the limited transmission capacity. Kikuchi, Takeo, and Kosuge (1998) proposed a teleoperation system in a dynamic environment with varying communication delay. Rovetta, Sala, Wen, and Togno (1996) demonstrated a telesurgical operation using satellites and optical fiber networks for data exchange. Wakita et al. (1996) proposed the snapshot function of intelligent monitoring to deal with the time delay and limited communications capacity of super-long-distance teleoperation. Goldberg et al. (1995) built a system that allows a robot manipulator to be teleoperated via the Web. But most of the past works were limited only to the SOSR teleoperation. Very recently, some efforts have been devoted to the MOMR teleoperation (Kheddar et al., 1997; Mitsuishi, Tanaka, & Tsuda, 1998; Suzuki et al., 1996). But, they did not deal with communication delays between physically separated operators.

This paper describes the coordinated control of two-telerobot cooperation in a remote environment impeded by transmission delays over the network. (See figure 1.) We have built a virtual experimental testbed and proposed different coordinated control aids to prevent collisions between two telerobots arising from transmission delays. To verify the validity of the proposed schemes, we conducted various experiments in planar object rearrangement employing graphics simulators over an ethernet LAN subject to simulated communication delays.

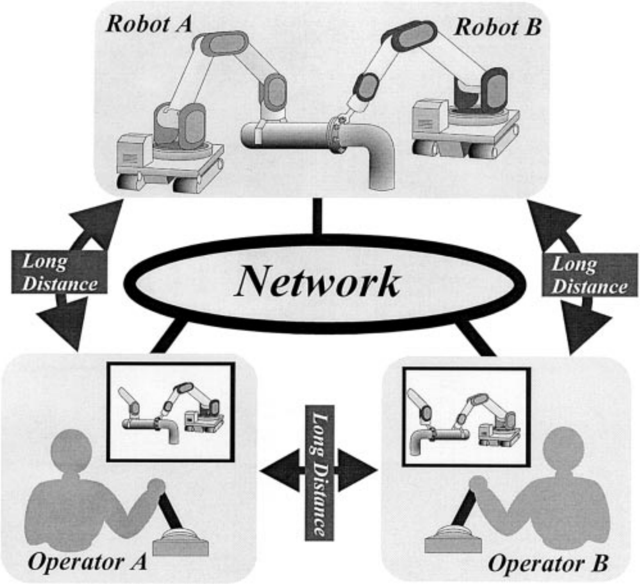

Figure 1. *Concept of remote MOMR tele-cooperation through a communication network.*

2 MOMR Teleoperation Through Time Delay

In teleoperation, local and remote sites are commonly connected to a communication network, and information is sent out and relayed over the network. Operators keep telerobots under observation to ensure that their intended actions occur properly or to make changes in the instructions. They usually give instructions through master controls with the aid of image feedback from the remote site. However, the images of telerobots are fed back to local operator sites through round-trip time delays: the command signal delay and feedback communication delay. The feedback delay includes the video image compression delay at the video broadcasting server in addition to the network transmission delay; it is also affected by the image reconstruction performance of the client system which has access to the video broadcasting server.

Over the past decades, the predictive display has been a well-tried approach for time delay in teleoperation. It typically provides the local operator with the immediate visualization of the master device instructions when the real video image feedback from the remote site is delayed (Kim & Bejczy, 1993). In contrast, assuming that two operators are physically at a distance, the telerobot not under the operator's control is difficult to predict. One reason is that it would not be possible to keep an operator immediately informed about another remote operator's master controls instructions. Accordingly, visual aid to the telerobot under another operator's control would not be provided without delay. This makes MOMR teleoperation over the long-distance network extremely difficult. Therefore, in the predictive display of MOMR teleoperation, operators need to cope with delayed image of telerobots under another operator's control to facilitate collision-free tele-cooperation at remote sites.

3 Virtual Experimental Setup

To illustrate and understand the framework of the MOMR tele-cooperation, a virtual experimental testbed was designed and built at the Robotics Department of the Mechanical Engineering Laboratory (MEL)[1] in Tsukuba, Japan. (See figure 2.) Prior to the employment of real telerobots interconnected through a long-distance network, we have performed experiments based on robot graphics simulators over the ethernet LAN subject to simulated delays. The experimental setup consists of one master control and one local predictive display, respectively in two operator sites and one common remote slave simulator interconnected through a LAN. Two human operators distant from each other manipulate their respective master control in the operator station to drive their predictive simulator without time delay, and the same commands are then sent to the common remote slave simulator through a one-way time delay.

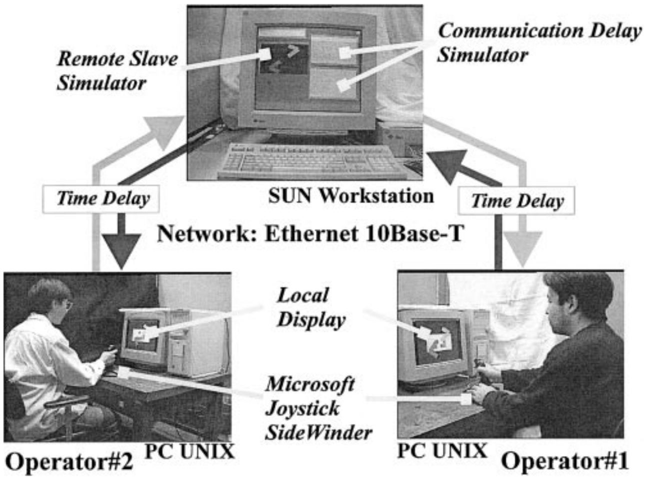

Figure 2. *Experimental setup for MOMR tele-cooperation at MEL.*

3.1 Underlying Assumptions

We make the following assumptions to simplify and facilitate the experiment.

