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Operability Evaluation using an Simulation System for Gripping Motion in Robotic Tele-surgery

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Abstract— **Tele-surgery enables medical care even in remote regions and has been accomplished in clinical cases by means of special communication lines. To make tele-surgery a more common method of medical care, the surgical environment must be made available using public lines of communication, such as the Internet. Moreover, a support system during operation is required as the use of surgical tools occurs in a delayed environment. In our research, we focus on the operability of certain tasks conducted by surgeons during a medical procedure, and aim to clarify the optimum environment for robotic tele-surgery using a simulation. In the present study, we conducted an experiment to evaluate this operability using a simulation system consisting of a virtual slave manipulator, network simulator and an organ deformation calculator. The operability of a task to grip soft tissue was evaluated using a subjective workload assessment tool, NASA Task Load Index (NASA-TLX). Results indicate that operability changed over a delay of 200 ms in the environment during the experiment. Future studies will focus on clarifying a comfortable tele-surgical environment using the present evaluation of operability. In addition, an intra-operative assistance system will be constructed using a simulation.**

I. INTRODUCTION

ROBOTIC tele-surgery is an example of newly discovered medical aids, and the network technology introduced into surgical environments allows surgery to be performed from remote locations. Utilization of robotic tele-surgery would eliminate the disparity in medical treatments between different regions such as uneven distribution of environments in which patients can get a suitable medical treatment. Moreover, surgeons would be able to avoid the risk of infection. Robotic tele-surgery has gained approval in clinical trials, but is not yet accepted as standard medical practice. An example of an actual tele-surgical procedure is the Lindbergh operation in September 2001, where a Zeus(r) surgical system (Intuitive Surgical Inc.) was employed using a special communication line to reduce data delay and data loss that was instrumental in the success of the surgery [1][2]. Considerable difficulty has been encountered in recognizing robotic telesurgery as a standard treatment method, because of the following specific problems:

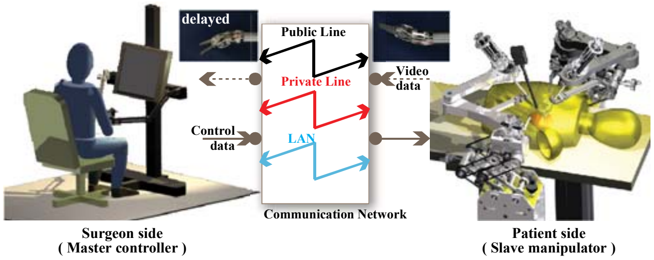

Fig. 1 Telesurgical environment. Note that this environment has three components: Master controller for a surgeon, communication network between a surgeon and a patient and a patient-side slave manipulator.

1) Lack of haptic sense from target organs
2) Limitation of visual information during surgery
3) Insufficient network quality of service (QoS)

To address problem (1), a bilateral control was studied for use on the network [3][4] as well as kinesthetic coupling [5]. To address problem (2), assistance using imaging systems such as MRI and CT was studied, and impedance matching was investigated in terms of positional control [6]. To stabilize the tele-surgical systems, fuzzy control [7], robust control [8], and efficiency improvement [9] have been employed. To address problem (3), in the field of tele-surgery research, a majority of the studies have focused solely on the time delay of the network [10][11]. Studies on network characteristics are focused on controlling and minimizing the time delay, and these systems are rather complex, as illustrated by the need to formulate predictive strategies within constrained dynamic systems [10], and prioritize control of the process through the introduction of dynamic scheduling [11]. Other researches have used special lines, such as satellite and exclusive lines, to secure wideband communication and restrain disorder of the data [12]. However, these solutions are inapplicable for standardizing surgical methods, since specific lines and related equipment must be prepared in the operating room. On the medical side, the influence on surgical performance such as difficulty of precise manipulation has been studied [13].

In the Lindbergh operation, the lines of communication had a significant impact on the success of the surgery. To make robotic tele-surgery feasible, the most important problem is to resolve differences between the hand movements of a surgeon and the motion of remote surgical tools. Construction of a surgical environment using a special communication line is useful for reducing these differences, but is very difficult. To make tele-surgery a common method of medical care, the surgical environment must be established as a system

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independent from communication lines that can effectively cope with differences in the hand movements of a surgeon and the motion of remote surgical tools generated by delay and loss of data.

