Position-Force Telecontrol with Wave-filter Using Teleoperation Support Robot IBIS

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***Abstract*—Endoscopic surgery is performed through a smaller incision than that is made in conventional surgery, and thus is superior in terms of reduced physical burden on the patient and shorter duration of hospitalization. To achieve this surgery, there is active research and development of surgical robots using master-slave system. However, operations without tactile sense may cause inclusion of a fatal accident. Although the master-slave system using the force feedback has been also studied, the velocity-force control algorithm is used because of guarantee of stability for close-loop system. However, velocity-force control involves the risk of causing a deviation in position between the master device and the remote robot if velocity information is missing due to network packet loss and/or the jitter of communication latency. In order to solve this problem, position-force control for an IBIS surgical robot is proposed in this study. First, the frequency characteristics of the surgical robot is measured, and it is shown that passivity is not achieved in the master or slave, and that direct connection will cause system destabilization. Next, a wave filter is designed for the proposed method based on the obtained frequency characteristics, and it is shown that implementing this method led to stabilization. Finally, a remote operation experiment shows that regardless of communication latency, the slave moves stably to the position instructed by the operator, and the reaction force detected by the slave can be transmitted to the operator.**

***Index Terms*—teleoperation, position-force telecontrol, stabilized control, communication latency**

I. Introduction

Endoscopic surgery is performed through a smaller incision than that is made in conventional surgery, and thus is superior in terms of reduced physical burden on the patient and shorter duration of hospitalization. On the other hand, endoscopic surgery requires a high level of skill due to the difficulties in freely approaching the target as the forceps must be moved within a limited field of view. As a result, the surgeon is forced to endure numerous technical challenges, and a successful operation is strongly dependent on his or her skill and experience. To resolve these problems, there is active research and development of surgical robots that perform confined operations for minimally invasive surgery as well as minute movements that are difficult for humans to achieve. Surgical robots are required to perform extremely fine movements and intuitive operations that implement the experience of the operator, and so a master-slave type manipulator is used. For example, the Da Vinci by Intuitive Surgical Inc.[1] has been put into clinical use, and the IBIS surgical robot, which has excellent back-drivability and uses a safer pneumatic cylinder, is being studied by Kawashima and Tadano in Japan[2]. Moreover, ZEUS[3] and similar robots[4,5] have been developed.

Meanwhile, in locations far from cities such as regional areas and remote islands, the dearth of physicians and insufficient medical facilities are problematic. Often, patients must travel to urban areas from regional areas in order to receive endoscopic surgery, which is a significant hardship. This problem could be resolved by using local surgical robots if they can be remotely operated from a city. However, to successfully implement remote operations using robots[6], it is insufficient for the operator to unilaterally operate a remote robot due to the risk of causing a serious accident. Indeed, operations using Da Vinci have included a fatal accident in Japan due to pressure exerted on the organs by the robot[7]. If the operator could have felt the rebound pressure that the robot incurred from the organs, the accident likely could have been avoided. Consequently, haptic feedback to the surgeon can be considered an extremely important element for safety during robot-assisted surgery.

There have long been studies on the stability and operability of master-slave systems that use bilateral control implementing haptic feedback. Spong et al. configured a stable bilateral control system using a scattering matrix to ensure that the communication unit fulfilled the requirements for passivity[8], while Niemeyer et al. developed a scattering matrix using a wave variable[9]. Hannaford et al. configured a bidirectional system by using passivity observer to satisfy the passive

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condition[10]. The remote surgery is eagerly awaited as the application of these technique, and there have already been reports on the experiments using IBIS by Kawashima et al[11]. These were conducted using velocity-force control, because it can secure stability regardless of the communication latency with the remote location as it easily assures the passivity of the master side and the slave side.

However, velocity-force control involves the risk of causing a deviation in position between the master device held by the physician and the remote robot if velocity information is missing due to network packet loss and/or the jitter of communication latency. Whereas, position-force control is a method that resolves this shortcoming as the issue of position deviation does not arise due to packet loss and/or latency by communicating position information. However, this method has the problem of system destabilization because master-side passivity is not guaranteed.

