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Description	

A Collaborative Multi-site Teleoperation over an ISDN

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We have developed an advanced infrastructure and technologies for collaborative remote operations, enabling multiple operators with large physical separation to control multiple slave robots in a common environment over the network. Human operators' delayed visual perception arising from communication time delays seriously affects the performance of collaborative multi-site operations and accordingly requires supplementary information locally available to operators irrespective of time delays. Few facilities exist to investigate remote multi-site operations, thus we have built an experimental test bed connecting Tsukuba and Kawasaki in Japan via an Integrated Services Digital Network (ISDN). In particular, an on-line predictive graphics simulator is incorporated to cope with image feedback delays from the remote site. Specifically, exploiting audio-visual features of the simulator, operators can detect a priori the possibility of collision between robots and guide them towards task goal through time delays. To verify the validity of the simulator assisted approach, we have performed a demonstration of prototype plant maintenance in April 2000 between Tsukuba and Kawasaki.

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KEY WORDS- multi-site tele-collaboration, time delay, predictive simulator, ISDN

1 Introduction

We are developing coordinated control technologies for multi-robot cooperation in remote environments, where an operator site is physically at a distance from the other operator site as shown in Fig. 1. This multi-site tele-collaboration has rapidly emerged to replace costly on-site operation and complement the workforce. However, few facilities exist to develop varied technologies, which requires the establishment of some advanced infrastructure for further research and implementation. It is commonly known that robot motions in remote environments are visualized by the operator with round-trip time delays. Thus the camera image feedback is often overlaid with the graphics images locally predicted from master control commands. We should point out that multi-site tele-collaboration suffers additional difficulties. In particular, the robot under the control of the other operator would not be straightforwardly predictable in the operator site. Accordingly robots are most probably exposed to the possibility of uncertain collision in remote environments due to the delays in receiving images and the lack of accurate local prediction. This does make multi-robot cooperation through remote teleoperation hardly feasible and need supplementary information for the operators to steer conflicting motions of remote robots safely irrespective of visual feedback delays.

Sheridan [17] has made an extensive survey of literature on teleoperation and telerobotics, where noticeable results over the past several decades were reported. Hirzinger *et al.* [7] proposed the tele-sensor-programming approach to control a first remotely controlled space robot from the ground station. Likewise, the advent of network communication technologies has brought a system that allows a robot to be teleoperated via the WWW [5]. In addition, Rovetta *et al.* [16] demonstrated a telesurgical operation using satellites and optical fiber networks for data exchange. Wakita *et al.* [18] proposed the snapshot function of intelligent monitoring to deal with the time delay and limited communications capacity of super-long distance teleoperation. But most of the past works were limited only to the Single-Operator-Single-Robot teleoperation.

Recently, some efforts have been devoted to the teleoperation of multiple robots. Amon them, Kheddar *et al.* [8,9] demonstrated a long distance teleoperation with several robots in parallel from a single operator. Goldberg *et al.* [6] built a collaborative system that permits a robot to be teleoperated by combining multiple operator inputs. But, no one has considered communication delay problems between remote operators not aware of each other's master control intentions. Elhajj *et al.* [4] proposed an event-based multi-site tele-cooperation technique through a virtual force feedback mainly in the case that one operator leads the task. Their work was to have a mobile platform track its on-top manipulator and event synchronized despite random time delay remotely controlled from two distant operators. Practically, to the authors' knowledge, multi-site tele-collaborative systems have not yet built and even studied extensively. This is partly because the real system requires costly facilities providing a communication link between the local operator and remote task sites. Another technical issue is the difficulty of coping with the delay in receiving visual and control information from the physically separated operator as well as the remote sites.

We have already tested several local coordinated control strategies to avoid collision between remote robots through various simulations in the virtual test bed in [2]. This paper mainly describes the construction of an experimental test bed to develop multi-robot cooperation technologies for multiple remote operators impeded by communication delays. In particular, an on-line graphics simulator assisted approach is proposed to avoid an uncertain collision between two slave robots and guide them towards task goals through communication time delays. To verify the validity of the proposed approach, we have demonstrated prototype maintenance works on a plant mock-up with one slave robot fixed on the floor and the other slave robot mounted on the top of mobile platform connecting two distant operator and a common task sites via some dozens of ISDN channels.