- *No communication between operators*: When two operators are physically distant, the communication between them is impeded by time delay and it would make the task more complicated. Likewise, one operator would not be able to respond to the information from another operator and revise the instructions within the communication delay which is less than about 100 ms. Also, there is no prior engagement on the task such as the priority of the arm movement or the detailed sequence of the task.
- *No machine intelligence at remote site*: Some recent research focuses on the combination of human supervisory control at local sites and telerobot intelligence at remote sites. For this, one should use many external sensors and on-board reasoning systems based on complex rules. However, the sensors may not be completely reliable, and decision-making rules might fail to adapt to the complexities of the

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

real-world environments. Thus, it would be difficult to employ remote intelligence especially when safety is of serious concern.

- *No fluctuations in time delay*: Fluctuations in time delay prevail in communication through networks such as the Internet. To minimize such difficulties, we will have exclusive use of a special subscriber-based network such as an ISDN. Very recently, several bilateral teleoperation control strategies under time-varying delay have been proposed to deal with time delay fluctuation (Brady & Tarn, 1998; Yokokohji, Imaida, & Yoshikawa, 1999).
- *Unconstrained cooperation*: It is usual in the literature to divide multirobot cooperation into constrained and unconstrained cases. Constrained cooperation implies cooperation of multiple robots to handle a common object. The robot motion is tightly associated with the other robots that are controlled to accommodate an object. In contrast, in the unconstrained case, each robot is basically controlled independently. However, robots need to avoid collision, because they are in a common workspace and are likely to perform conflicting motions unless the detailed task sequence is fixed beforehand.

3.2 Operator's Master Control Station

Each operator's master control station is composed of a master joystick (the Microsoft SideWinder) and a local predictive simulator display (a Pentium II PC at 450 MHz, running Linux). (See figure 3.)

3.2.1 Master Joystick. The joystick has six axes and nine buttons and transmits 300 bits per second position data, uses a 25 MHz processor, and tracks hand movement through an optical infrared camera inside the housing. It has access to the predictive simulator through the standard MIDI port on the sound card (the Creative Labs Sound Blaster). (Its driver for Linux can be downloaded off its public Web site located at ftp://atrey.karlin.mff.cuni.cz/pub/linux/joystick/.)

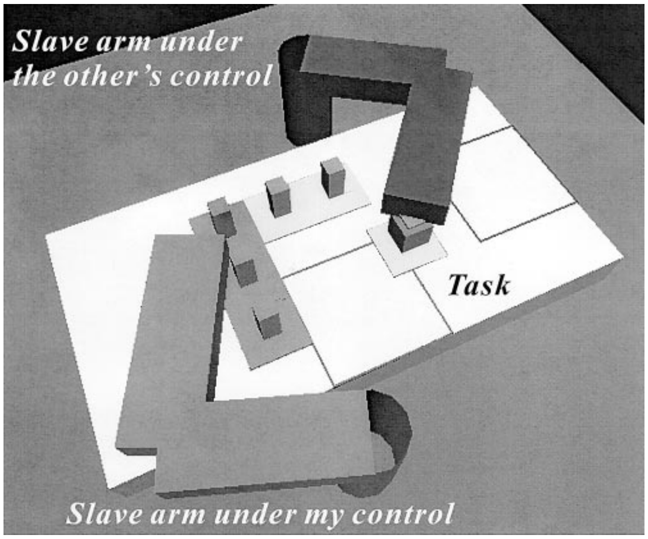

Figure 3. *Operator's predictive display with the counterpart slave robot delayed.*

3.2.2 Local Predictive Simulator. The local predictive simulator replaces the video image feedback and is built based on the Mesa OpenGL-like graphics library. OpenGL is a software interface for graphics hardware to produce color images of 3-D objects, view models interactively in 3-D space, and manipulate images. The viewpoint can be changed arbitrarily to help the operator understand images and facilitate the task. The remote slave robot under the operator's control is immediately visualized in the local predictive simulator in response to joystick commands. Specifically, the position data of the joystick axis is mapped into the velocity commands of the end effector of the simulated robot and its joint configuration is controlled by the same control law that controls the remote slave robot. This is a well-known approach in SOSR teleoperation systems with time delay. But, in contrast, the slave robot not under the operator's control is impeded by round-trip delays.

3.3 Remote Slave Simulator and Networking

The remote simulator has been developed on the workstation (Sun UltraSPARC 170) and simulates two

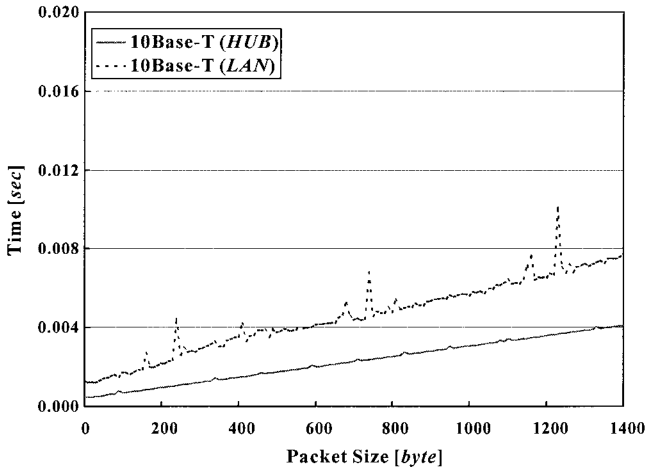

Figure 4. *Network delays over an Ethernet.*

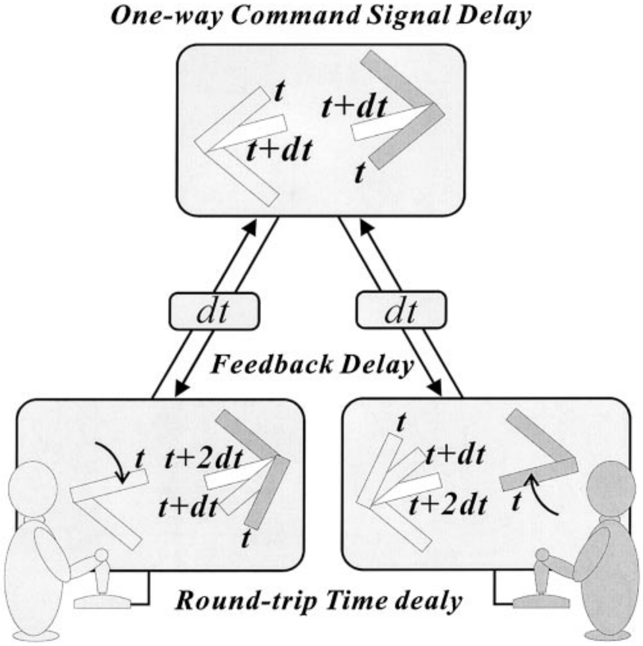

Figure 5. *Time delays at each site.*

slave robot motions in the remote environment commanded from the corresponding joysticks with time delay. The predictive simulator communicates with the remote simulator via shared memory and a TCP/IP socket connection. Similarly, the communication delay simulator controls the transmission delay over the network (10Base-T ethernet with TCP/IP protocols) in which a bidirectional Unix TCP socket link manages the communication between the processes in the local predictive simulators and the remote slave simulator. An arbitrary transmission delay can be simulated to have various distances and different networks tested.

