Teleoperation of Real-time Robotics

We have been working on technologies for controlling robots remotely via mobile communication networks, and focusing on various technical issues that occur in environments where a communication delay exists. In this article, we propose a methodology that allows bidirectional, realistic senses of force and touch, which has so far proven difficult to achieve with the conventional methods, and present results of performance evaluation tests.
This research was conducted jointly with the Ohnishi laboratory (Professor Kouhei Ohnishi), the Department of System Design Engineering, Faculty of Science and Technology, Keio University.

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1. Introduction

DoCoMo aims to expand its businesses that support the everyday life infrastructure, based on it's business providing communication infrastructure. In this context, consumer-oriented robots constitute one of the noteworthy areas, and the market is expected to grow dramatically in the everyday life-related fields in the future [1]. With the current technologies, autonomous robots with human-like intelligence and dexterity cannot be expected to appear in everyday or business situations until far into the future; remote controlled robots (telerobots), on the other hand, are a realistic step on the way, and this technology can be considered mature enough to be applied in the near future.

In such applications, remote control technologies constitute a key factor in enabling people to operate robots and carry out various tasks efficiently in their everyday lives and in various business situations. Furthermore, in situations where a robot is placed at a remote location and is operated via networks, the ideal technology would provide transparent and bidirectional remote control that would allow the robot to behave as if the operator were present at the location.

There are many technical issues involved when building telerobot systems, including issues related to actuators, sensors and other devices, but in this work we focused on the control and network issues in order to identify the requirements to establish the current and future communication infrastructure for remote robot control (teleoperation). Among these issues, establishing bidirectional and transparent real-time teleoperation technologies that can communicate senses of both force and touch to the operator, i.e., not limiting the teleoperation to simple radio control, is an important and challenging issue. Conventionally, feeding back an accurate sense of touch to the operator when a remote robot arm comes into contact with an object exposed various technical difficulties such as ensuring stability. This article provides an overview of the main technologies we examined so far.

2. Bilateral Control

One of the methods that can be adopted for remote control of robots is a system where a human operates a master arm and the slave arm tracks the movement of the master arm to carry out a task. Such a system is called a master-slave manipulator. In this system, the robot (slave side) should not only perform the operation instructed by the human operator (master side) exactly as instructed, but also feed back accurate information of position and force obtained as a result when it grabs something or collides into something, allowing to achieve advanced operability. Such control is referred to as bilateral control (**Figure 1**).

In the figure, F_m represents the information of force applied by the operator to the master robot arm, F_s is the information of force applied by the slave robot arm to the environment, and X_m and X_s indicate the position information of the master and slave robot arms, respectively.

The following methods are used in conventional bilateral control schemes.

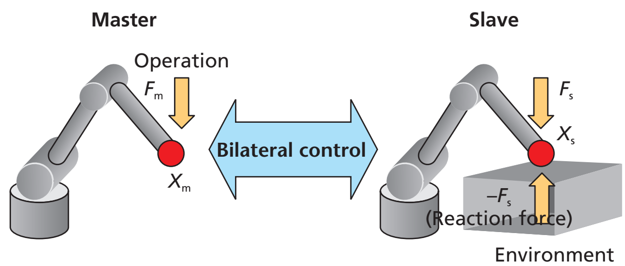

Figure 1 Conceptual overview of bilateral control manipulator

1) Symmetric Position Servo Control

Driving force is applied in the direction that minimizes the difference between the positions of the master and slave robot arms. This control scheme does not require any force sensors or similar devices and is highly stable and easy to configure, but the operation typically feels heavy, as it is influenced by the force of inertia and friction in the system (**Figure 2**).

2) Force Reflection Control

The slave robot arm is equipped with a position servo loop, and the reaction force is detected by a force sensor on the slave side and transmitted to the master side. In this scheme, the reaction force acting on the slave robot arm is transmitted correspondingly to the master robot arm, but the master mechanism is affected by it and the operation is felt heavy (**Figure 3**).

3) Force Feedback Servo Control

This control scheme compensates for the shortcomings of the force reflection control. The master robot arm is equipped with a force servo subsystem as well, which makes it light to operate. The transmission of reaction force on the slave robot arm is also favorable (**Figure 4**).