2 Multi-site Tele-collaboration

In teleoperation, human operators must keep slave robots under observation to ensure that their intended actions occur properly or to make changes in the instructions. However, the existing networking facility restricts the operator's timely access to information about slave robots in remote environments. The slave robot motions are informed back to the local operator through round-trip time delays. Over the past decades, the predictive display has been a well-tried approach for the time delay in teleoperation. It typically provides the operator with the immediate visualization of the master control commands where the real video image feedback from the remote site is delayed [11]. Effective calibration techniques have been proposed pertinently to have the predictive display confident [12,15].

As for the collaborative multi-site teleoperation, where one operator is distant from the other operator, it would be hardly possible to make an accurate prediction for the robot under the other operator's control. Practically, it is not possible to keep an operator informed about the other operator's robot motion beyond what we can achieve using the existing video image transmission techniques. The main problem is that, in addition to the network transmission delay due to the throughput of the network, there would be currently unavoidable delays such as source compression delay at the video broadcasting server and image reconstruction delay at the clients. Accordingly, operators are not able to get correct visual aid to the robot under the other operator's control in time and have to wait image feedback from the remote site. This does make multi-site tele-collaboration extremely difficult especially when the operators are physically at a distance from each other. We need to have another supplementary information available to operators, therefore, to help them tackle the time-delayed visual perception on the slave robot not under their control. This requires one operator to send her master control commands simultaneously to the other operator as well as the remote sites. Then, this data can be incorporated in the other operator's predictive simulator and has both slave robot motions visually available ahead of delayed real image feedback.

3 Experimental Test Bed

We believe that experimental tests are crucial, but few facilities exist to develop, integrate, and demonstrate the technology for collaborative multi-site teleoperation. Thus, we have built a real test bed connecting the AIST in Tsukuba and the Toshiba R & D Center in Kawasaki in Japan via an ISDN as shown in Fig. 2. This section goes into details about the components in our test bed.

3.1 Overall System Configuration

The AIST has one master control station and the Toshiba R & D Center has the other master control station and the task site where two slave robots cooperate with each other. Both places are about 90 Km distant and connected via an ISDN. Specifically, each master control station consists of a prototype master robot and an on-line graphics simulator in addition to the real video camera image feedback display. In the task site, a 7 DOF slave robot (PA-10, Mitsubishi Heavy Industries Ltd.) is fixed on the floor and another 6 DOF slave robot (Prototype, Toshiba R & D Center) is mounted on the top of the mobile robot (XR4000, Nomadic Technologies, Inc.) that has the holonomic drive system to offer 3 DOF's. A simple plant mock-up is built and placed nearby the fixed based robot. Also, 6 video cameras are placed to provide the two local operators with the top view, side view, and hand-eye view of respective slave robots.

3.2 Networking Facility

It is often mentioned that the fluctuations in time delay prevail in the communication through the network such as the Internet. Recent efforts have been made to deal with the bilateral control of teleoperation under time-varying delay [1,10,14,20]. In this work, to avoid such difficulties, we have subscribed to the Nippon Telegraph and Telephone East Corporation (NTT) INS-Net 1500 (1.5Mbps) and INS-Net 64 (64Kbps) and have the exclusive use of ISDN's. With this network, communication delays are kept almost constant once connected, which is different from the communication over the Internet subject to time-varying delays. Fig. 3 shows the round-trip time delays according to data size between Tsukuba and Kawasaki over the Internet and the INS-Net 64, respectively. The INS-Net 1500 networking composes of 23 bearer channels carrying 64 Kbps each over an optical fiber and 1 data channel operating at 64 Kbps. The bearer channel transmits user information such as voice, data, and images over one telephone line and the data channel carries transmission control signals and is used for packet transmission. The number of channels to be in use varies with the size of transmitting information and also can be fixed up appropriately. An ISDN router (RT140p, Yamaha Corporation) connects the ISDN line and an Ethernet LAN in the local operator site

(Fig. 4). Overall communication control station (PC Intel Pentium III 667 MHz, Windows) on the network gets all the communications between local and task sites connected or disconnected. The AIST sends and receives both control and image data via the 1.5Mbps line while the Toshiba R & D Center uses the 1.5Mbps line only for image data communication and the 64 Kbps line for control data communication.

