Teleoperated Robots Haptic Communication Bilateral Control

Collaboration Projects

Haptic Communication Technology Using Real-time Robotics

We are advancing research with the goal of establishing communications technology for remote control in mobile environments, and confirmed that it is possible to perform bidirectional haptic communication in environments with large delay for teleoperation of robots. 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.

Minoru Takahata, Kouki Hayashi and Hirotaka Furukawa

1. Introduction

Robot-related technical development is advancing in various specialized fields, such robots for surgery with minimal invasiveness[*1] or for remote construction tasks, which require precision beyond human skills or must be carried out at dangerous locations such as disaster recovery sites [1]. The ability to connect specialists to remote locations is very significant, and the mobile market can be expected to expand as mobile robots become more common. However, up to this time there are very few examples of business applications in teleoperation fields using mobile communication networks due to the cost, connectivity, reliability and delays of these communication channels. Although most of these reasons should be improvable through development of communication technologies, developing technology to address the fundamentally unavoidable issue of time delays will be essential.

When performing teleoperation, there is a preparation stage, looking at what the target is like (environment recognition) and what types of operations are required (trajectory planning), and then an execution stage, where the work is actually done (robot motion control). Real-time control is particularly important in the execution stage, which has deep relations with communication technologies. Due to this, we focus on motion control, a technology used to achieve remote robot operation. Motion control is based on acceleration information, which can be derived from either position or force. Acceleration control makes it possible to control the robot without a sense of the weight or rigidity of the robot itself and to satisfy both operability and stability of teleoperation. Further, by using motion control at high accuracy and frequency and transmitting sensation (haptic information) about the environment that the remote robot is in contact with back to the operator, natural and safe remote control is possible.

A type of architecture for remote robot control is called the master-slave teleoperation system. With this system, the remote slave is controlled based on information from the master, operated by the human operator as shown in **Figure 1**. High operability can be achieved by precise information feedback to the master when the slave contacts something in its environment. As the master and slave are tightly connected, exchanging information, this method is called bilateral control. It has been able to reproduce the action-reaction principle by applying a four-channel bilateral control method where the master and slave exchange two types (positioning and force) of information in a round-trip fashion [2], but traditional systems

*1 **Minimal invasiveness**: In this article, this refers to surgical treatments that impose less impact on the human body. For example, surgical technique with smaller incisions would be less invasive, and could be expected to result in effects like a reduced burden on the patient, shortened hospital stay, and better post-operative recovery period. However, remote operation is based on limited information, so in some cases it is difficult surgery to perform.

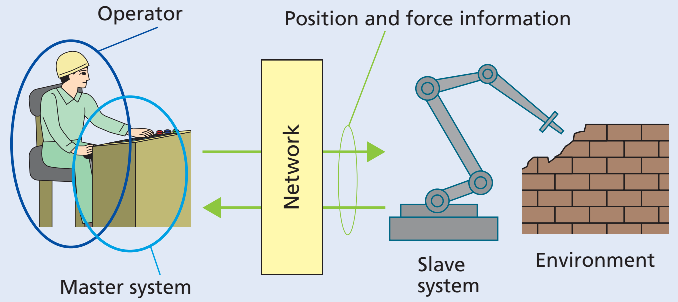

Figure 1 Example of a master-slave system

are particularly susceptible to delays in the communications path.

In this article, we describe an overview of two technical elements of a proposed motion-control system for remote-control operation when communication-channel time delay (network delay) is assumed. These are the Communication Disturbance OBserver (CDOB) , a scheme which compensates for network delay, and multi-rate control, a processing-interval scheme which improves performance. This research has been conducted jointly with the Ohnishi Laboratory of Keio University, a world leader in the area of high-precision motion control enabling haptic communication.