Ethernet is not a guaranteed time network. Thus, it is difficult to know a priori how quickly the data will arrive to the counterpart operator. Some experiments were done to characterize the delays. Figure 4 shows the average round-trip time (RTT) delays between two pairs of PCs measured ten times for linearly varying packet sizes. The solid line is RTT between a pair of PCs in the same room connected directly through a switching hub. The dotted line is RTT between a pair of PCs in the same building over the LAN. The time delays are linearly proportional to the data size, but the dotted line shows some fluctuations as it may travel across multiple switching hubs. For our experiments, we directly connect two PCs through one switching hub to make sure that the delays are almost kept constant, but the network delay was negligible as shown in figure 4.

To move the remote simulator, operators send joystick axis position commands to their slave robot in the local predictive simulator. Then, the inverse kinematics routine is executed and their joint configurations are updated without delay. These joint configurations are relayed to corresponding slave robots in the remote simulator through network delay. Thus, two slave robots in the remote simulator move with a one-way time delay. Calculating the minimum distance between the two robots based on the forward kinematics of two slave robots, collision is checked in the remote simulator. Then, the remote simulator sends the respective operator stations the position/orientation and status (on/off) of the end effector of the counterpart slave robot through another one-way feedback time delay. Then, the inverse kinematics for the delayed slave robots is solved and their joint configurations are updated with one round-trip delay in the predictive simulator. Thus, in the local predictive simulator, operators have their slave robot move without time delay and counterpart slave robot with one round-trip time delay. Figure 5 illustrates that the time to travel across each site depends on the simu-

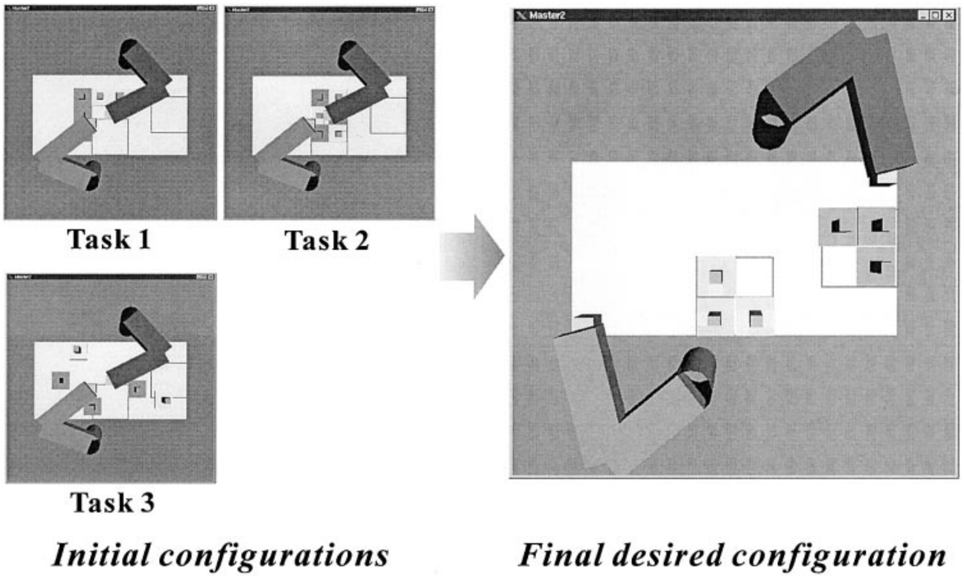

Figure 6. *Three exemplars in MOMR tele-cooperation.*

lated delay, *dt*, when the delay simulator is incorporated. The time required to calculate the inverse kinematics and graphics rendering of the planar two-link arms was considered negligible.

3.4 Block Rearrangement Task

At the remote site, six blocks of two different colors are located for three tasks. (See figure 6.) Each task is to use the slave simulators to reach out and pick up blocks and move them to their predefined depots according to the color. The operator switches on/off the joystick button to open/close the slave simulator end effector: when the robot end effector is sufficiently close to a block, the operator switches on to make the robot grasp the block and move it along with the robot end effector. When the block is moved into the depot, the operator switches off to put the grasp block in the available space. A detailed sequence is not prearranged. In the task, one slave robot sometimes hands over blocks to the counterpart robot if need be, because both slave robots might not be able to reach all of the initial and final positions of objects. A reachable robot should pick up the block and directly hand over to the counterpart robot or place the grasped block in the counterpart robot's workspace to help the robot take the block to its depot. This is a typical multirobot cooperation in the stockroom of a factory where robots sort things without conveyors.

In the task, collision will likely occur unless the slave robots are carefully coordinated because they are commanded from the remote operator site through a network with time delay. To perform these tasks with complete safety, operators should take proper precautions to prevent collisions. They usually commit to a "move-and-wait" strategy and wait to move their slave robot until the counterpart slave robot comes to a halt in the predictive simulator. To bring each block into their corresponding depot quickly, however, we should move both slave robots simultaneously, coordinating their motion appropriately.

4 Coordinated Control Against Possible Collision

Human operators would feel nervous about collision when giving instructions to their slave robot if they are not certain of the movement of the counterpart slave robot. Operators monitor both slave robots through the predictive simulator display, but a priori knowledge of the slave robot not under their control would not be available without time delay. Thus, operators cannot take large instruction steps and always keep their slave robot distant from the counterpart robot. To prevent collision resulting from time delay over a long-distance network, we need to develop a coordination control scheme. In this section, our recent efforts to develop different coordinated control aids in MOMR telecooperation are described.