3.3 Master Control Station

Fig. 5 illustrates a set of equipment in the operator's master control station which consists of a 6 axis prototype force-reflecting master robot (Toshiba R & D Center) and an on-line predictive simulator (PC Intel Pentium II, 450 MHz) running on a UNIX based operating system (Linux, Slackware v.7.0). A client PC (Pentium III 667 MHz, Windows) which has access to the video broadcasting server receives the real video camera images from the remote site. The images are projected onto a large screen to help the operator get a better view of it. Also, another bilateral communication is needed to make each other aware of the other operator site. Thus, each operator informs the other operator of the connection of the network, beginning and end of the task, change of camera angle and zoom, emergency during the task execution, and so on using an extra camera and a microphone.

3.3.1 Master System

The prototype master system is small and light-weight and has feedback force reflection capability (Fig. 6). Please refer to Table 1 for detailed specifications. This general-purpose device employs the twin pantograph mechanism for its positional 3 axes. If its handle is guided by the operator, the master position will follow a similar path on a reduced scale. Also, the gimbal-like mechanism for its orientational 3 axes permits the master handle to turn freely in any direction. This arrangement is effective to decrease the computational burden in coordinate transformations in dissimilar master-slave teleoperation systems. Several types of sensory information are incorporated in a real-time controller developed within a QNX environment. The schematic picture of the controller system is shown in Fig. 7.

The controller 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, where the master position is interpreted as an end-effector position command of slave robot through coordinate transformations. The displacement from the initial position drives the slave to move on an appropriate scale [13]. When the master position reaches its limit, it has to be returned to a nominal position to generate further displacement with this retrieving displacement nullified. This intermittence would be a drawback. To overcome the limitation of 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 slave and similarly force is interpreted as an end-effector velocity of the slave, too. 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 slave robot force is not reflected to the operator hand. These modes have trade-offs and can be implemented according to task conditions.

3.3.2 Graphics Simulator

We built an on-line graphics simulator using the OpenGL graphics system [19], where the construction of 3-D graphics models of the two slave robots and the plant mock-up were performed. OpenGL is a well-known software interface for graphics hardware to produce color images of 3-D objects and view models interactively in 3-D space and manipulate them. Note that we have installed a graphics accelerator (Voodoo3 3000 AGP, 3dfx Interactive) not to be caught up 3-D graphics rendering burden. The slave robot graphics model is controlled by the same master control law that controls the real slave robot. This enables local operators to visually verify their master control commands without having to wait real video camera image feedback from the remote site.

For the local communication, the graphics simulator has access to the master controller through an Ethernet LAN. As an inter-process connector between them, a pair of cooperating sockets manage the communication via shared memory. The interface is made by two programs: a client and a server. Specifically, to transmit master control commands to the simulator, first, the servo control programs in the master controller writes the sensory information on the shared memory, then the client sends this to the graphics simulator. In the simulator, the server receives transmitted data and writes it on the shared memory. The simulator finally reads the master data and have its graphics models of slave robots respond to the operator's master control commands as intended.

3.4 Multi-media Broadcasting Server

We placed video cameras in the remote site to have multi-camera views of the task environment: top view, side view, and robot hand-eye view. To broadcast these camera views to the local operators, we used a PC-less server that enables real-time streaming of video images over the Internet (Fig. 8). Through incorporation of the system's plug-in software into a popular web browser, the system's video images can be viewed from a client PC (Fig. 10) which has access to the server. The task environment images can be transmitted to the two operator sites at the maximum video rate 30 fps when only one camera channel is input. In this experiment, the operator may have 4 different camera views from the remote site, then the video update rate becomes less than 2 fps in the local operator site.