2. CDOB

Network delay exists in the master-slave bilateral remote control system, but under a mobile environment, it is extremely difficult to estimate the delay accurately ahead of time. Thus, we describe a control method which does not rely on accurate estimations of network delay. The elements of one side of a bilateral control system can be shown with a block diagram[*2] as in **Figure 2**. Applying a force, F, to the slave based on data received from the master, the slave's velocity, sX (s is the Laplace operator, expressing the derivative of the slave position, X) can be obtained by integrating the added force, F, and excluding the inertial moment, J, of the slave. In the absence of network delay, this sX is fed-back to the master as-is. Network delay is defined as the time delay element[*3], and if delay time is T, it is expressed by e^{-Ts}. Here, delay time T is the sum of the delay from master to slave, T_1, and the delay from the slave to the master, T_2. sXe^{-Ts} is fed back to the master, and we use the fact that this is equivalent to the case in **Figure 3**.

The figure shows the network delay that may occur in the network added on the slave side, handled as an external noise force, $F(1-e^{-Ts})$ (hereinafter referred to as network disturbance). As shown in **Figure 4**, compensation for network delay is possible by introducing a scheme that applies control with an estimation of network disturbances. We have called this element a CDOB, and have verified its effectiveness through theoretical analysis and physical experimentation. A CDOB can be designed using a low-pass filter [3].

The configuration of the experimental bilateral control system is shown in **Figure 5**. Experiments were carried out by having the slave end effector (the part which directly con-

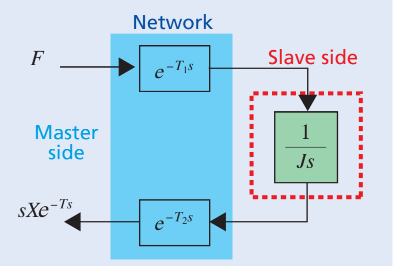

Figure 2 A bilateral control system with network delay

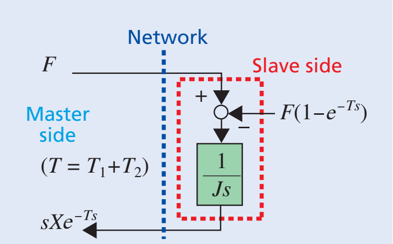

Figure 3 Approach to network disturbances

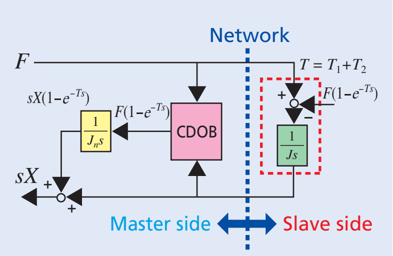

Figure 4 Bilateral control system using CDOB

*2 **Block diagram**: A line diagram used to show the system architecture and signal flow graphically, focusing on the elements needed to implement the function.

*3 **Time delay element**: An infinite-dimensional factor that appears in the exponential form. If time delay element is included, there are an infinite number of poles, so it is very difficult to handle. Also, phase in the frequency domain is proportional to frequency and time delay, so it has an unlimited delay property, which can cause serious effects such as instability in the control system.

tacts objects in the environment) rotate until it comes in contact with an object. The position (angle) information which is given by the operator is used as the control. A list of experimental results is shown in **Figure 6**, which shows the results of a large, two-second delay in RTT applied on the network emulator for communication between the master and the slave. Stable control was not possible without using a CDOB, and unpredictable behavior resulted, but with a CDOB, stable control was achieved, with the slave following the master's motions with one second delay. This also applies to the shaded area, where the slave was in contact with an object, but because the slave could not move after coming into contact, its position is restricted (slave response in Fig. 6 (c)). The reaction force is a torque resulting when the slave comes in contact with the object, as shown in Fig. 6 (d), where the force generated by the slave returns to the master about one second later.