First, to evaluate the time-delay effect in remote collaboration in MOMR teleoperation, some preliminary experiments were performed with various time delays. In this experiment, the two subjects were a 27-year-old man and a 25-year-old woman. The time delay was set in turn to 0, 0.5, 1.0, and 2.0 sec. in the communication delay simulator. Accordingly, 0, 1.0, 2.0, and 4.0 sec. time delays were present in the other operator's slave robot, which was driven by the data sent from the operator's master station. The subjects were not informed of the delay present during each task. Five trials were executed for each time delay for a total of twenty trials. Subjects were asked to finish the task as soon as possible without any collision. Figure 7 shows a collision detected at the remote slave simulator when the time delay was present on the network while both operators' local displays showed no collision. If a collision occurs, the task is considered to have failed. Table 1 shows experimental results with task 1, in which the completion ratios were exactly dependent on the time delay. But, in some cases, the trial was successfully performed despite a long time delay. In this case, operators committed to a wait-and-move strategy, and typical collaboration could not be seen. Also, we did not count the collision case when we averaged the completion time.

4.1 Prediction Approaches

In this subsection, two prediction approaches are investigated for the delayed counterpart robot.

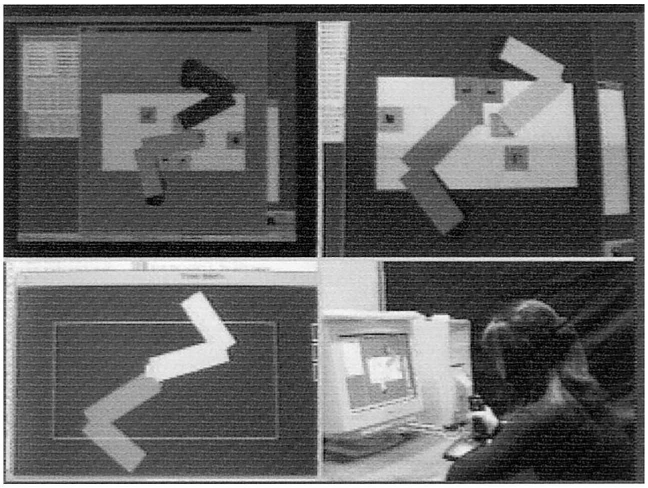

Figure 7. *Collision in a common remote site when one-way time delay is 1 sec. Top left: Operator 1's local display; top right: Operator 2's local display; bottom left: Remote site; bottom right: Operator 1's control station.*

4.1.1 Virtual Thickness Enlargement (VTE). The Virtual Thickness Enlargement (VTE) scheme is rather simple to implement. The slave robot under the counterpart operator's control virtually enlarges in thickness in the local predictive display. (See figure 8.) The uncertainty of delayed counterpart robot motion through round-trip delays is obscured by the added thickness. Operators control their slave robot to reach out and manipulate objects against the enlarged counterpart robot. (See figure 9.) Two slave robots can be considered not to collide at the remote site after a one-way time delay, provided that operators do not make their slave robot collide with the enlarged robot in the predictive display. The VTE is attractive because it easily compensates different time delays with thickness changes and clearly shows the operator the forbidden areas. But the VTE actually has available dead space around the enlarged robot. Also, it is likely that it has a deterrent effect to the operator who is considering moving his or her slave robot to the vicinity of the enlarged robot.

4.1.2 Estimated Predictor Overlay (EPO). The Estimated Predictor Overlay (EPO) scheme allows the predicted wireframe image to overlay the delayed

Table 1. *Task Completion Time and Ratio with Task 1*

	One-way time delay [sec.]			
Trial number	0.0	0.5	1.0	2.0
1	147	Fail	Fail	Fail
2	129	135	137	Fail
3	130	Fail	Fail	Fail
4	158	112	Fail	Fail
5	Fail	Fail	Fail	Fail
Average time [sec.]	141.0	123.5	137.0	N/A
Completion ratio [%]	80	40	20	0