3.5 Demonstration Task

In the remote site task environment, two slave robots cooperate closely with each other to dismantle a simple plant mock-up that has a height of 1.4 m as shown in Fig. 9. A removable lid of valve that weighs 1.1 Kg with a length of 265 mm diameter is bolted on the base pipe structure. The two operators have to remove two M16 bolts from the lid to proceed with routine inspection or maintenance. In particular, the operators must insure that robots are not collide and the environment is not damaged. The task we have demonstrated is to have each of two robots approach the mock-up at the same time and loosen one bolt each on the lid. Taking out one bolt quickly, the robot grips the handle and supports the lid against the gravity while the other robot unbolts. If not, an excessive force is applied on the second bolt and impedes the progress of the other robot that loosens the bolt. After the second bolt is taken out, the robot recedes from the mock-up and the supporting robot pulls out the lid and moves it back to some safe position. Then the next procedure follows to dismantle the mock-up completely. This is one of prototypes of inspection or maintenance sequences periodically to be done in the plant.

In this kind of multi-robot task, collision will occur most probably, because the two robots are commanded from the remote local sites with communication time delays. Thus, the two operators are likely to commit to "move-and-wait" strategy and/or control their robot at very low speed. To overcome this difficulty, we need to compensate for the operators' delayed visual perception, which requires the operators to have predictive simulator and some supplementary information available locally irrespective of the communication time delay.

4 Time-delay Tolerant Operation Using Predictive Simulator

Even the network delay is present, operators can monitor the slave robot motion under their control using the predictive display that visualizes their master control commands graphically without time delay. However, *a priori* knowledge of the slave robot under the other operator's control would not be available where the other operator is physically at a distance. Thus, the delays in receiving the visual information on the other slave robot require operators usually to send a very limited velocity command and keep their slave robot distant from the other robot. In this section, we describe the use of on-line predictive simulator to cope with the delay in receiving visual image feedback from the remote site (Fig. 11). To enable the graphics simulator to predict and display the motions of both robots, there is a need for the operators to be aware of each other's control commands without time delay. For this, we have the predictive simulator connected to the network and accessed to the other operator's master control information to visualize both slave robot motions immediately. This will complement delayed visual information available through camera image feedback. Furthermore, we exploit the audio-visual features of the predictive simulator to avoid collision between two robots and guide their positions towards task goals through time delays [3].

4.1 Operation with Multi-camera Views

Usually, a task can be achieved by a sequence of separate instructions along the different coordinate axes in the operational space. This requires local operators to have different views of the remote site using multiple cameras. Even though the operators should observe all the multi-camera views to detect collision, they would not be able to simultaneously observe all of them carefully. According to the first author's experience, operators concentrate on one specific camera view which is of the most concern at the moment. Then, after the current critical instruction is over, the following control instructions are to be done using another view. This sequential procedure works partly because the video camera positions and angles are usually fixed during the task. Once set, the angles of multi-camera views are not changed, because, even it would be possible, frequent change of the camera angle and zoom will not do any good to the operator performance. To make the matter worse, due to the image transmission delays over the network, the operators can not detect collision without time delay from the feedback camera views. Furthermore, the camera views are sometimes not synchronized and difficult to observe collision. Thus, we need to have another source of supplementary information available to detect collision more effectively irrespective of network communication delays.

4.2 Audio-visual Warning of Near-miss

The advantage for the graphics simulator should occur when viewing is degraded. As is often the case with the multi-camera views, one slave robot may obscure the other slave robot in some views as if they collided with each other, which is highly confusing and impedes the task. In this work, we set the view point of the predictive simulator so that we may observe some different angles of concern or the hidden angles that are difficult to see with the fixed cameras. Thus, possible collision can be detected in the predictive simulator. More practically, provided that the minimum distance between two slave robots approaches a predetermined critical limit in the simulator, the simulator signals to the operator using its audio-visual features prior to real collision happens. Here the critical limit is determined according to the possible motion ranges of the other slave robot throughout the delay in receiving its master control data. This delay is not significant in many cases and also can be handled with the coordinated control aids proposed in our previous simulations in [2]. Specifically, we get the preserved audio file running and the nominal color changing in the simulator until the slave robot get out of current area and keep its distance from the other slave robot. Thus, even if operators observe feedback camera views, they can respond to the near-miss warning signals and revise current control commands safely. This permits operators to concentrate on any camera views of their concern confidently.