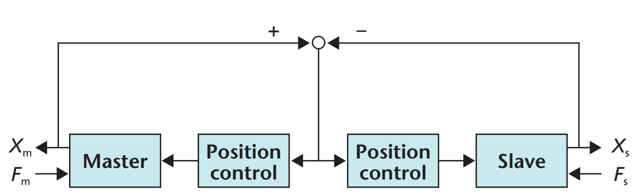

Figure 2 Symmetric position servo bilateral controller

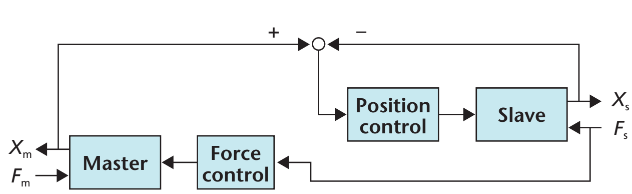

Figure 3 Force reflection bilateral controller

Typically, these conventional bilateral control systems are designed by tuning the control gains taking the influence of external disturbances such as operation feel, friction and various forms of noise, into consideration. Stable bilateral control systems are achieved by decreasing the control gains when taking the influence of external disturbances such as communication delays into consideration, but, on the other hand, low control gains have led to a poor operation feel.

To address this issue, we propose a new robust bilateral control method. This control method has various excellent characteristics, in the sense that it is possible to design "reproducibility," "operability" and "stability" independently of one another. By satisfying these characteristics, it is possible to design highly transparent and bidirectional systems that can transmit senses of force and touch. From a mathematical point of view, a remote control system is completely defined by the positions of the two robots and the forces acting on them [2]. In order to achieve perfect transparency, as shown in **Figure 5**, the position of the slave robot is controlled by the difference in acceleration between the master and slave robot and the force is controlled by the sum of their accelerations.

Reproducibility means the degree how accurately mechanical impedance from objects in the environment sensed on the slave side can be transmitted to the master side, meaning that a fine sense of touch can be transmitted by achieving satisfactory reproducibility.

Operability means the degree to which the operator on the

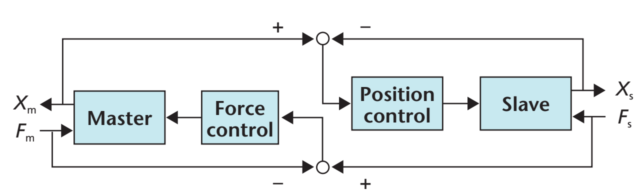

Figure 4 Force feedback servo bilateral controller

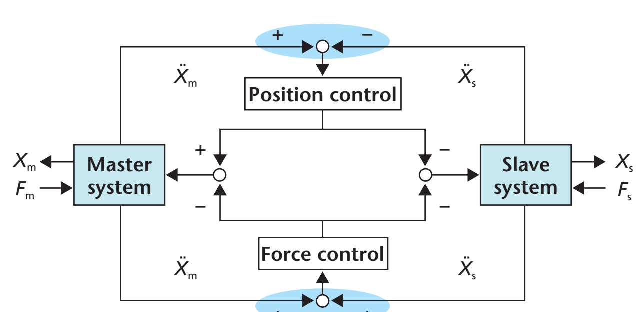

Figure 5 Overview of robust bilateral controller

master side can feel actual reaction forces from objects in the environment transmitted from the slave side; achieving satisfactory operability means that light operation of the system can be achieved, so the operator does not have to feel the actual rigidity of the system.

Stability is a basic control requirement; it is highly important in terms of maintaining the safety of human operators as well as system, since it means that system responses do not diverge.

We did not attach force sensors to the master and slave robot. Instead, an observer, which is a systematic way of estimating the acceleration obtained from position information and system states, was utilized. We implemented observers to estimate both external disturbances and reaction forces for both the master and slave sides [3]. In this way, it was possible to obtain information with a wider bandwidth than when using only force sensors.

3. Experimental Results

3.1 Bilateral Control Robot Transmitting Sense of Force and Touch and Experimental Result

In order to validate the system, we built a forceps robot for remote surgery and conducted an experiment. **Photo 1** shows an endoscopic forceps used as surgical tools. The scissors at the tip can be opened and closed by handle operation, it is a single degree of freedom mechanism.

We divided the forceps into a handle and a nipper and connected a linear actuator with high positioning accuracy for each part; two of these devices were designated as master and slave robot, respectively. Real-time control operation was achieved by means of a real-time PC-based operating system (RT-Linux). **Photo 2** shows the external view of the master and slave robot.

First, we connected the master and slave robot to the same PC and measured the responses of position and force when the master side is operated so that soft objects (e.g., a sponge) and hard objects (e.g., metal) are grabbed by the slave side. Both the master and slave followed the control well and we confirmed stable operation during contact even in case of hard objects, for which stability problems had often been observed for conventional methods.

Next, we connected the master and slave robot to separate PCs, connected the PCs with a network, and then conducted a remote control experiment.