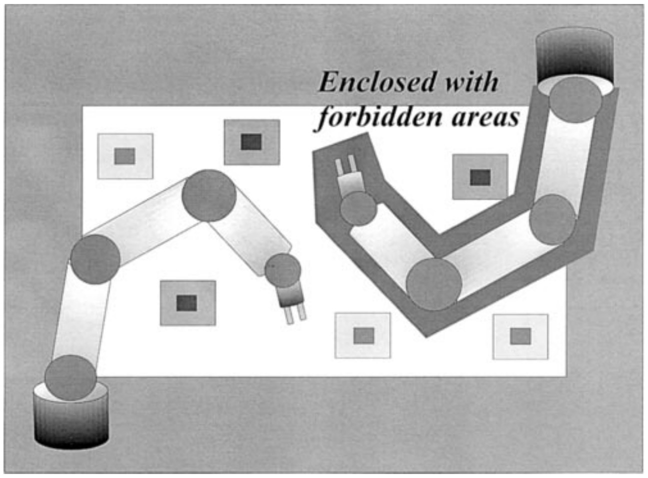

Figure 8. *Delayed slave robot virtually enlarges in thickness.*

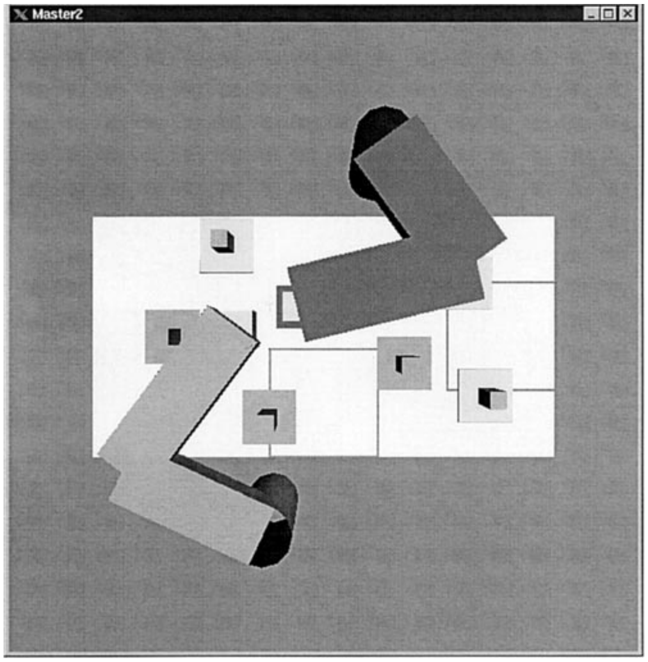

Figure 9. *Predictive display with the counterpart robot enlarged.*

slave robot in the predictive display. (See figure 10.) Specifically, we average velocities over the last five sample periods and make the delayed robot move with the averaged velocity through one round-trip time delay. Let X_t and $\hat{X}_t$ denote the delayed position and the estimated position of the end effector of the slave robot, respectively, under the counterpart operator's control at time t. Also, let $\bar{V}_t$ denote the averaged velocity over the past sample periods given by

$$\bar{V}_t = \frac{1}{N}\sum_{j=0}^{N}\left(\frac{X_{t-j} - X_{t-(j+1)}}{\Delta t}\right), \qquad (1)$$

where N is the number of sample periods and Δt is the duration of the sample period. Then, letting the round-trip time delay through the network be T, we can estimate $\hat{X}_t$ as

$$\hat{X}_t = X_t + \bar{V}_t T. \qquad (2)$$

We finally superimpose the predicted image on the delayed robot. Operators drive their slave simulator

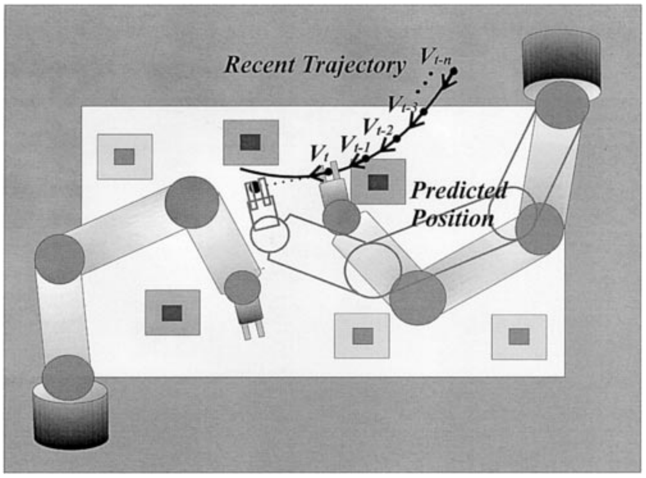

Figure 10. *Predicted image superimposed on the delayed robot.*

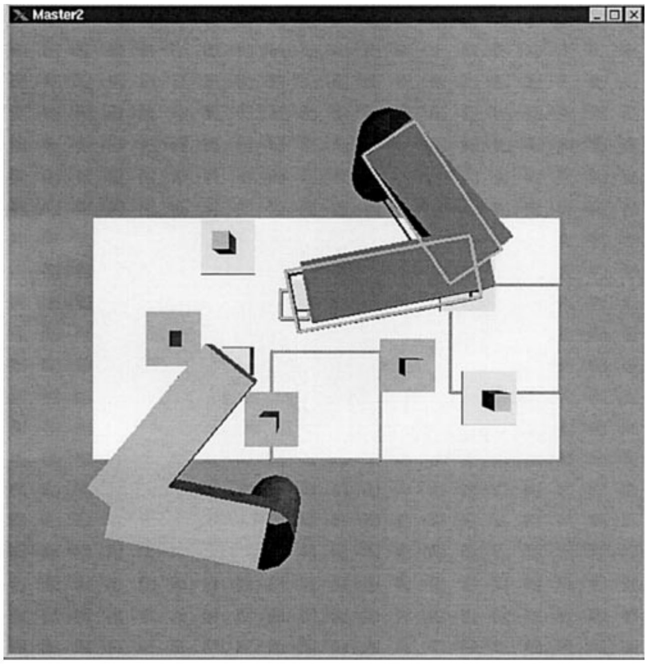

Figure 11. *Predictive display with the counterpart robot overlaid.*

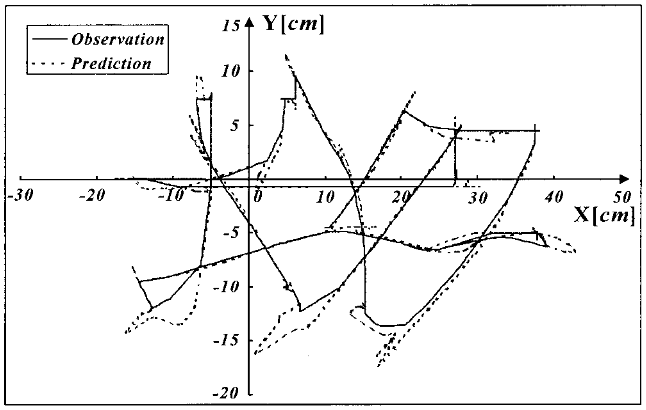

Figure 12. *Prediction of counterpart robot position delayed by 1 sec.*

against the wireframe predictive image as shown in figure 11, but, in the EPO, we do not consider the counterpart operator's control input. Thus, it would be difficult to make the prediction precise. Figure 12 shows the prediction accuracy of the counterpart robot with 1 sec. latent delay when the previous five sampling times were incorporated. There was some mismatch especially when the counterpart operator changed the command direction to avoid collision. Before more-sophisticated estimation techniques are applied, the feasibility of the EPO approach is investigated in this work.