4.3 Audio-visual Guidance toward Task Goal

Operators often have difficulty fine-tuning the position and orientation of slave robot's end-effector smoothly to satisfy certain task requirements. Using the existing image transmission facilities, which is confusing due to some unavoidable delays, operators are likely to drive their slave robot to pass over the task goal back and forth and keep readjusting the end-effector position even it is already positioned properly in the remote site. Otherwise, the operators perform the task by a "move-and-wait" strategy. This requires the operators to rely on the predictive simulator that is not affected by time delay. As is commonly known, the operator's slave robot motion can be predicted accurately responding to its master control commands. When the end-effector position and orientation reach desired task destinations, the predictive simulator signals to the operator accordingly. Then the operator confidently transmit further master control commands to finish the task, irrespective of deviation from the destination in the video image feedback. Specifically, the operator can notice the situation timely when preserved audio file is sounded and color change is made in the end-effector. The readiness can be confirmed as the position and orientation of slave robot end-effector is meet with the task goal or within an allowable deviation predetermined according to the specific feature of the task.

5 Results

An experimental test bed was built connecting the AIST and the Toshiba R & D Center via an ISDN to investigate possible remote cooperation between two slave robots controlled from two operators with large physical separation. It is fairly straightforward to extend this set up to include more number of operators and slave robots on the network. A maintenance demonstration on the plant mock-up were carried out repeatedly in the test bed. The task was performed successfully without any prearranged procedure and facilitated by timely cooperation of two slave robots. To the authors' knowledge, this was the first trial to test the feasibility of practical plant maintenance controlled from remote multiple operators. It is noted that the master data which conveys the operator's intentions was simultaneously transmitted to the remote and the other operator sites. Then, the graphics simulator visualized two slave robot motions prior to camera image feedback from the remote site, which was effective to help the local operators overcome their time-delayed visual perception. Local impedance control was incorporated to stabilize the slave robot motions when it interacted with the mock-up.

The usefulness of the predictive simulator was evaluated using a measure such as the task completion time. We compared this measure and investigated how the predictive simulator works in collision detection and task guidance through time delays. Operators often paused and hesitated before they drove their slave robot to move, mainly because feedback camera views were delayed and sometimes were not synchronized. The operators without predictive simulator performed tasks more tentatively than with it. Most pairs of subjects could not complete the task successfully in 5 minutes only with camera feedback. For the same pairs of subjects, with the help of predictive simulator, the task were completed within 4 minutes on an average which approaches the level of practical use. This is because the operators were partly released from the anxiety about collision and accordingly could give larger master control commands with confidence. Table 2 shows the task completion time by two pairs of subjects, where M denotes mean time over 10 trials and s standard deviation. While the operators observed any feedback camera views, they could respond to the near-miss warning signal and revised current control commands safely. Moreover, it was shown that the overall configuration of slave robot was monitored through the simulator and operators did not drive the slave robot into a singular configuration. This would permit the multi-camera views to zoom in on the points of interests to give a better view to the operator.

6 Conclusion

A collaborative remote multi-robot teleoperation technology through communication time delays was proposed to meet future application objectives. The test bed we have built is thought to be the first one to allow multiple operators with large physical separation to collaborate on prototype tasks. We have an additional information on slave robots available locally to the operators not aware of each other's master control intentions. Specifically, to assist the human operators suffering from the delayed visual perception on slave robots not under their control, we employed the predictive multi-robot graphics simulator driven by operators' master control commands. We believe that this simulator guided approach takes the lead in the coordination of multi-robot cooperation in the remote site especially when the operators are physically at a distance. To improve the operator's confidence and performance during the task, more sophisticated operator guidance systems are currently under development. A high level of productivity is demanding in the coming society with the decrease of workforce. This study showed the possibility that the experienced could collaborate remotely with unskilled on-site operators on a periodical inspection and/or an unexpected accident pressed for time. Furthermore, the proposed technology has possible application to a multitude of areas such as space, terrestrial, and commercial applications in hazardous environments. The current implementation provides an advanced infrastructure on which additional experiments can be carried out for further research and development, thereby seeding new concepts and emerging technologies in multi-site tele-collaboration.

