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Asynchronous Force and Visual Feedback in Teleoperative Laparoscopic Surgical System

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***Abstract*— Force feedback systems have been developed to improve the user-friendliness of robotic surgery systems. In teleoperative surgery, one of the major problems is the delay of the transmission of the information from the operation site to the surgery site. The transmission delays of the control signal and force information are less than the that of the image signal. In many cases, the visual information is synchronized with the force information in order to avoid a time gap between them. In this paper, we propose that force information be presented earlier than the visual information. This approach reduces the damage to the organs in surgical operations even though there is a time gap between the delay of force information and visual information. In addition, we propose a method to present predicted force information to avoid damage to the organs due to time delays in teleoperative surgery. The liver can be treated with a contact force of less than 0.8 N and a grasping force of less than 1.1 N by applying the proposed method. The method can realize a teleoperative surgery without damaging the patient's organs.**

I. INTRODUCTION

Surgical assistance systems employing image processing and display technology have been developed. In laparoscopic surgery, surgical instruments are inserted through the small hole in the human body. The posture of an instrument is restrained by a trocar. Endoscopic surgery is therefore difficult, and a highly advanced technique is required. To conduct endoscopic surgery more easily, an assistance system needs to be developed.

The expectations of teleoperative surgery have increased with the improvement of networking structure. Studies on remote operative surgery have already been reported. Marescaux et al. performed a teleoperative surgery with ZEUS in 2001 employing a leased line between New York and Strasbourg[1]. Anvari et al. remotely operated on 21 patients using ZEUS and a connection between Bay and Hamilton (straight distance 400 km) in 2003 [2].

One problems in using teleoperative surgical systems is the delay in the transmission of information. In general, the transmission delay of the control signal of the manipulator is less than that of the image signal. This is because compression and expansion of the image signal in the CODEC system is time consuming. In [3], it is pointed out that the time-delay reduces the operability. The effect of delayed visual feedback on tele-operation is investigated in [4]. It is clarified that the incremental time delay of visual feedback is associated with the significant deterioration of the operability.

Another problem associated with teleoperative systems is the loss of the haptic information. The haptic sense is important to surgeons and it has been verified that the presentation of haptic information improves the operability of teleoperative surgery. Hannaford *et al*. reported that when force information is presented in a master-slave system, the force on the target is small, the operation time is less, and the number of the mistakes made in the operation was decreases [5]. It is recognized that force information plays a key role in the field of medicine, and force sensing have been researched.

Robotic surgery systems with force feedback have been developed worldwide. Tavakoli et al. listed the requirements of a surgical haptic interface as small backlash, small inertia, small friction, and a large force (more than 11 N) [6]. Tholey, *et al*. developed disposable forceps that could measure force with a strain gauge [7]. Rosen *et al*. developed a master-slave-type surgical instrument for endoscopy, which could present force information, and measured the mechanical property of an organ [8]. Wagner *et al*. decreased the force acting on an object by presenting force information [9]. They also showed that the force decreased when the gain of the force feedback was increased [10]. Kitagawa *et al*. realized an excellent suture by presenting force, visual, and hearing information using the da Vinci system [11].

In the force feedback systems used for teleoperative surgery, the force signals measured at the surgery site can be transmitted to the operation site much faster than image signals because the force information does not need to be compressed for transmission. This leads to a time difference between the display of force information and visual information.

Thompson *et al*. reported that the asynchronous feedback of an image signal and control signal increased maneuverability in a remote surgical operation since the controller of the system was stable in the case that the time delay of the control signal was small [12]. It was inferred that asynchronous force and visual feedback decrease performance in [12], but this has not been verified.