II. MOTIVATION

A surgeon, dependent on the communication environment in robotic tele-surgery, encounters great difficulty when operating under conditions where data is delayed or lost. This problem of data delay and data loss increases the mental workload of a surgeon during a procedure, so easing of the workload is important. However, few studies have evaluated the intra-operative workload of a surgeon responding to the differences in data. In the present study, we focus on the workload of the surgeon and the influence of data delay and loss on that workload. The creation of a robotic tele-surgical environment is required to evaluate the workload, and depends on the temporal alterations in network conditions, line traffic and individual differences in the physical properties of internal organs. Therefore, we designed the simulation technology to meet the configurability and repeatability requirements of experimental conditions. A simulation of the tele-surgical environment allows the operability of medical procedures of the surgeon to be evaluated under several conditions. The evaluation of workload using a simulation is described in this paper. First, section III includes the description of the simulator, including three components used in the evaluation of workload. Next, the results of the evaluation are explained in Chapter IV.

III. SIMULATION SYSTEM FOR EVALUATION OF OPERABILITY

A. *Virtual slave manipulator*

A slave manipulator controlled using a material master manipulator in real-time was initially constructed to verify the control methods suited for robotic surgery and to reproduce surgical tools, such as forceps. Specifications of the system are listed in Table 1 and a configuration and system overview are shown in Fig. 3.

B. *Network simulator*

In robotic tele-surgery, data delay and data loss are not a homogeneous turbulence; these disorders are dependent on the communication environment in a surgical room and the volume of data being transmitted. From the results of network quality measurements [14], a simulation system for reproducing an optimum network environment was constructed. Data packets were able to arrive at the receiving side during each transmission cycle without delay and thus could be represented within a peer-to-peer environment. The interval for packets arriving at the receiving side differed from the cycles on the transmitting side, because the network was subject to latency and jitter. During construction of the simulator, latency and jitter were generated by including receiving intervals for packets on the receiving side. Moreover, packets caught up with the subsequent packets during the next unexpected delay; therefore, jitter was reproduced using the receiving function for short periods.

C. *Organ deformation calculator*

An organ deformation simulation requires real-time calculations to support a time-oriented environment. In the present study, the Mass-Spring-Damper (MSD) method was adopted as a calculation technique for reproducing dynamic characteristics such as deformation of internal organs to obtain more real-time quantitative calculations than possible using the Finite Element Method (FEM) [15]. A three-element model was adopted to represent visco-elasticity (the dynamic character of the organs) using the MSD method and a lattice-shaped model was developed as the prototype simulator.

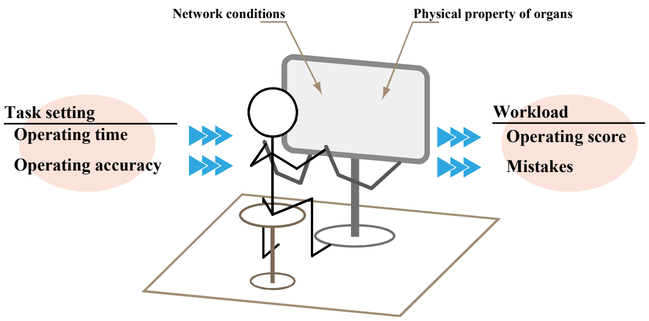


Fig. 2 Requirements of proposed simulation system. Operability must be evaluated with actual human use, and the simulation environment must reproduce several conditions within the tele-surgical environment.

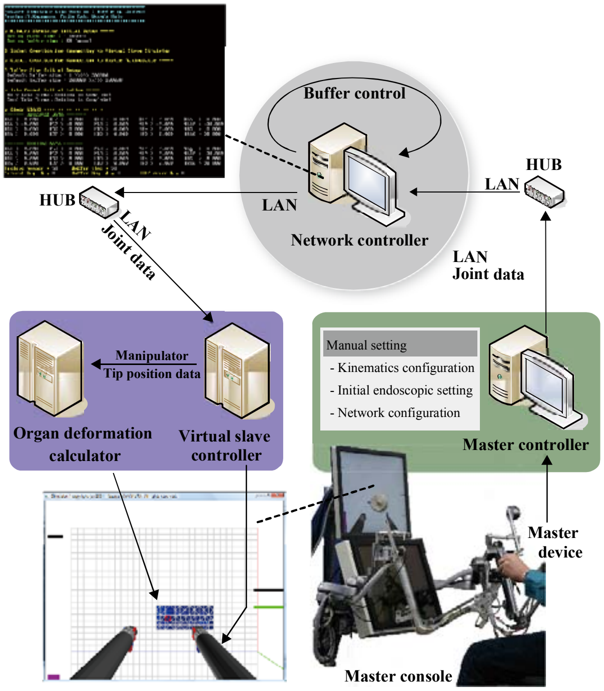


Fig. 3 Simulation system diagram. This diagram illustrates the configuration of the proposed system: the master controller, network simulator, organ deformation calculator and virtual slave manipulator.