Figures 6 and **7** show the responses of position and force when the master and slave PCs are connected using a wired

Photo 1 Endoscopic forceps for surgery

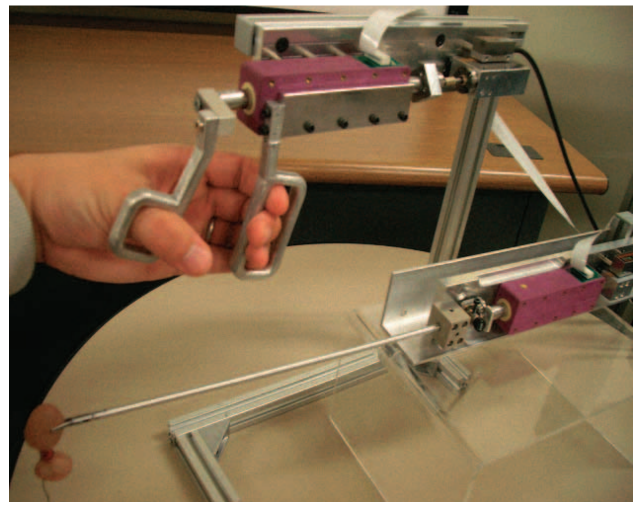

Photo 2 Master and slave forceps robot

LAN (Ethernet; 100BASE-TX), grabbing a hard object. We were able to confirm stable teleoperation under conditions where the network Round-Trip Time (RTT) between the master and slave sides was only in the range of 1 to 4 ms, and the touch of the object grabbed by the slave robot was reflected to the master operation on the operator side.

Figures 8 and **9** show the responses of position and force when the master and slave PCs are connected using a Wireless LAN (WLAN; IEEE802.11g). Although RTT was generally in the range of 2 to 8 ms, large delays with an order of 100 ms occurred periodically. The overshoot observed in the master position was thus much larger than in the case of bilateral control using Ethernet. Furthermore, as the overshoot became larger, a large torque was generated to counter the excessive output error, which meant that the master robot was pushed back too much and the response fluctuated. In the responses shown in the figures, large deviations occurred during the intervals from 1.5 to 2 s in both position and force due to large communication delays (up to about 150 ms).

3.2 Bilateral Remote Operation Experiment and Experimental Results

Since large communication delays lead to control phase

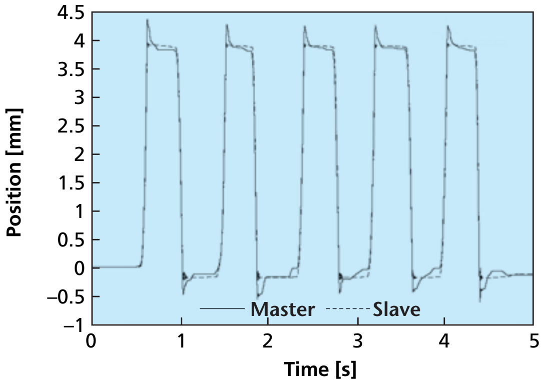

Figure 6 Position response (Ethernet)

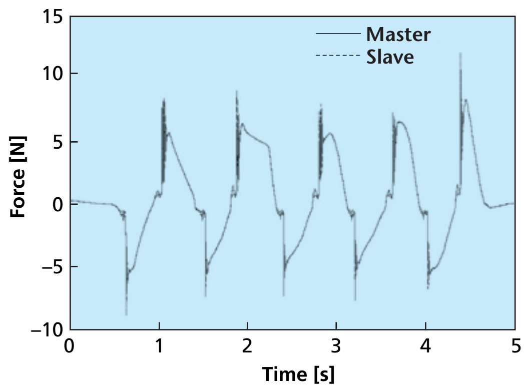

Figure 7 Force response (Ethernet)

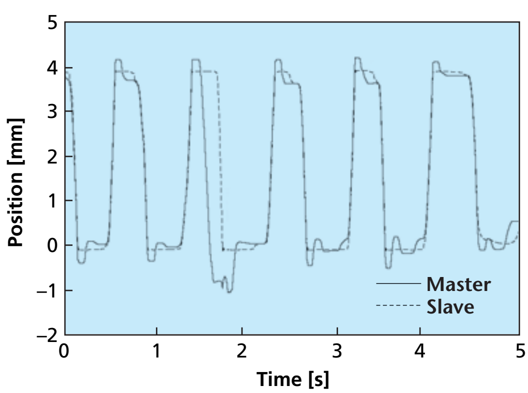

Figure 8 Position response (WLAN)