4.2 Input Scaling Approach

This subsection addresses an input scaling approach. The prediction approaches give operators a visual aid for the delayed robot, but it is difficult to give any physical assistance to collision avoidance at the remote site. For instance, even if the operator realizes the danger of collision in the predictive display, he or she cannot instantly stop the slave robot at the remote site. Subjects sometimes made their robot collide even when no delay was present. (See table 1.) If the velocity of the slave robot is limited, the operator can avoid collision, but it would not be efficient to set a limit to the velocity of the slave robot over the whole task period. Thus, we do not constrain the velocity limit of the slave robot as far as circumstances permit and propose a new scheme based on the input scaling approach (Kosuge, Itoh, & Fukuda, 1996). This approach scales down the original master input to make sure that no collision will occur at the remote site.

It is common knowledge that the relative scale of mo-

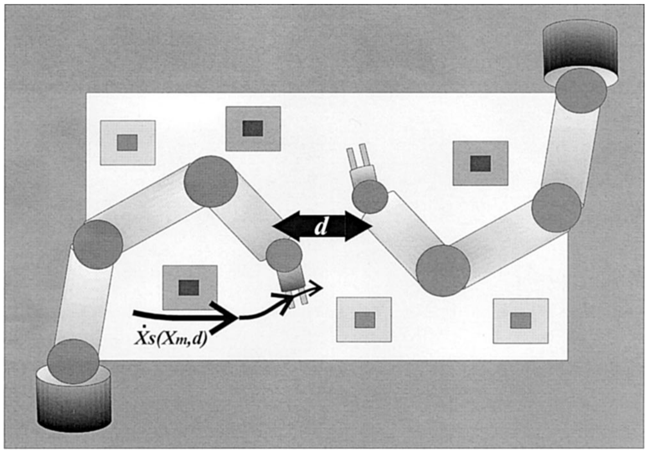

Figure 13. *Minimum distance affects the speed of slave robot in predictive display.*

tions can be specified between the master and the slave robot. Let X_s and X_m denote the generalized coordinate vectors representing the position and orientation of the slave robot end effector and the position of the master with respect to its respective local coordinate system. Here, if we consider the positive scaling factor K_s, then the velocity of the slave robot end effector is related to a function of the position of the master given by

$$\dot{X}_s = K_s f(X_m), \tag{3}$$

where $|\dot{X}_s| \leq s_{allow}$, the maximum permissible velocity, and f is a set of functions relating the master position and the slave robot velocity. The slave robot velocity tracks the master position, and K_s coordinates the scaled mapping between them. We propose this control aid, called *Scaled Rate Control* (*SRC*), that allows the operator to adjust the slave robot velocity by changing the scaling factor on condition that collision is expected. Specifically, the velocity of the slave robot end effector is decreased in the possible collision areas with the same joystick position. (See figure 13.) When the distance between two slave robots is not sufficiently secured in the predictive simulator, the joystick instructions are automatically scaled down according to the distance, and the scaled-down commands are sent to the remote slave robot. This may get the slave robot velocity controlled safely in the remote site and accordingly release the operator from the anxiety about unforeseen collisions.

More specifically, let $S_1(t)$ and $S_2(t)$ denote the sets in the operational space occupied by each slave robot. Also, let $\hat{S}$ denote the enlarged set of $S(t - T)$ including all the positional sets possibly occupied through one RTT delay T and $d(A, B)$ the minimum distance between two sets A and B. d_{col} implies the distance wherein the two slave robots can collide and d_{allow} the minimum distance wherein the slaves are safely moving out of the danger of collision. The minimum distance between two slave robots are calculated in the local predictive display. Thus, the scaling factor can be coordinated dynamically between the nominal value K_n and 0 given by

$$K_s = \begin{cases} K_n & : \quad d(S_1(t), \hat{S}_2(t)) \geq d_{allow} \\ K_\varepsilon & : \quad d_{col} \leq d(S_1(t), \hat{S}_2(t)) \leq d_{allow} \\ 0 & : \quad d(S_1(t), \hat{S}_2(t)) \leq d_{col}\,, \end{cases} \tag{4}$$

where the variable scale factor, K_ε, changes according to the distance between two slave robots, and d_{col} is appropriately set according to the time delay.

5 Experiment

5.1 Hypothesis

Many works have reported that the total time required to complete the given task is in proportion to the time delay in SOSR teleoperation (Sheridan, 1992). Moreover, it has been considered that speed and accuracy would not be achieved at the same time in teleoperation with time delay. This would be particularly certain in the case of MOMR teleoperation. It is expected that robots manage to perform tasks successfully even with the time delay if the operators greatly reduce the speed of robot. Our concern is how to simultaneously increase the speed of the robot and the accuracy of task in the MOMR teleoperation system. Here, we assume that both robots move with nearly constant velocity without any jerk when no collision is expected. Then, it is possible to predict a priori where the other's robot

Table 2. *Subjects Used in the Experiments*

Group	A		B		C		D	
Sex	M	M	M	M	M	M	F	M
Age	33	27	28	24	31	24	25	27

will be at most times. We try to determine how the local aids for collision-free control affects the performance of remote multirobot systems with time delay. We mainly investigated two aspects: collision-avoidance capability for safety and total time required to complete the task for efficiency.

5.2 Methods

We employed four pairs of subjects who were researchers and graduate students in the AIST Tsukuba, Japan. (See table 2.) Before the evaluation trials, we made each subject perform practical trials to familiarize them with the system. The subjects were told to complete each task as quickly as possible while avoiding collision. The task and the latent delay were changed each time, but the subjects were not informed of the time delay for each task. Each pair of subjects changed their master station and robot during the trials. Also, the order of trials was chosen randomly so that the habits of the counterpart operator were not learned during repeated trials of the same task. We measured the time when both subjects completed their tasks. Collisions were checked in the remote robot simulator. Subjects were separated by a blind partition and were told not to communicate with each other. If a collision occurred, the trial was stopped and considered a failure.

All objects are initially located within reach of the corresponding robots in task 2. There is no reason for handover of an object. Thus, task 2 can be independently completed by the robots without waiting for the other robot's assistance if collision is of no concern. But, in task 1 and task 3, one object and two objects, respectively, should be delivered into the workspace of one robot by the other robot. Thus, the graphical aids in the local display will guide each robot against possible collisions between robots during the handover process, which may result in a high success ratio at the expense of a relatively long operating time.