TABLE I

Specifications of component of the proposed system

Element of proposed system	Master controller	Network simulator	Organ deformation calculator
OS	QNX	QNX	Windows
CPU	3.0 GHz	3.0 GHz	2.8 GHz
GPU	N/A	N/A	nVidia GeForce
Memory	512 MB	512 MB	2048 MB
DOF	6+1(gripper)	N/A	6+1(gripper)

IV. EVALUATION OF OPERABILITY

In robotic tele-surgery, the major portion of the workload still rests on the surgeon, and is a result of the difference between the hand movements of the surgeon and the motion of the remote surgical tools. From this perspective, quantitative evaluation of the workload is required for successful utilization and eventual construction of a robotic tele-surgery system. Moreover, this evaluation will lead to the establishment of the necessary skills for tele-surgical support. In our current research, we focus on workload as an indicator of operability. In the present study, we examined an operation requiring precise movements, such as stopping blood loss, and conducted the experimental procedure in a virtual space. Operability was evaluated using both subjective data (workload) and objective data (accuracy of task). This section describes the quantitative evaluation of workload using the three simulators.

A. Experimental method and results

In this experiment, the specification of the simulation system is shown in TABLE I. The target, assumed to be a hemorrhage, was a hexahedron shaped soft tissue model of a blood vessel, and was displayed at random positions within the virtual space. The hemorrhage was located at random positions on the soft tissue model, as shown in Fig. 4. The subjects operated the virtual slave manipulator in fixed time to accomplish some gripping tasks; the evaluation of operability was conducted using the simulated stopping of blood loss under delay conditions. In this experiment, the distance between the tip of the forceps and the target in the direction of the screen depth was displayed on the right side of the simulation viewer. Six subjects including one surgeon participated in this experiment, and the workload was evaluated using a subjective workload assessment tool, NASA Task Load Index (NASA-TLX) for each completed task [16]. The operation conducted in the environment without a delay in communication time (time delay condition: 0 ms) was imposed on the subject to ease the experience. The experimental setup is shown in Fig. 4. Mean workload is shown in Fig. 5, and the mean time for each task is shown in Fig. 6. The cross-section rate of the gripping area (gripping task error rate) calculated after the experiment to verify the accuracy of the task is shown in Fig. 7.

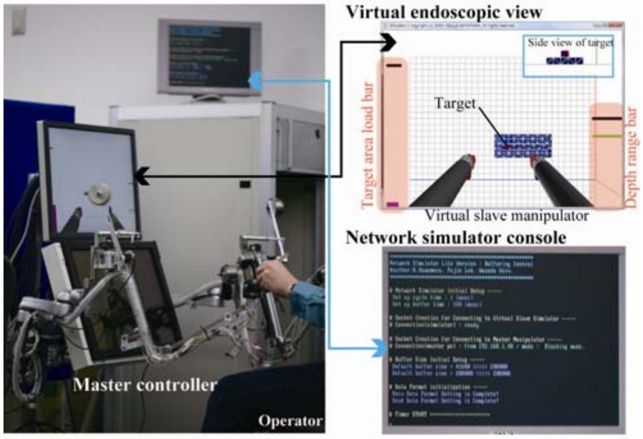


Fig. 4 Experimental setup. The experimental tools are shown during evaluation of workload. This setup includes a master controller, virtual slave manipulator, organ deformation calculator and network simulator.

TABLE II

Experimental Conditions

Parameters	Conditions
Range of delay time [ms]	0, 100, 200, 300, 400
Number of experiments	6 (per person / per delay condition)
Number of subjects	6
Evaluation method	NASA-TLX

B. Discussion

1) Mean workload

The workload score of each subject was high during long delay conditions of the communication time, as shown in Fig. 5. These results suggest that the workload of a task under a delay of 300 and 400 ms was heavier than workloads of tasks

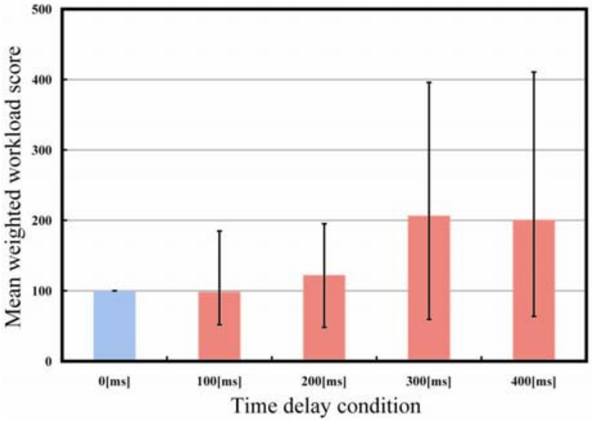


Fig. 5 Mean weighted workload scores. Data represent the mean workload scores for six subjects. The y-axis is the total workload score and the x-axis is time delay.