In this paper, we propose the use of asynchronous force and visual feedback in teleoperative surgery to improve safety. In our approach, force information is presented to surgeons earlier than visual information in teleoperative surgery. This will reduce damage to the organs of patients and improve the safety of operations. A second approach presents predicted forces to overcome the time delay of

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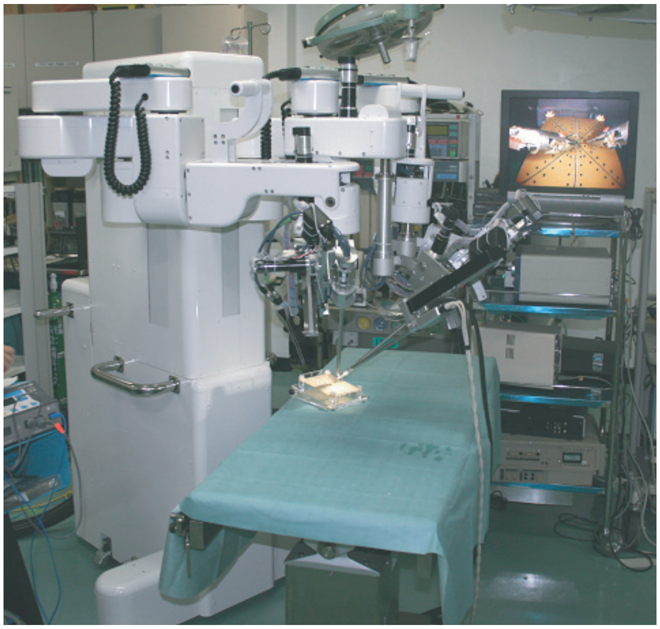

Fig. 1. Slave manipulator

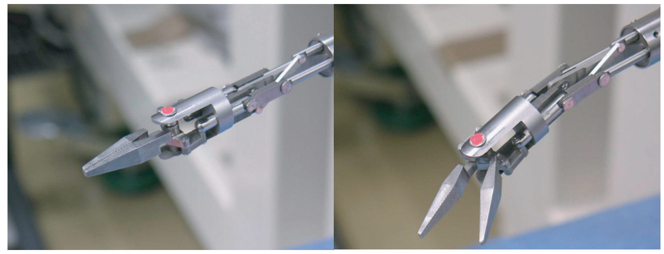

Fig. 2. Link type forceps

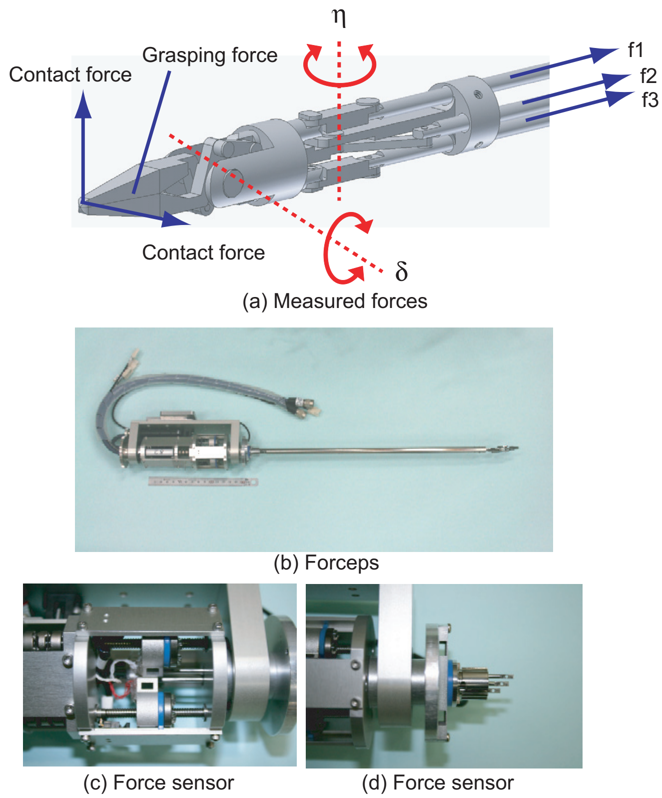

Fig. 3. Device to measure the force

teleoperative surgery.

This paper is composed as follows. In section II, the system setup and the concepts of our approaches are described. Asynchronized force and visual feedback and predictive force feedback are explained. An experiment to verify our method is described in section III, and the effect of the time difference between the display of force and visual information is clarified. In section IV, conclusions and future works are discussed.