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Figure Caption List

Figure 1. Multi-site tele-collaboration via a network.

Figure 2. An experimental test bed for multi-site tele-collaboration.

Figure 3. Network delay between Tsukuba and Kawasaki.

Figure 4. An ISDN router.

Figure 5. Operator's master control station in AIST.

Figure 6. Prototype master device with twin pantograph mechanism.

Figure 7. Schematic structure of master controller.

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Figure 9. Slave robot systems in the task site.

Figure 10. Multi-camera image feedback in the client.

Figure 11. On-line predictive graphics simulator.

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Table 1. Specifications of master device.

Table 2. Task completion time.

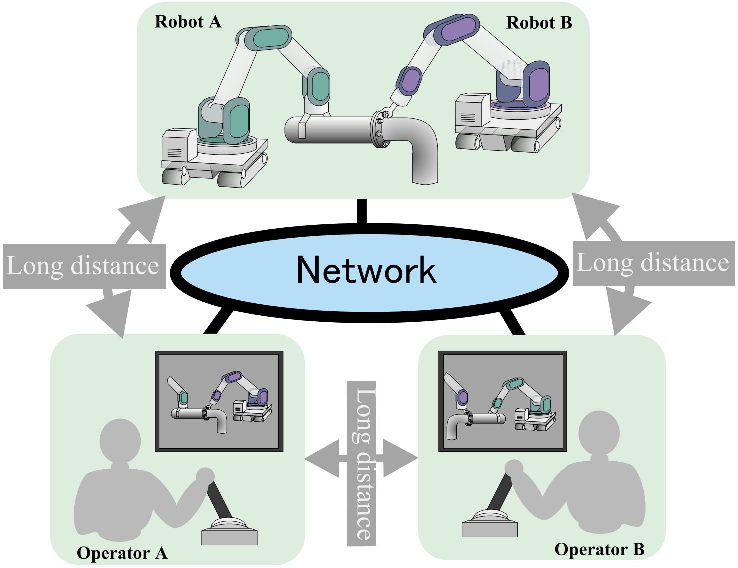

Figure 1: Multi-site tele-collaboration via a network.

Table 1: Specifications of master device

Axis	1	2	3	4	5	6
Motion limit	$\pm 25mm$	$\pm 25mm$	$\pm 38mm$	$+60^\circ/-60^\circ$	$+80^\circ/-40^\circ$	$+60^\circ/-60^\circ$
Reduction Ratio	Timing belt 1.5 Pantograph 1/4	Timing belt 1.5 Pantograph 1/4	Timing belt 1.5 Pantograph 1/3	Spur gear 200/9	Spur gear 200/9	Harmonic drive 80
Encoder	$2500ppr$	$2500ppr$	$2500ppr$	$2000ppr$	$2000ppr$	$360ppr$
Force sensor	$487\mu\epsilon$ $2.3Kg_f$	$478\mu\epsilon$ $2.3Kg_f$	$431\mu\epsilon$ $2.3Kg_f$			
Torque sensor				$838\mu\epsilon$ $6.7Kg_fcm$	$838\mu\epsilon$ $6.7Kg_fcm$	$1622\mu\epsilon$ $6.7Kg_fcm$
Force/Torque	$25N/0.5Nm$					
Size	$250mm \times 400mm \times 400mm$					
Weight	$9Kg$					

Table 2: Task completion time [second].

No. of Trials		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*M*	*s*
Pairs of Subjects	*A1 & T*	195	215	196	190	160	220	168	156	145	175	182	25.245
	A2 & T	186	166	223	268	332	223	205	208	176	295	228	53.951