Specifically, in the experiments with the VTE, each pair of subjects made twelve sets of trials with four cases in thickness (1.0 times, 1.25 times, 1.5 times, and 2.0 times the original thickness) for three different tasks each with latent delays of 2.0 sec. A total of sixty trials were made by each pair of subjects as five trials were repeated for twelve sets of trials. The three thicknesses of the robot are devised to cope with the short delay, medium delay, and long delay. In the experiments with the EPO, five trials were repeated for each task, and a total of fifteen trials were made with the latent delays of 2.0 sec. We reemployed the same pairs of subjects to test the input scaling approach. They made fifteen trials for task 3 with three different time delays (0.5 sec., 1.0 sec., and 2.0 sec.). Task 3 was chosen as a sample task because it was likely to take the longest time among the three tasks. The same numbers of trials were made with the move-and-wait approach, in which one operator waited to move his/her slave robot until the other slave robot completely receded from the common workspace. Thus, for each pair of subjects, a total of 105 trials were made.

5.3 Results

Table 3 shows the overall experimental data with prediction approaches. The latent time delay was 2.0 sec. The average completion time and the standard deviation were taken over all sets of trial data because the number of sample groups and tasks were limited. Comparing with the no-compensation case, the two schemes are shown to be effective and meaningful in a sense that the complete time was reduced up to 20%; the completion ratio (the number of successful trials with no collision over the total number of trials) was increased by 50% as well. But, in view of the fact that the completion ratio is of more concern to most cases, current prediction approaches would not be practically applicable. They still do not guarantee 100% operating safety. Also, the use of excessive forbidden space in VTE sometimes causes a long operating time as shown in figures 14 and

Table 3. *Experimental Results with Prediction Approaches*

Compensation method	None	VTE	EPO
Number of groups	4		
Task types	Task 1, 2, 3		
Number of trials/group	15	45	15
Average time [sec]	102.71	96.43	80.10
Standard deviation	9.72	5.68	10.94
Completion ratio [%]	48.89	61.11	73.33
Standard deviation	6.24	4.23	11.01

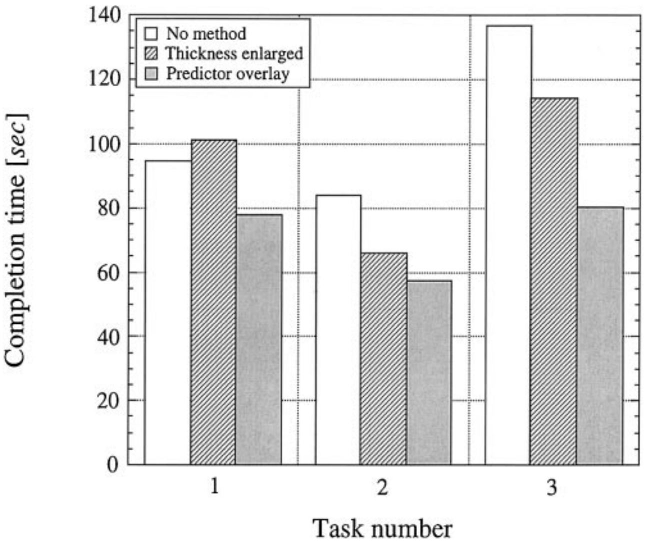

Figure 14. *Task completion time with prediction approaches (group A).*

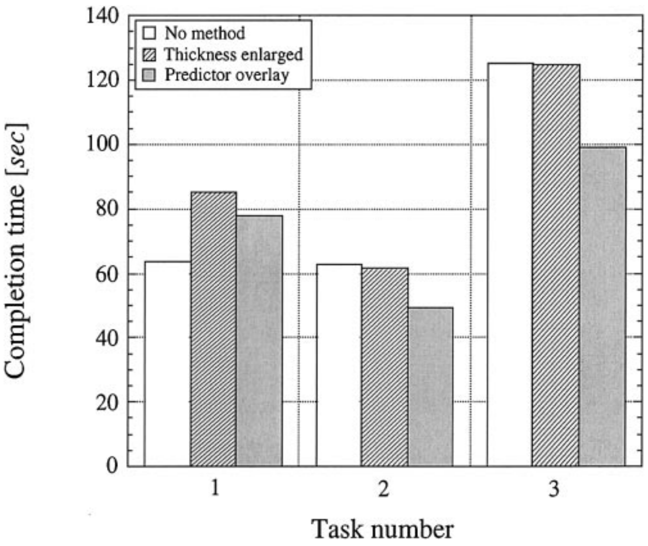

Figure 15. *Task completion time with prediction approaches (group B).*

15. For instance, in the case of task 1, the objects of the counterpart robot were initially positioned near the operator side. Thus, the operator should not enter a large area when the counterpart robot comes to pick up the objects, which results in an increase of total time to completion. Likewise, we had feedback from some subjects that the overlay in the EPO sometimes confused them. This is also known from the fact that the standard deviations of EPO are relatively large.

Figures 14 to 17 show the results of three sample tasks, performed by groups A and B with the prediction approaches. Similar trends were observed across two sample groups. In this case, the thickness was 1.5 times the original thickness with the VTE. The predicted position after 1 sec. was overlapped with the EPO considering that a one-way time delay from the master station to the remote site was 1.0 sec. Therefore, the operators had the position of the other robot at the remote site predicted in the local display. However, it is difficult to predict the counterpart robot's motion exactly. Figure 12 shows the mismatch between the estimation and the observed real position of the counterpart robot end effector with a 1 sec. latent delay. This estimation was based on the previous trajectories. We are convinced,

