Virtual Repulsive Force Field Guided Coordination for Multi-telerobot Collaboration

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Abstract
The Intelligent Systems Laboratory (ISL) has been developing coordinated control technologies for multi-telerobot collaboration in a common environment remotely controlled from multiple operators physically at a distance from each other. We have built a test bed and conducted a series of experiments, where we learned more about how the transmission delay over the network deteriorates the performance of telerobots. Previously, to overcome the problems arising from the throughput of the network such as the operator’s delayed visual perception, we have suggested several coordination approaches in the local operator site. Likewise, this paper discusses the use of virtual repulsive force field in the on-line predictive simulator to assist the operator to cope with the collision between telerobots in remote environments. In the test bed, the operators control their master robot to get remote telerobots to work cooperatively with the other telerobots in a task. Specifically, the operator detects a priori the possibility of collision in the predictive simulator that runs in near real-time and the use of virtual force field prevents the telerobots from coming into collision. We have demonstrated various tasks by two telerobots and two operators via an Ethernet Local Area Network (LAN) subject to simulated communication delays and evaluated the validity of the virtual force field guided approach in Multi-Operator-Multi-Robot (MOMR) tele-collaboration.

1 Introduction
The current on-site work and maintenance that usually require a lot of travel is to be substituted for remote teleoperation over the network in a cost-effective way. Thus, we expect that the collaborative multi-telerobot system would be an alternative to support the coming society in which the working population decreases. In teleoperation with time delay, remote telerobot motions controlled from local operators would be visualized with round-trip time delays, thus the video camera image is often overlaid with graphics model predicted from local master control instructions. However, in the MOMR tele-collaboration as shown in Fig. 1, the telerobot under the control of the counterpart operator would not be straightforwardly predictable and accordingly the telerobots are most probably exposed to the possibilities of collision in remote environments. This seriously affects operators’ decision-making and accordingly the performance of telerobots. Thus, to cope with the operator’s delayed visual perception arising from the throughput of the network, we need to feed another supplementary information locally to the operator to safely steer remote telerobots through time delay [5].

To date, many works have been reported in the control of telerobot over the network and Sheridan extensively reviewed them in [13]. In addition, Goldberg et al. [7] [8] built systems that allow a robot to be teleoperated via the WWW. Brady et al. [1] proposed a new method for controlling telerobots over vast distances, where communication propagation delays exist. But most of the past works were applied only to a single telerobot controlled by a single operator. Recently, some efforts have been devoted to the teleoperation of multiple telerobots [9], [14]. But, they did not consider communication delays between local operators with large physical separation over the network.

In this work, we have built an experimental test bed to research the remote tele-collaboration through time delay between two distant operators. Specifically, to assist the operator suffering from the delayed visual
perception on telerobots not under the operator’s control, we developed an on-line graphics simulator that provides the operator with the work site view in near real-time. This simulator also feeds virtual force to the operator, which signals any possible collision between two telerobots. Thus, the operator can coordinate conflicting motions of multi-telerobots in remote sites even the counterpart operator is physically at a distance. The validity of the use of virtual force in the predictive simulator was verified through a series of experiments with two telerobots in a common work site controlled from two operators.

2 Use of Predictive Simulator

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 [10]. Likewise, the predictive simulator has played a major role in monitoring collision between telerobots and fine-tuning their end-effector position towards task goals when the network is subject to time delays [4]. But, to get the simulator-based approaches available, a priori models of remote environments are necessary. For this, recently, an interactive modeling tool based on the on-board sensor has been developed to build a reliable 3-D model as quickly as possible [6].

As is previously mentioned, telerobot motions not under the operator’s control can not be predicted in local operator sites. Thus, the counterpart operator’s robot motions are displayed with round-trip time delays and the operator’s robot motions are predicted without time delay. Accordingly, there should be some mismatch between the graphics update of two cooperating telerobots in the simulator. To overcome this difficulty, we have already proposed several local coordination strategies and verified their validity through experiments using the graphics models of two planar robots [2] and real telerobots [3]. This work addresses another use of predictive simulator that feeds virtual force reflection to the operator to get the telerobots cooperating without any collision over the network with time delay.