II. MATERIALS AND METHODS

A. Hardware

The master manipulator is a system used by a doctor to measure the position and posture of instruments. Instructions are transmitted to the slave manipulator. The manipulator is composed of right and left arms, each having seven degrees of freedom-three translational axes, three rotational axes, and one grasping axis. A link mechanism ensures that the posture of the hand does not change during the translational motion, which reduces the computational complexity of the control .

The slave manipulator is a system that controls the instruments and endoscope according to the information transmitted from the master manipulator. The manipulator is composed of a base for support, an arm that determines the position of the instrument insertion and operates instruments such as forceps and an endoscope, and a tool that can be separated from the arm (Fig. 1).

Multi-axis forceps and an electric knife are available to the system. The multi-axis forceps have two bending axes-a rotational axis and a grasp axis. The forceps used in this paper are a link type (Fig. 2).

The contact and grasping forces need to be measured at the tip of the multi-axis forceps. The requirements for the force measurements are a rating of 10 N and resolution of 0.5 N for the contact force and a rating of 30 N and resolution of 0.5 N for the grasping force. In the force measurement, the cleanliness of the surgical manipulator is an important issue, and it is difficult to implement the force sensor at the tip of the manipulator because the manipulator is inserted into the body. The force at the tip of the forceps is thus calculated from the force that drives the shaft, which transfers the torque to the tip of the forceps. The force required to drive the shaft is measured with a sensor mounted on the forceps drive unit, which is arranged outside the body, and the force is thus calculated indirectly (Fig. 3).

When the bending angles of the forceps are η, δ in two directions, the relation between the force at the tip of the forceps F and the force at the driving shaft f is

$$F = K(\eta, \delta) \cdot f \tag{1}$$

where K is a proportionality coefficient calculated from the

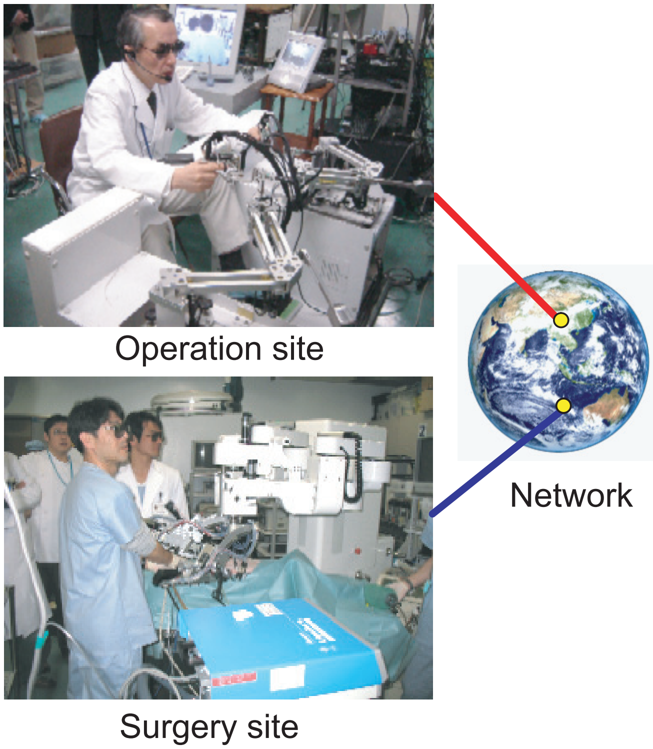

Fig. 4. Tele-operative laparoscopic surgical system

bending angles of the forceps. There is a proportional relation between the force at the driving shaft and the force at the tip of the forceps, and K is a function of the bending angle of the forceps. It was verified that the resolution of the force sensors is approximately 0.3 N, which meets our requirements.

B. Description of the time delay problem in tele-operative surgery

In general, a teleoperative surgical system comprises a master system at the operation site and a slave system at the surgery site (Fig. 4). The surgeon operates the master system at the operation site, and the actual operation is performed at the surgery site. The two sites can be connected by various networks such as LAN, ATM, and ISDN, and the robot control signal, images, voice, and other information are transmitted.