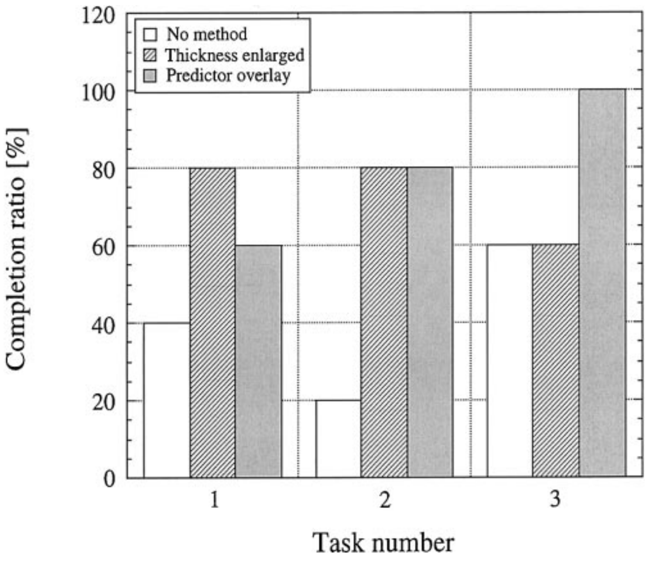

Figure 16. *Task completion ratio with prediction approaches (group A).*

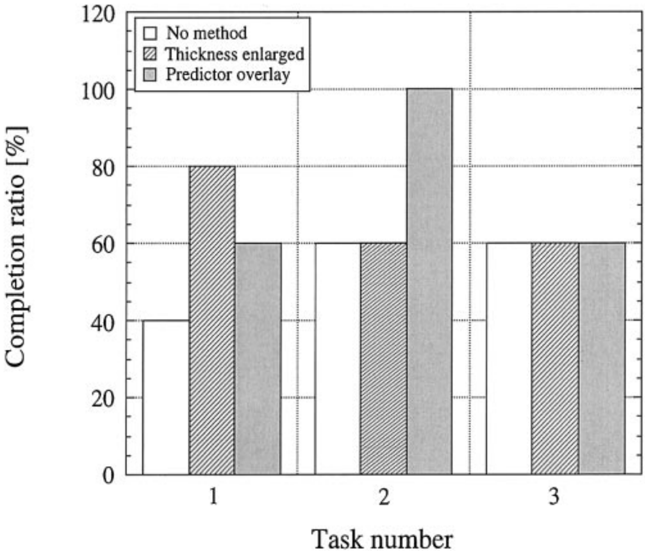

Figure 17. *Task completion ratio with prediction approaches (group B).*

Table 4. *Experimental Results with Input Scaling Approach*

Compensation method	Move-and-wait	SRC
Task type	Task 3	
Number of trials	15	15
Average time [sec]	190.02	85.33
Standard deviation	8.18	4.12
Completion ratio [%]	100	

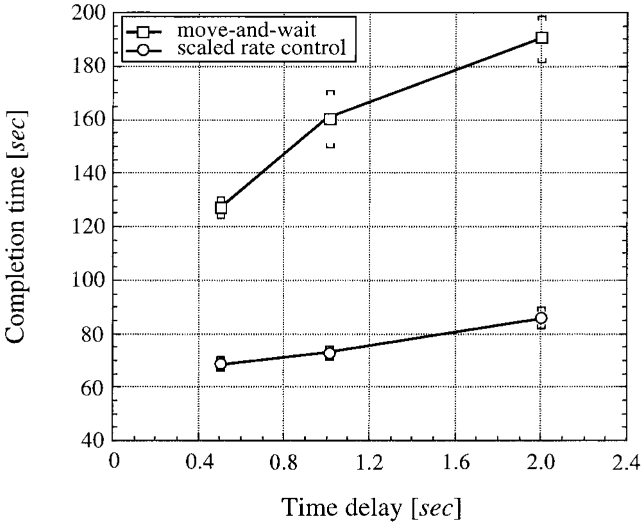

Figure 18. *Task completion time with SRC (group A).*

however, that the current prediction can be improved by using optimal estimation techniques such as the Kalman filter, as we incorporate user control input data.

Table 4 shows the data on task 3 with the input scaling approach. Data shown are for group A. Same with the prediction approaches, the latent time delay was 2.0 sec. The completion time was reduced compared to prediction approaches. Moreover, no unsuccessful trials caused by collision were present because the joystick commands were nullified and, accordingly, the remote slave robots were stopped when one slave robot approached its counterpart robot across the boundary of d_{col}. This would satisfy the safety requirements in practical applications. The speed of operation should be compared under the same level of completion ratio. Figure 18 compares the task completion time with the move-and-wait strategy and the SRC according to the delay. Operators were able to confidently manipulate their joysticks with larger position inputs and reduce task completion time by about 50%. Note also that the standard deviation of the mean for repeated trials denoted by brackets is small with the SRC. If the remote site is more complicated and the robots are more likely to collide, the speed of robots might be decreased during most of the operation. This would be indispensable to prevent the robots from colliding. Also, we found one noticeable problem with the SRC: the maneuverability of the master joystick was not kept constant over the whole task period. The slave velocities are often decreased or increased with the same joystick position, and this will make the operator lose his/her rigorous sense of operation. Eventually, the overall performance might deteriorate in some cases. Thus, it would be desirable to instead change the impedance of the joystick to keep the maneuverability constant over the whole task period.

6 Conclusion

To overcome the throughput limitation of the network and large physical separation between multiple operators, three coordinated control aids were proposed and verified through experiment in the simulation environment. As a basic investigation, three planar pick-and-place tasks were tested in two-operator–two-robot teleoperation over a LAN that was subject to simulated communication delays. It is likely that human operators would be nervous about collision when controlling remote telerobots through local displays in which the image of the counterpart telerobot is delayed. To assist the operators who might be overly cautious about the delayed telerobot not under their control, we explored coordinated control schemes that guided two telerobots toward collision-free cooperation at a common remote site. With the prediction approaches, we have increased the collision avoidance capability by 50% at the remote site over a network with a 2 sec. time delay. With the input scaling approach, no collisions were found in our experiments. Moreover, each operator could reduce the task completion time approximately 20% to 50%. This is because the operator was partly released from the anxiety of the unforeseen collision and accordingly could give larger master instructions with confidence. The proposed methods satisfactorily steered a couple of telerobots to perform remote planar pick-and-place tasks without collision and showed the feasibility of coping with communication delays in MOMR tele-cooperation. We believe that experimental tests are extremely important to meet future application objectives in MOMR tele-cooperation and have built a real experimental testbed. Our efforts devoted to experiments done in this testbed will be addressed in the accompanying paper.

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