3 Experimental Test Bed

This section goes into details about the test bed. (See Fig. 2)

3.1 Master control station

Fig. 3 illustrates a set of equipment in the operator’s master control station. It consists of a proto-
type 6 DOF force-reflecting master system developed by the Toshiba R&D Center and an on-line graphics simulator running on a UNIX based operating system (Pentium II 450 MHz, Linux). Real video camera images from the task site is displayed in another PC (Pentium III 667 MHz, Windows) which has access to the video broadcasting server.

### 3.2 Transmission control

100Base-T Ethernet and dual-speed Ethernet hub are used to transmit information among two master stations and a task site. The communication control program in the Control Tower Station (Sun UltraSPARC 170, hereafter CTS) on the network gets all the communications between each site connected or disconnected. Likewise, the CTS also stores data in a buffer, which enables the communication over the LAN to simulate different time delays.

### 3.3 Video camera and broadcasting server

Local operators can have a better view of the task site if multi-camera views are incorporated. We mounted video cameras on the ceiling and the wall in the task site and also on the top of the gripper of each telerobot, respectively. To broadcast these camera images to local operators, we used a PC-less server (MegaFusion eWatch MD-100) that enables real-time streaming of video images over the Internet. Through incorporation of the system’s plug-in software into a popular web browser, the system’s video images can be viewed from a PC. The video image can be transmitted to the operator site at the maximum video rate 30 fps when one camera channel is input. The operator may have 4 different camera views from the task site, then the update rate becomes less than 2 fps which is impeded by source compression delay at the server and the image reconstruction delay at the client in addition to network transmission delays.

### 3.4 Telerobots and task environment

Two 7 DOF robots (PA-10, Mitsubishi Heavy Industries Ltd.) are positioned in opposite sides of a common working table as shown in Fig. 4. Different shaped and different colored acrylic plastic plates with a handle are on the table and are to be properly fitted into their pre-specified places by the cooperation of two robots. Some objects are out of reach of one robot. To proceed with the task, the objects should be delivered within the reach of the robot by help of its counterpart robot.

### 4 Virtual repulsive force field guided approach

The throughput of the network restricts the operator’s access to information about remote environments. To overcome the problems such as the operator’s delayed visual perception, we have already proposed several coordination approaches in the local operator site [2]. Likewise, this paper discusses the use of virtual repulsive force field in the predictive simulator. We have the virtual force directly reflected to master operators to assist them to cope with collisions between telerobots in remote environments. It is well known that reflected force to the operator can improve the performance of task. Very recently, for the ground teleoperation of a space robot, reflected force was successfully used to improve the performance of the operator despite time delay [11]. Also, an algo-
Algorithm has been implemented based on virtual springs in force-feedback teleoperation to keep a Stewart platform inside the useful workspace [12].

4.1 Predictive graphics simulator

We developed the predictive simulator using the OpenGL graphics system [15] that helped the operator visually verify their telerobot motions without time delay. (See Fig. 5) Specifically, the construction of 3-D graphics models of the telerobots and the task environment were performed. The robot graphics image is controlled by the master and its data are transmitted to the real robot. The CTS receives the robot data (e.g., joint configuration data) from the simulator and directly relays it to the counterpart operator’s simulator. On the other hand, the CTS relays the same data to the real robot with time delay by storing the data in a ring buffer until the specified timer expires.

We installed a graphics accelerator (3dfx Voodoo3 3000 AGP) not to be caught up 3D graphics rendering burden. As an inter-process connector between the master controller that runs on the QNX and the graphics simulator on the Linux, a pair of cooperating sockets manage the communication via shared memory.

4.2 Force-reflecting master device

We first evaluate the fidelity of the force reflection at the master. We get the teleoperator approaching to a massless buffer with stiffness \( k \) and damping coefficient \( c \) in the predictive simulator as shown in Fig. 6. The input velocity of \( x \)-axis of the master is also shown in Fig. 6. Then, neglecting the inertial effect of the teleoperator for simplicity, we can calculate the reaction force \( F_w \) at the end-effector of the teleoperator by

\[
F_w = -kx - cx. \tag{1}
\]

Fig. 7 shows the calculated force \( F_w \) from Eq. 1 and reflected force measured at the master. It is noted that the reflected force conforms to the \( F_w \) and the rise of reflected force before contact comes up due to the friction and viscous damping of the master device.