Authors previously proposed a wave filter[12] that builds upon the method of Niemeyer, and proved that stability was maintained despite using position-force control. The present study empirically demonstrates that by applying our method to the IBIS surgical robot, it is possible to achieve stable position-force control even if there is communication latency.

II. Experimental Apparatus of Tele-operation

The experimental device used in this study is the surgical support robot system developed by Kawashima and Tadano[2]. This surgical support robot system consists of a haptic interface (master side) and a surgical forceps manipulator IBIS (slave side), and in this experiment, these were connected by a network emulator in order to reproduce communication latency.

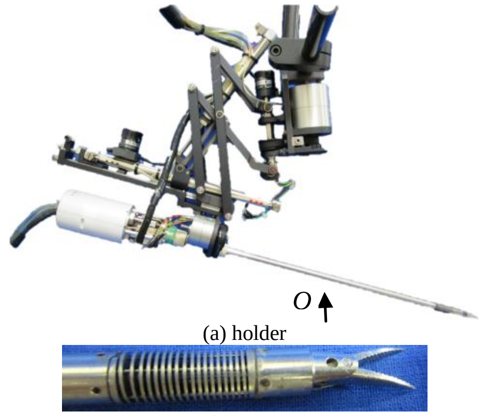
A. 3D Haptic Device Geomagic Touch (Master Side)

The master uses Geomagic Touch[14] as shown in Fig. 1. This is 3D I/O device that enables high-precision haptic interactions. They are characterized by a 6-degree-of-freedom (DOF) position sensor that can also be used for fine movements, and by 3-DOF force feedback via torque control using DC motors.

Figure 1. Geomagic Touch as master device

B. Surgical Forceps Manipulator IBIS(Slave Side)

The outer appearance of the pneumatic surgical manipulator IBIS is indicated in Fig. 2. It is produced by the Kagawa/Kawashima laboratory at the Tokyo Institute of Technology[2]. It is configured from a forceps manipulator ("forceps unit") and a holding manipulator that holds it ("holder"), and it has a total of 6 DOF. The holder has three rotational joints (parameters q_1, q_2, q_4), and one prismatic joint (parameter q_3). All joints are driven by a pneumatic actuator.



(a) holder

(b) forceps unit

Figure 2. Outer appearance of pneumatic surgical manipulator IBIS.

In the Fig. 2, the forceps unit is configured from a drive unit in which are mounted four low-friction pneumatic cylinders and potentiometers, and a tip unit that includes a pneumatic opening/closing grasping section and a flexible joint with a precision spring. A superelastic alloy wire is used to transmit motive force to the forceps tip unit from the cylinders, and the motion of the wire controls the forceps tip joint (parameters q_5, q_6). The joint parameters q_1 to q_6 are measured using the potentiometers, and the forceps tip position is calculated from those values based on kinematics. See the reference[2] for detail. This IBIS has the following superior characteristics:

(1)High back-drivability

The actuators configuring each joint are all driven pneumatically and thus have high back-drivability. In other words, if an unexpected operation is performed, the manipulator can be moved manually, facilitating a response in abnormal circumstances. With this device, the medical accident described in the introduction likely could have been avoided.

(2)Presence of a fixed point

The holder is designed so that point *O* is a fixed point, which enables pivoting movements of the forceps unit centered on the point of insertion into the body. As a result, the operator needs to focus on only the movement of the forceps within the body, and this contributes to improved safety against the body.

(3)Sensor-free external force detection

The external force acting on the forceps tip can be measured without using a force sensor by using the pneumatic pressure value from the pneumatic actuators. As a result, the structure of the forceps tip can be made simple, and the sterilization procedures required for surgery can be easily performed.