3. Multi-rate Control

The performance of digital control greatly depends on the sampling rate in the system, but even with CPU and device technology advancing as it is today, there is a limitation to how high the sampling rate can be made. Moreover, the sampling rates may have different orders among each subsystem within the control system. As such, we present an example applying a multi-rate scheme to improve performance. A

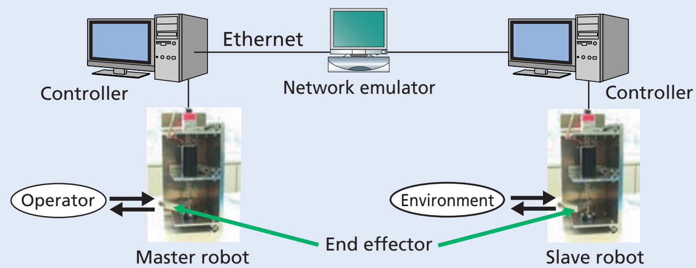

Figure 5 Experimental bilateral control system

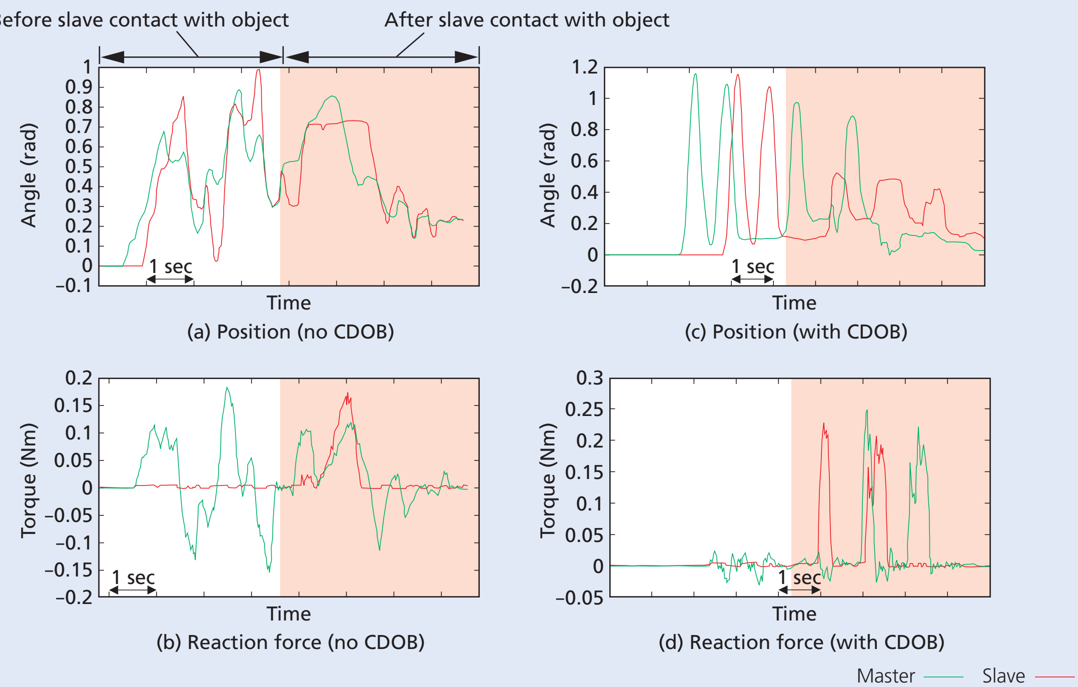

Figure 6 Experimental results with CDOB

basic overview of the multi-rate control system is shown in **Figure 7**. The input interval for updating the input information used to control the robot is T_u, the robot control result output interval for acquisition of the sensor signals is T_y, and the control interval of the controller is T_r. With general control methods, the longest of these intervals is used as the common interval time (single-rate system). In contrast, multi-rate systems try to achieve better performance by allowing these rates to be set independently of each other.

On a visual servo-controller using external camera measurements as an example, the sampling interval times would be set to around T_u = 1 ms (motor driver), T_y = 33 ms (camera frame rate), and T_r = 10 μs(Digital Signal Processor (DSP) control). In order to increase performance, the longest of these, T_y, must be made shorter by, for example, interpolation or using a high-frequency camera. On the other hand, to present more-accurate haptic sensation, a higher-frequency, higher-precision sensor would be required. Semiconductor laser encoders could be used for more accurate measurements, and in this case, settings down to around T_y = 100 ns would be possible. Then, in contrast to the visual servo-controller described above, the input interval, T_u, would be longer than the control and output intervals, but the input interval to drive the motor, T_u, is difficult to reduce significantly because it is limited by the motor driver. Thus, rather than settling on the longest input interval, T_u, an approach using the shorter output interval, T_y, is needed. Here, we applied multi-rate control adding the key-component, the disturbance observer for acceleration-based robust control[*4]. Having the control and output update intervals shorter than the input update interval, it has two effects as described below.