4.3 Multi-telerobot coordination

In this work, the virtual reaction force \( F_w \) calculated in the simulator is directly fed back to the master controller. We employ this \( F_w \) to coordinate the motions of multiple telerobots by getting this force reflected to the master operator. The operator feels...
Figure 8: A virtual repulsive force field around the counterpart telerobot.

a barrier when making their telerobot approach its counterpart robot. Specifically, in the predictive simulator, a virtual repulsive force field is generated around the end-effector of the counterpart robot. (See Fig. 8) When one telerobot approaches its counterpart robot, the repulsive force $F_w$ pushes the approaching robot back and keeps its distance from the robot. While the distance between two robots is secured enough, then the force field does not work anymore.

Let $S_1(t)$ and $S_2(t)$ denote the sets in operational space occupied by each teleoperator. Also let $d(A, B)$ denote the minimum distance between two sets $A$ and $B$. $d_{col}$ implies the distance wherein the two telerobots are possible to collide. $d_{col}$ can be calculated based on the maximum permissible velocity of telerobot over the communication delay from the CTS. Telerobots safely move out of the danger of collision if the distance is over $d_{col}$. Thus, according to the distance between two telerobots, the spring and damping coefficients $k_e = [k_e]$ that generate the virtual force field can be given by

$$k_e = \begin{cases} 
0 & : d(S_1(t), S_2(t)) \geq d_{col} \\
\kappa_e & : d(S_1(t), S_2(t)) \leq d_{col}. 
\end{cases} \quad (2)$$

Here, for simplicity, we assume that the collision occurs only between the end-effectors of two robots.

5 Experimental Results and Discussion

We have several pieces of objects scattered on the table. The operators control their robot and collaborates with the counterpart on arranging the object in order. We compared the task completion time with changing the network delays and also investigated how the predictive simulator works in collision detection without time delay. Several pairs of subjects evaluated the operation solely with the camera view. The same pairs also evaluated the trials with the predictive simulator as well as the camera view. Table 1 is cited from [3] where the audio-visual resources featured the simulator in collision detection.

Without the predictive simulator, operators usually control their robots at very low speed, otherwise they might fail to coordinate the conflicting motions of robots successfully. On the contrary, observing the predictive simulator, operators could make robots safely avoid the collision, since they were guided by an audio-visual information from the simulator. The simulator signals to the operator by getting the preserved audio file running and the original color changing when the robot comes in contact with its counterpart robot and/or the working table. In addition, from the simulator’s overall view of robots and work site, the operator quickly make decision which direction they should move their robot and confidently move at a relatively high speed. Thus, the task completion time was reduced as shown in Table 1.

Our previous works showed that predictive simulators were effective in the collision detection thanks to its audio-visual characteristics. However, the operators should make strict observations about the predictive simulator to take precautions against collision between robots. The operator, moreover, might miss or neglect the advance notice of collision. Thus, in this work, we added telerobot contact force against a virtual barrier around the counterpart robot to the existing operator information. This force is directly delivered to the operator hand through the master controller. The virtual repulsive force field is not merely a precautionary information but also safeguard telerobots against approaching counterpart robots. This is more dependable level of operation whereby operators are almost completely released from the danger of collision. Thus, irrespective of whether novice operators make a mistake and control their telerobot toward its

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Table 1: Task completion time in 2 telerobot collaboration. (See [3].)
counterpart robot, the force field will not allow them to collide. In the simulator, the stiffness and damping coefficients of the force field are designed not to make the master device unstable at the instant of getting into/out of the force field.

6 Conclusion

Predictive simulators play an important role to improve the operators’ performance in collaborative MOMR tele-operation systems. The use of virtual repulsive force field in the predictive simulator was described to help the operators overcome the delayed visual perception and securely ensure the collision-free cooperation between telerobots over the long-distance network. We have built an experimental test bed, where several example tasks were conducted with two operators and two telerobots over the LAN subject to simulated communication delays. Within the results of current experiment so far, the use of virtual force field satisfactorily steered a couple of telerobots to perform a task cooperatively without any collision and showed the feasibility to cope with the communication delay in MOMR tele-collaboration. Each operator could give larger master commands more confidently without having to consider collision of telerobots, because the virtual force field in the predictive simulator would constrain master commands where collision is likely to happen. Operators accordingly become released from the anxiety about the collision even the counterpart operator is physically at a distance from each other. This work hopefully will form the framework of MOMR tele-collaboration in the coming society as an alternative of costly on-site operations.

References