C. Network Emulator

The network emulator sets the communication latency between the master and slave, the variance in communication latency, out of order packets, bandwidth limiting, the rate of packet loss, and so forth.

D. Configuration Using Conventional Velocity-force Control

Bilateral control system configuration from conventional studies using IBIS is shown in Fig. 3. IBIS is driven pneumatically as described above, and the pneumatic control is performed by a control box. The master uses the universal haptic interface device Phantom Desktop from SensAble Technologies Inc., and is capable of position/attitude inputs with 6 DOF to the slave, as well as haptic presentation with 3 translational DOF to the operator. In this system, pneumatic control of the slave is performed according to the speed control commands input from the master side, and at the same time, the external force information inferred at the slave side is transmitted to the master side. UDP/IP communication is used to transmit speed commands and force information. By using bilateral communication, the operator can feel the external force from the IBIS. Note that this figure does not include a network emulator.

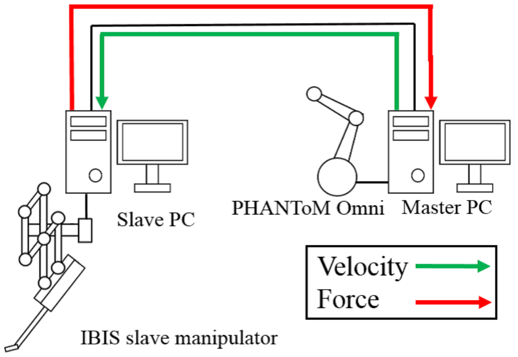


Figure 3. Configuration using conventional velocity-force control

E. Configuration Using Proposed Position-force Control

The position command system configuration used in this study is shown in Fig. 4. Position commands are transmitted from the master side to the slave side, and inferred external force information is transmitted from the slave side to the master side. Two PCs (Hondaset:rabbit and cow) are interposed between them for implementing the wave filter of the proposed method. And also the network emulator is inserted on the network.

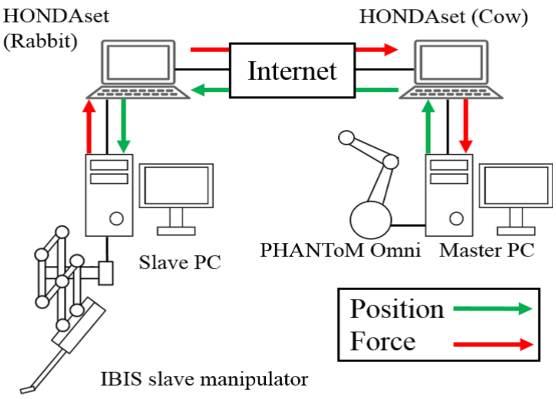


Figure 4. Configuration using proposed position-force control

A schematic diagram of the configured system is shown in Fig. 5. The PC performs the computation illustrated in the block diagram in Fig. 5, and eliminates control instability in environments where passivity is not achieved.

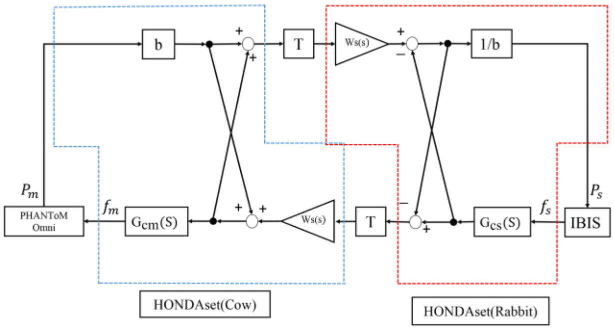


Figure 5. Block diagram of controller in Honda set

III. Master/Slave Frequency Characteristics and Wave Filter Design

The wave filter design method is based on linear control theory, and so the frequency characteristics of both devices were measured, and the various design parameters were estimated based on them. Strictly speaking, this system is nonlinear, but the parameters were designed for a linear system as an approximation, and the validity of the parameters will be confirmed through experiments using the actual machines.