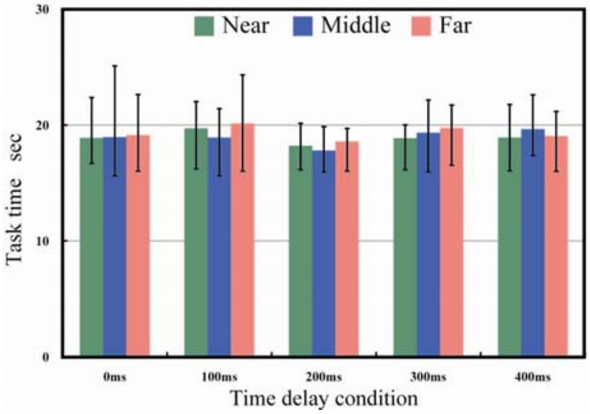
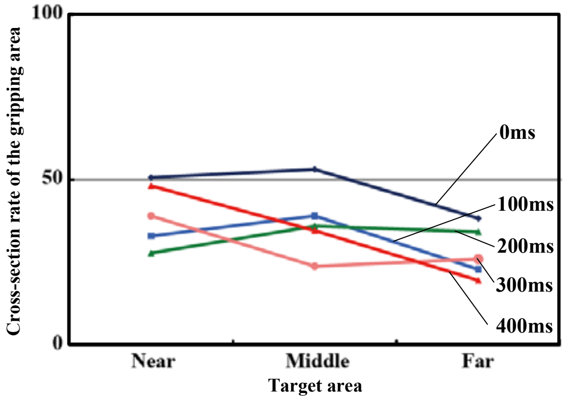
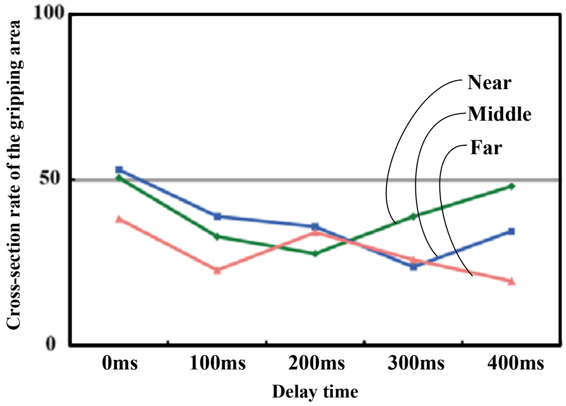


Fig. 6 Time to complete gripping task. Data represent the mean task time for all experiments. The y-axis is the task time and the x-axis is the time delay.



(A) Accuracy of Operation by target area



(B) Accuracy of Operation by time delay condition

Fig. 7 Results of the error rate. The vertical axis is the cross -section rate of the gripping area. (A) The x-axis is the distance from the center of the display. (B)The x-axis is the time delay.

conducted under 100 and 200 ms delay conditions. The workload changed significantly between a delay of 200 and 300 ms. On the other hand, a significant difference was not observed in the time required to complete the task, as shown in Fig. 6. The results indicate that the distance between the tip of forceps and the target in the direction of the screen depth were presented as supporting information in this experiment.

2) *Task time and error rate*

The results of task time and error rate in the direction of the screen depth showed little variation in the present study. Task time did not vary because the distance between the tip of forceps and the target was presented on the simulation viewer during the experiment. Moreover, it is possible that the lack of variation in the task time resulted from the absence of a force feedback function. The error rate resulted from the subject operating the virtual slave manipulator more widely when the target was displayed far apart from the tip of slave manipulator (Fig. 7(A)), and decreased as the position of the target varied during the experiment. The error rate also decreased as a result of careful operation of the slave manipulator and overshooting the target gripping area when the time delay was large (Fig. 7(B)). The ability to evaluate operability was confirmed using the simulation system.

V. CONCLUSION AND FUTURE WORK

The operability of completing a gripping task during a simulation of stopping blood loss was evaluated using NASA-TLX. Results indicate that workload changed significantly between a delay of 200 and 300 ms in the simulated environment; however, a significant difference was not observed in the time required to complete the task. Moreover, the error rate decreased as a result of careful operation and overshooting the target gripping area when the time delay was long. The ability to evaluate operability was confirmed using the simulation system, and future studies will evaluate operability of the system under varying conditions of comfort.

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