A problem encountered in teleoperative surgery is the delay in the transmission of information from the surgery site to the operation site. In the case of teleoperative surgery, the time delay that the operator experiences is calculated as

(Time delay) = (Transmission delay of control signal from the master site to the slave site) + (Response of slave) + (Transmission delay of image or force from slave to master)

Data of the time delay in teleoperative surgery are presented in [3]. Although the length of the time delay depends on the configuration of the network used for the operation, the transmission delays for image data ranged from 250 ms to 400 ms, and the transmission delays for the control signal ranged from 6 ms to 65 ms. Even though the transmission delays for the control signal for the slave manipulators are small, there are large transmission delays for image data from the surgery site to the operation site.

In the case of a surgical system in which there is force feedback from the surgery site to the operation site, the time difference between force data and image data should be considered. As mentioned above, the force signals measured at the surgery site can be transmitted to the operation site much faster than image signals because the force information does not need to be compressed for transmission. This leads to a time difference between force and visual information.

Thus, three kinds of transmission delay should be considered in teleoperative surgery: delays of the control signal, image signal, and force signal. (Fig. 5). Thus far, the time difference between the control signal and image signal has been investigated [12], but the time difference between the image signal and force signal has not.

C. Asynchronous force and visual feedback

We propose asynchronous force and visual feedback in a teleoperative surgical system and insist that force presentation earlier than the display of visual information reduces damage to organs of patients. The reason is that surgeons can deal with organs properly if the haptic information is available as early as possible.

In the case that all available information is delayed, surgeons have no means to deal with a quick response from the organs during the operation. This may cause serious damage to the organs.

Therefore, we believe that it is better to provide force information to surgeons as early as possible to improve the safety of operations even if the time difference between the display of force and visual information reduces maneuverability. In addition, the reduction of the maneuverability using this approach can be limited if the force feedback method is applied only to specific tasks.

D. Predictive force presentation

Even though the transmission delay of force information is relatively small, there is still a time delay between the movement of the operator and the force presentation This time delay may result in damage to organs since information of the contact with an organ is delivered to a surgeon with this time delay.

Thus, we propose that force information be presented with a prediction to overcome this time delay. To present force information without a time delay, it is necessary to predict the moment of contact with the organ.

To predict contact with an organ, a virtual area is introduced around the organ to detect the approaching instrument (Fig. 6). Assuming that the position and shape of the organ are known and fixed, a virtual area is set around the organ. At the moment the surgical instrument enters the virtual area, a virtual force is presented to the operator.

In this system, the positions of the instruments are estimated from kinematics and the virtual areas are defined in Cartesian coordinates.

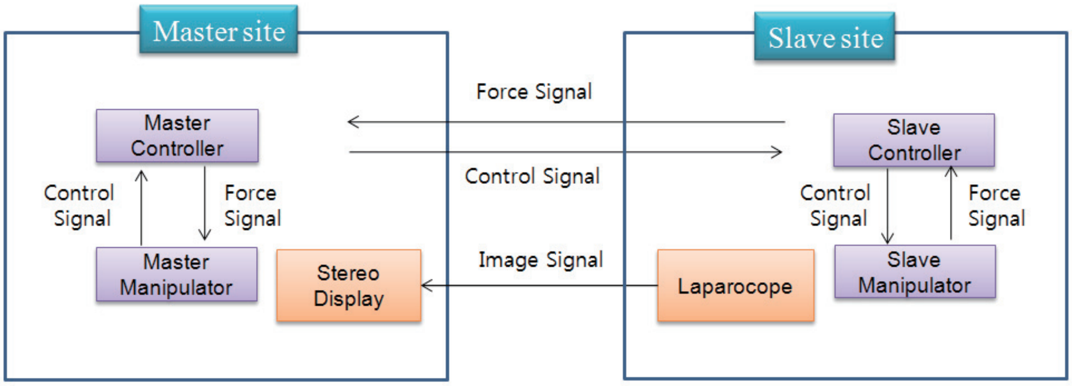

Fig. 5. Transmission of signals in tele-operative surgical system

This approach makes it possible to present force information earlier than the presentation of information of actual contact and thus the surgeon knows the moment of contact with organs with a smaller time delay. This will reduce damage to organs in teleoperative surgery.