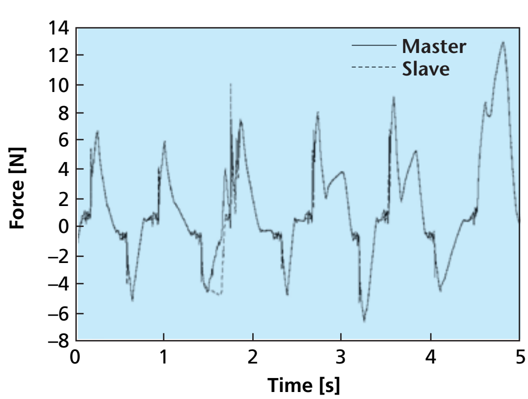

Figure 9 Force response (WLAN)

lag, it is very important to confirm that the system is stable. As a case study of a bilateral remote operation system involving locations separated by a significant distance, we connected robots placed at Shin-Kawasaki K2 Campus of Keio University (Japan) and University of Maribor (Slovenia) via the Internet and conducted an experiment. The manipulators used in the experiment were rotating manipulators with one degree of freedom for both sides and external disturbance observers monitoring the communication delay were implemented [4].

Figure 10 shows the fluctuation of RTT. From the figure, it is seen that the network delay introduces a considerably large delay in the control system, along with considerable jitter. From the position response shown in **Figure 11**, although there is some excessive movement on the master side at hard contact (indicated by the dotted circles), the master does follow the slave. Moreover, from the force response shown in **Figure 12**, it can be seen that the reaction force from the environment on the slave side is reproduced on the master side.

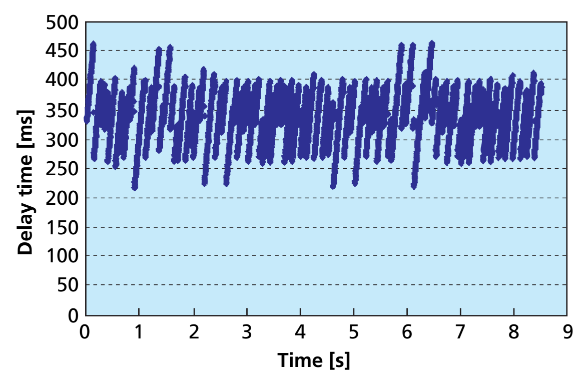

Figure 10 Fluctuation of network RTT

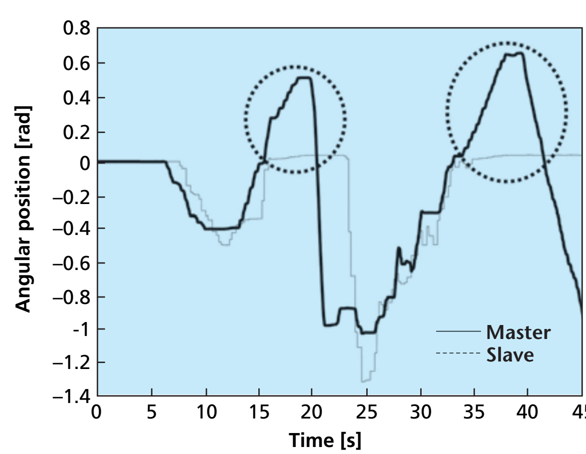

Figure 11 Position response (Internet)

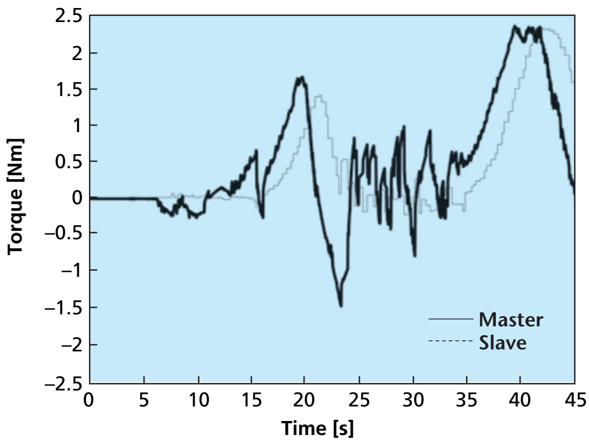

Figure 12 Force response (Internet)

4. Conclusion

We examined remote control technologies that allow transmitting realistic senses of force and touch bidirectionally, and conducted experiments with bilateral control of manipulators via networks. From these experiments, we were able to confirm the basic concepts of systems that are able to adapt flexibly to the network conditions. In the future, we would like to establish control technologies of telerobots that allow a fine level of feedback with a bandwidth in the vicinity of 300 Hz, which is considered to be the fastest force input human sense of touch receptors can respond to, and clarify the network requirements to achieve delicate sense of touch communication.

References

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