A. Method for Determining the Frequency Characteristics

(1) Master

With the grip for the operator in a free state, the force information in the horizontal direction was input using a sine wave, the position information in the horizontal direction of the master device was output, and the response was measured in each frequency band. When the operator firmly grips the master, the master is nearly stationary, and so the output can be approximated as 0.

(2) Slave

As shown in Fig. 6, with IBIS, a washer in a vise was gripped with the forceps tip, thus immobilizing the forceps tip, and the position information in the horizontal direction was input using a sine wave. The force information in the horizontal direction estimated at the forceps tip was output, and the response was measured in each frequency band. When the slave is freely moved, the force output can be considered.

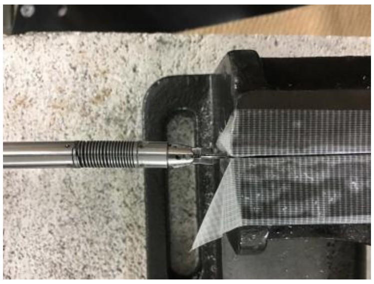


Figure 6. Experimental condition of frequency characteristics in slave side

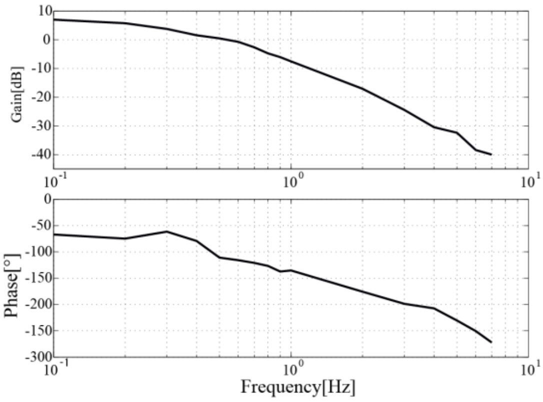
B. Frequency Analysis Results

(1) Master

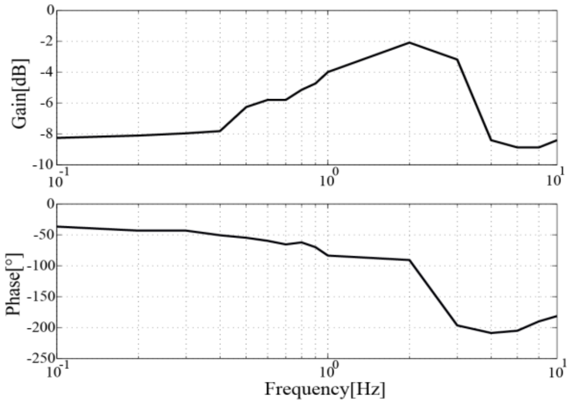
The obtained frequency response characteristics of the master are shown in Fig. 7(a). Here, input/output = 100 mm/1 N is defined as 0 dB. The master has frequency characteristics for force to position, and so the phase lag in the frequency band of 0.5 Hz or greater exceeds 90 deg, and passivity can be confirmed to be lost.

(2) Slave

The obtained frequency response characteristics of the slave are shown in Fig. 7(b). here, input/output = 10 N/10 mm is defined as 0 dB. The slave has the frequency characteristic of position to force with resonance at 2 Hz, and passivity can be confirmed to be lost in the frequency band of 2 Hz or greater. In addition, the phase lag in the low-frequency region is theoretically 0 degrees, but in actuality there is a time lag in the response due to the pneumatic cylinders, and so phase lag was confirmed to be present even at 0.1 Hz.