III. EXPERIMENTAL RESULTS

A. Evaluation of earlier force presentation

1) Preliminary experiment: Experiments were conducted to investigate the effect of the time difference between force and visual feedback on the performance of the surgeon in teleoperative surgery. In these experiments, the transmission delay of the control signal was set to zero since the controller should be stable during the operation.

Two tasks were imposed on 10 examinees, including one doctor, and the force on the tip of the forceps and completion time of the task were measured. The first task imposed on examinees was to touch the four columns shown in Fig. 7(a) in sequence. The transmission delay of the image was set to 400 ms . The time difference between force and image information was varied from 0 to 400 ms.

The experimental results are shown in Fig. 7. The completion time did not depend on the time difference between the display of force and image information, but the force on the target decreased as the force was presented earlier. There was no reduction in the maneuverability with the earlier force presentation, with the operation time not changing. When the time difference between the display of the force and image information was 300 and 400 ms, the force on the target significantly reduced. The results show that the force on the target could be decreased while maintaining maneuverability. The method of presenting force information earlier than visual information will thus be effective for the safe treatment of organs in teleoperative surgery.

The second task imposed on examinees was to grasp a target and move it to a specified area. As shown in Fig. 8(a), a urethane tube was used as a target and set in the area of view. The multi-axis forceps with force sensor were mounted