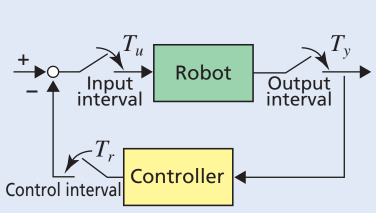

Figure 7 Overview of multi-rate control

The first is that the amount of data points increases, that is, the resolution increases significantly, so the cutoff frequency for the disturbance observer can be set higher. In this way, the phase-delay is reduced, increasing control performance. The second is that the interval of the disturbance data is shortened, so the responsiveness to disturbance is improved, which should make the system more robust.

An example of a comparative experimental study to verify the multi-rate bilateral control method is shown in **Figure 8**. Both single-rate control (Fig. 8 (a)) and multi-rate control (Fig. 8 (b)) show the reaction forces when the master is operating and the slave contacts an object in the environment (signs are opposite due to the action-reaction principle). It is apparent that the small oscillations produced while contacting an object while using single-rate control tends to be suppressed when using multi-rate control. Further performance improvements were observed when using multi-rate control, including an expanded range of stability, quicker rise time, and improved responsiveness. In the experiments using multi-rate control, stable control was even possible at cutoff frequencies where single-rate control became very unstable.

We also verified the multi-rate method through experiments shortening the input interval only, and the output interval only, comparing with the single-rate control as a benchmark. The results clearly showed that shortening the output interval was more effective than shortening the input interval, confirming the effectiveness of multi-rate control [4].

4. Conclusion

Through this joint research, we verified the fundamental and important idea that network delay can be treated as equivalent to force disturbance (noise) introduced into a control system. By building an experimental system, we also showed that remote control of a robot and transmission of haptic information is possible.

We also demonstrated a multi-rate approach for improving performance. This is an important technology applic-

*4 **Robust control**: Control that achieves the desired output without being affected by unforeseen disturbances or parameter fluctuations in control. Robust systems are loyal to the desired behavior, and the more complex and high-level of behavior is required, the more robust the system must be. High-precision estimation of disturbance is important.

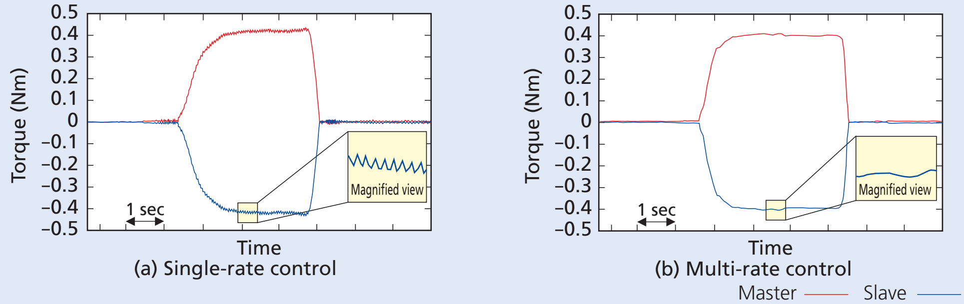

Figure 8 Comparison of reactions by control method

able to the disturbance observer as well as various other control elements.

These technologies are not limited only to bilateral control, but can be used together with the knowledge gained in research of another article, "Evaluation of Five-finger Haptic Communication with Network Delay", to further develop mobile communication technology for yet more-robust teleoperation information. Next, we hope to help develop new mobile communication media as support infrastructure for life and industry in the future, by examining these technologies in various network environments.

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