(a)Frequency characteristics of master

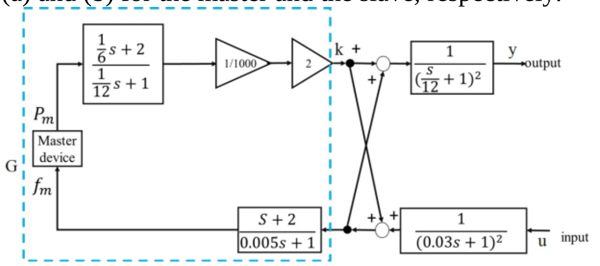


(b)Frequency characteristics of slave

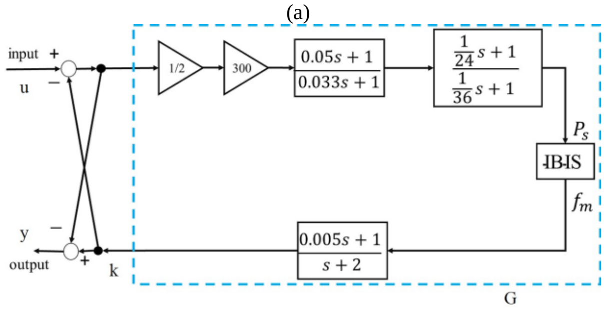
Figure 7. Bode diagram of master/slave

C. Wave Filter Design

Even if this master and slave which lack passivity are connected to a network circuit with communication latency' forming a closed loop, it is easy to imagine that the result can become unstable. Thus, the gain and compensators for the wave filter were designed to stabilize a closed loop while taking into consideration the various frequency characteristics. The resulting control block is shown in Fig. 8(a) and (b) for the master and the slave, respectively.



(a)



(b)

Figure 8. Block diagram of stabilized controller in PC

D. Frequency Characteristics in Experimental Units

To check the validity of the designed parameters, the frequency response characteristics between input and output in Fig. 9 were gathered while the proposed remote-control system was implemented. The experimental method for this was the same as that described above for each device. The theoretical values (dashed line) predicted during the design process in the previous section and the experimental results (solid line) are compared in Fig. 9. Based on the graph, the open loop gain can be confirmed to be no greater than 0 dB in all frequency bands, and so the proposed control method can be expected to stabilize a system based on the small-gain theorem.

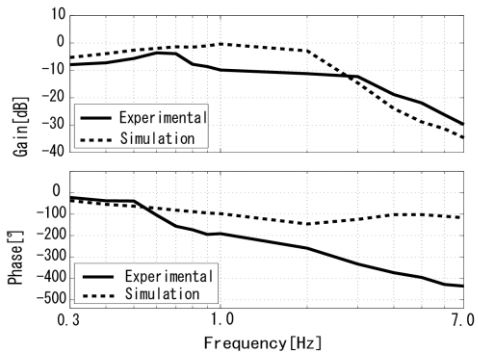


Figure 9. Block diagram of controller in PC

IV. Verifying the Efficacy of the Proposed Method

To confirm that the controller designed in Section 3 is valid, the network emulator was used to introduce communication latency of 20 ms, and an experiment was performed in which IBIS was operated through manual handling of the master. The experiment was performed under the conditions shown in Fig.10. Specifically, (1) a reciprocating movement was performed in the horizontal direction while there was nothing at the IBIS tip, (2) external force was applied while the forceps tip was restrained, and (3) the forceps tip was pressed against an object.

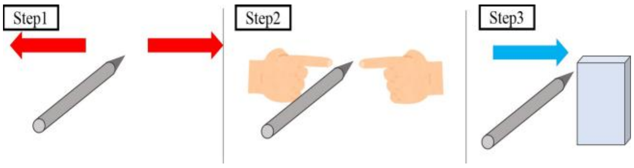


Figure 10. Illustration of experimental condition

The experimental results from condition (1) are shown in Fig. 11. The dotted line in the figure is the forceps tip position information instructed by the master to IBIS, and the solid line is the actual IBIS position. From these results, IBIS was confirmed to be performing stable movement according to the position commands of the master.