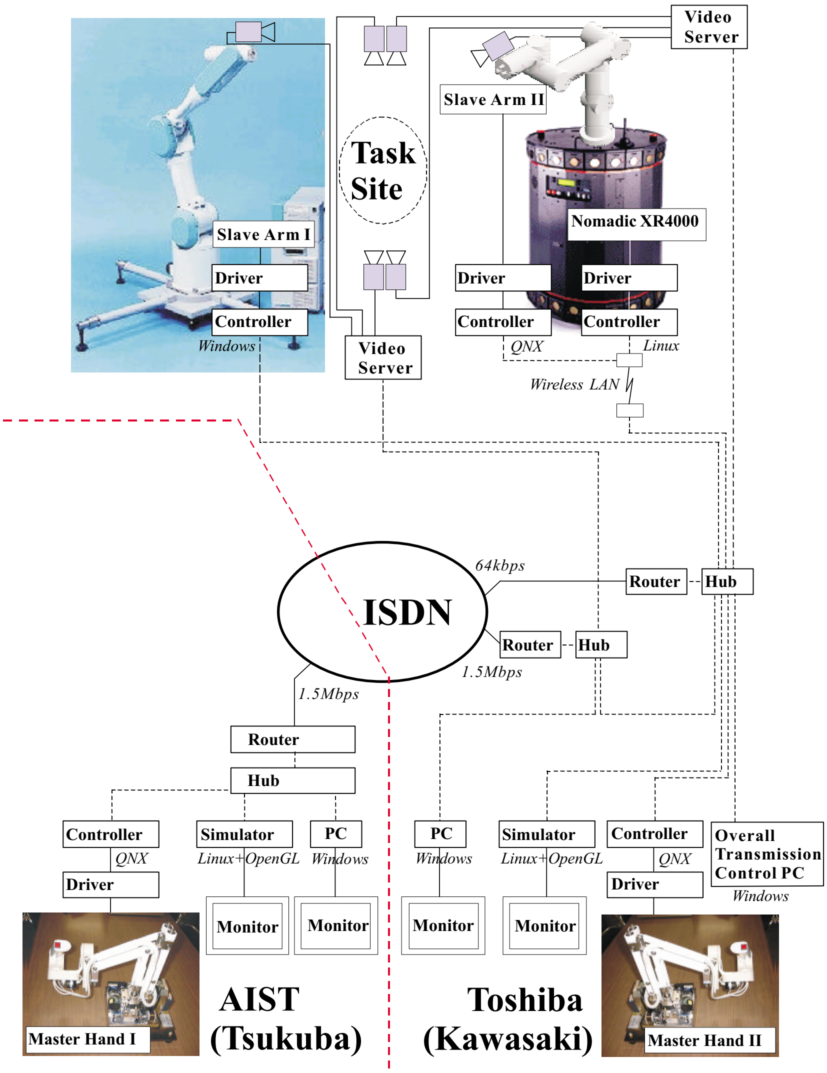

Figure 2: An experimental test bed for multi-site tele-collaboration.

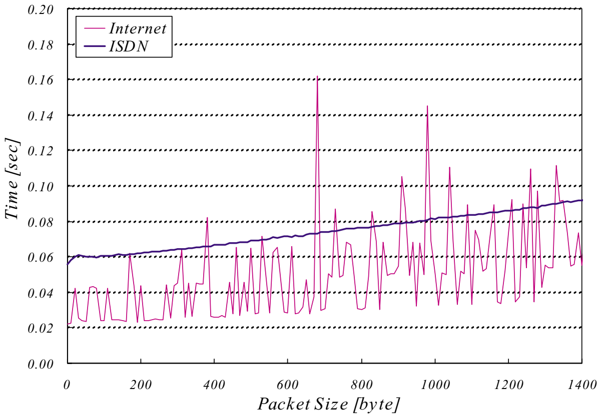

Figure 3: Network delay between Tsukuba and Kawasaki.

Figure 4: An ISDN router.

Figure 5: Operator's master control station in AIST.