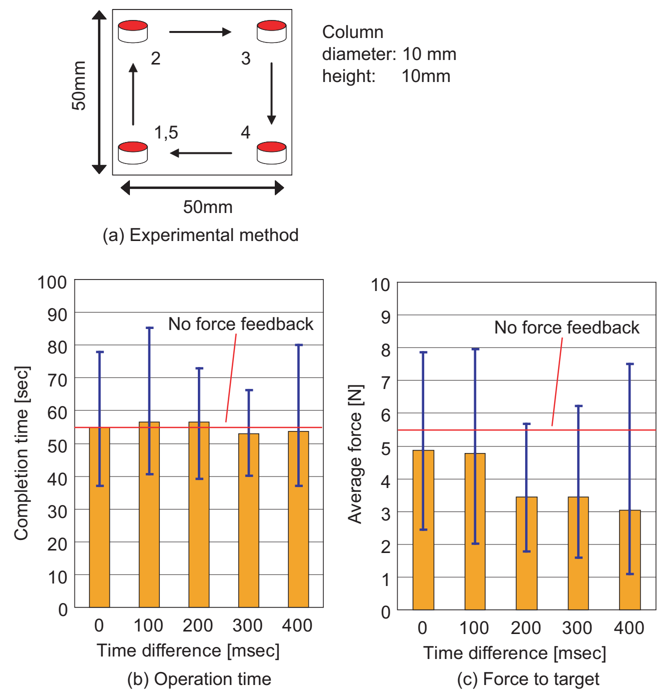

Fig. 7. Effect of earlier force feedback - contact force -

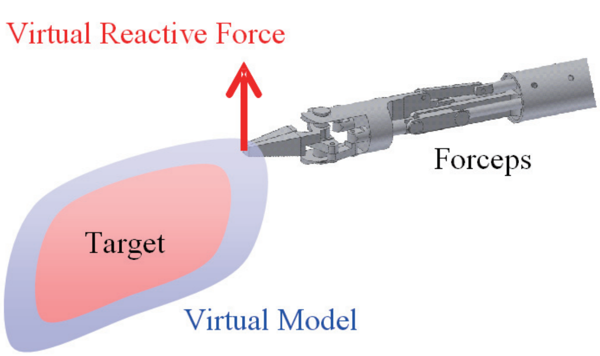

Fig. 6. Concept of predictive force feedback

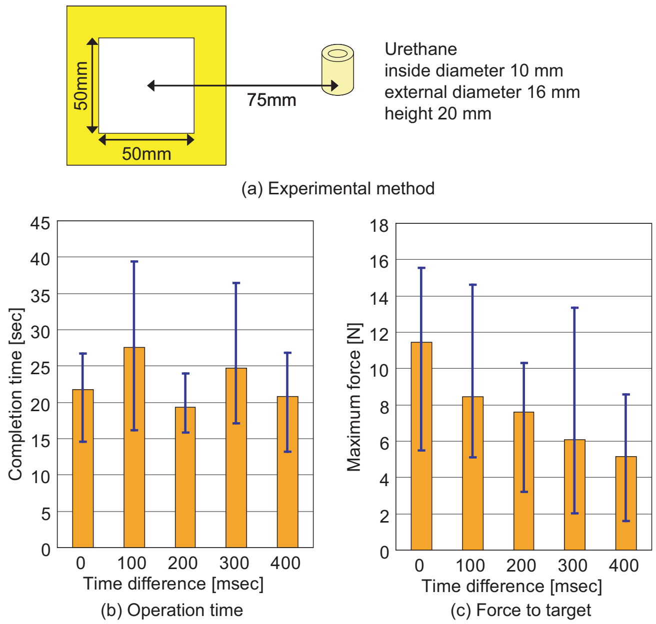

Fig. 8. Effect of earlier force feedback - grasping force -

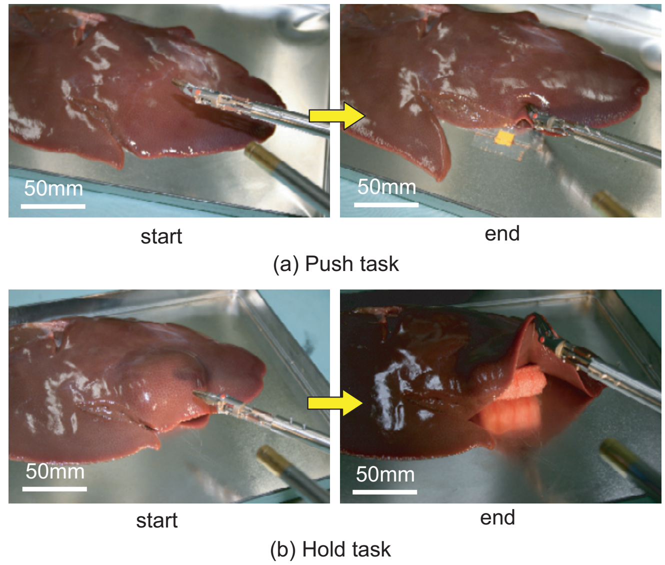

Fig. 9. Experimental method

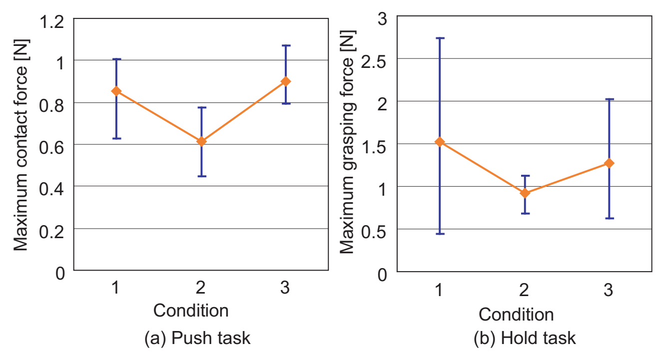

Fig. 10. Result of experiment

on the teleoperative surgical system. No influence of the time difference on the operation time was observed, as shown in Fig. 8(b). After the experiment, the examinees indicated that they were not aware of the earlier force feedback. The maximum force on the target decreased as shown in Fig. 8(c). When the time difference was 400 ms, the effectiveness of force presentation earlier than visual information was significant.