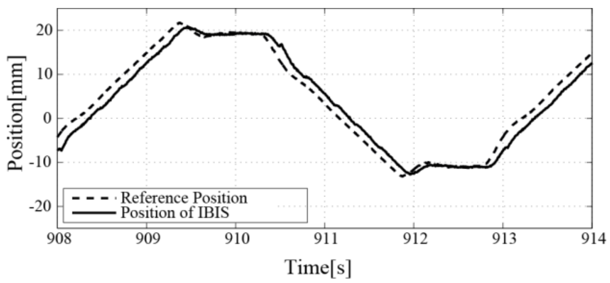


Figure 11. Comparison between reference position and actual position on time domain

In addition, the experimental results from conditions (2) and (3) are shown in Fig. 12. Condition (2) was from 40 s to 80 s, and subsequent to that was condition (3). In the upper panel of Fig. 12 (forceps tip position), in condition (2), although the command position to IBIS (dotted line) has slight fluctuations, it is steady at about -20 mm, and the actual forceps tip position (slid line) is at a different location. This is a phenomenon resulting from bending of the forceps when external force acts on them, and so this is a normal waveform. Although The same phenomenon could be confirmed under condition (3) as well, in this case, the operator commanded the more depressed position than actual forceps tip position.

In the lower panel of Fig. 12, the dotted line is the external force detected by IBIS, i.e., commanded force to the master, while the solid line is the actual force. Both values generally match, and so it was confirmed that the actual reaction force was appropriately conveyed to the operator. Also, under condition (2) in the upper part in Fig. 12, the slight fluctuations of the position command to IBIS from -20 mm were caused by the position of the operator's fingertips being shifted from a specific position due to the reaction force.

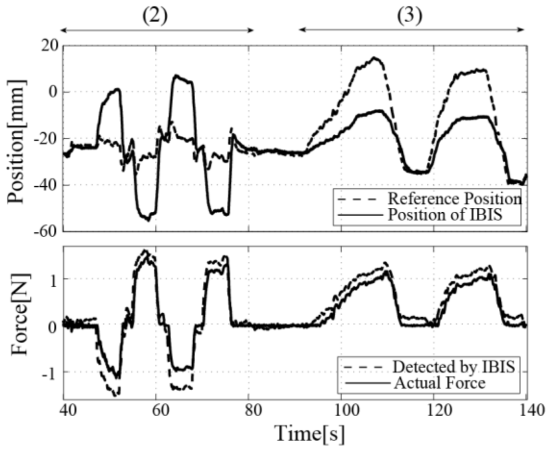


Figure 12. Transient position and force under experimental condition (2) and (3)

For confirmation, the experimental results from condition (3) in the state of not using the proposed wave filter— that is, the case where the master and IBIS are directly linked through a network emulator—is shown in Fig. 13. Since extremely severe fluctuations were observed, it was confirmed that the proposed method achieved stable remote control regardless of communication latency.

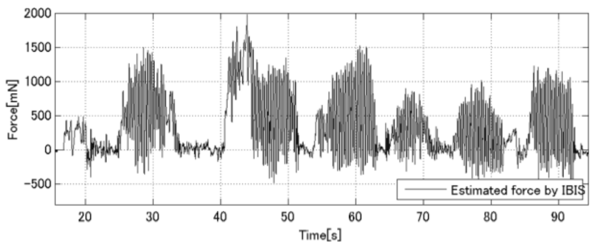


Figure 13. Instability without our proposed stabilized controller under communication latency 20ms

V. Conclusion

This study was performed in order to use position-force control for an IBIS surgical robot. First, the frequency characteristics of the surgical robot were measured, and it was shown that passivity was not achieved in the master or slave, and that direct connection would cause system destabilization. Next, a wave filter was designed for the proposed method based on the obtained frequency characteristics, and it was shown that implementing this method led to stabilization. Finally, a remote operation experiment showed that regardless of communication latency of 20 ms, the slave moved stably to the position instructed by the operator, and the reaction force detected by the slave could be transmitted to the operator.

At present, the stability verification has only been performed in the horizontal direction, and we plan to proceed to testing of movements with 3 DOF in the future.

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