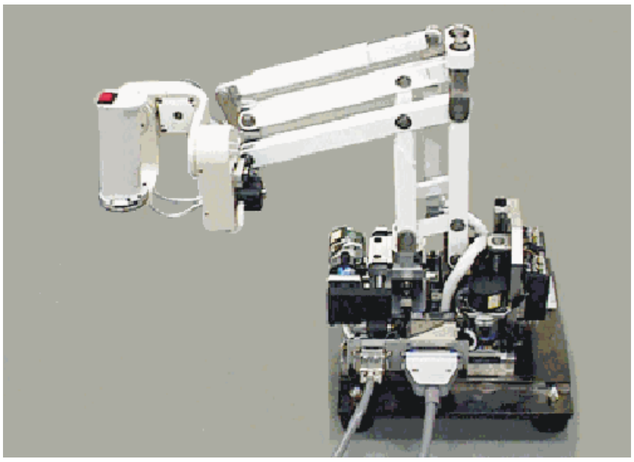

Figure 6: Prototype master device with twin pantograph mechanism.

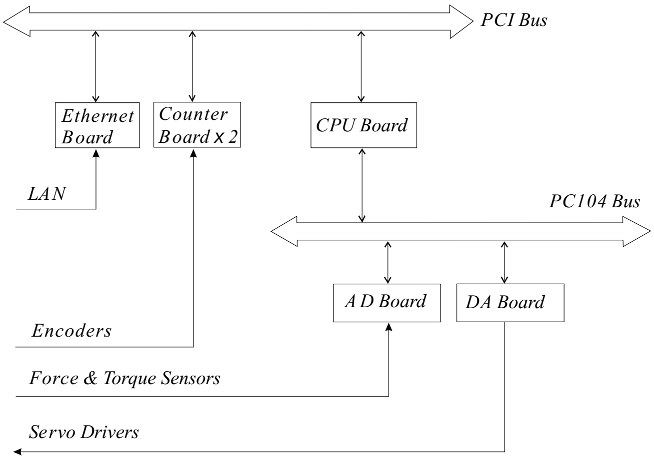

Figure 7: Schematic structure of master controller.

Figure 8: Multi-media broadcasting server and dual-speed Ethernet hub.

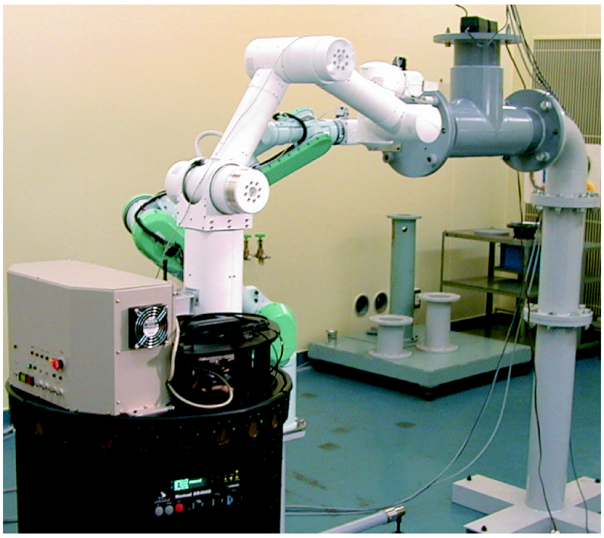

Figure 9: Slave robot systems in the task site.

Figure 10: Multi-camera image feedback in the client.

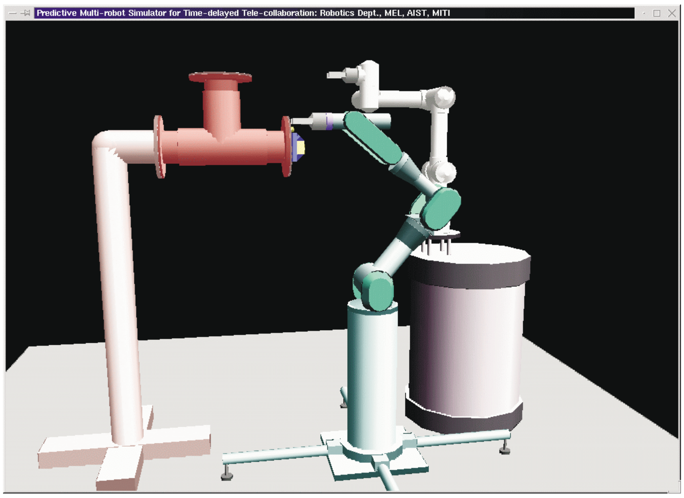

Figure 11: On-line predictive graphics simulator.