2) Experiment with pig liver: The pig liver was used as a target in this experiment, because it is one of the delicate organs that should be treated carefully in laparoscopic surgery. Tasks were imposed on one doctor, and the asynchronous force and visual feedback was evaluated. In this experiment, the transmission delay of the control signal was set to zero, the delay of the image signal was 400 ms, and the delay of the force signal was 100 ms. The task was to push the pig liver away and hold it up, which imitated the motion of retraction of the liver in surgery. The procedure of the experiment is shown in Fig. 9. The pushing task was regarded as completed when a 10 mm sponge set under the pig liver was observed. The holding task was regarded as completed when a sponge under the liver was observed.

The contact force was presented in the pushing task, and the grasping force was presented in the holding task. Each task was repeated in the order of (1) not using the proposed method, (2) using the proposed method, and (3) not using the proposed method, and each task was repeated five times. The experimental results are shown in Fig. 10. Using the proposed method, the maximum contact force was 0.8 N in the pushing task and the maximum grasp force was 1.1 N in the holding task. When the proposed method was not applied, the maximum force was 1.1 N for the contact in the pushing task and 2.7 N for the grasping in the holding task. The results show that the forces on the organ decreased with the application of the proposed method. Hence, asynchronous force and visual feedback may reduce damage to organs in teleoperative surgery.

B. Evaluation of predictive force presentation

An experiment to evaluate the force presentation with prediction was conducted. The task imposed on examinees was to touch the four columns shown in Fig. 11(a) in sequence. The force on the tip of the forceps was measured during the operation. The position and shape of the urethane tube was known and a virtual area was set around the urethane tube to predict the moment of contact. A virtual model that was larger than each column was prepared, and a reaction force of 1.0 N was presented to the operator when the forceps entered the virtual model (Fig. 11(a)). The virtual model has an external diameter of 20 mm and height of 20 mm. The results presented in Fig. 11 , show that the operation time decreased with the force presentation and the average force on the target decreased. This result implies that the proposed method for force feedback may reduce damage to organs in teleoperative surgery.

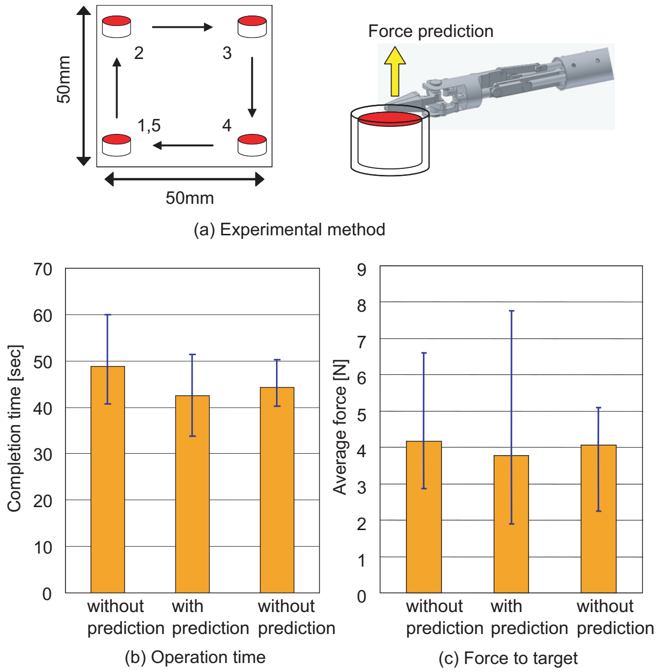

Fig. 11. Force feedback with prediction

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper, we proposed that force information be presented earlier than visual information in teleoperative surgery to improve safety. In addition, we proposed a method to predict forces in the operation. Experiments were conducted to verify our approaches. The results showed that our approaches reduce the damage to an object and the time required to complete specified tasks. Hence, asynchronous force and visual feedback do not result in the deterioration of the performance of the operator. This implies that the proposed method of force feedback improves the operability of the robotic system and safety of teleoperative surgery.

B. Future Works

We verified the effectiveness of asynchronous force and visual feedback in this study. Next, we will evaluate the effectiveness in a more practical situation considering tasks that are more complex and practical. In predictive force feedback, we assumed that the position and shape of the object are known and fixed when predicting the moment of contact with the object. We will further refine the method to predict force information. Prediction using visual feedback will allow the system to work adaptively.

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