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Pneumatically Driven Handheld Forceps with Force Display Operated by Motion Sensor

Ryoken Miyazaki(1, Takahiro Kanno(2, Gen Endo(2, and Kenji Kawashima(2

Abstract—**Development of intuitive user interface of a dexterous forceps with wrist joint for minimally-invasive surgery (MIS) is important for reducing the surgeon's confusion and fatigue. In this paper, a wearable robotic forceps manipulator is proposed. By measuring the wrist attitude of the surgeon by a motion sensor and driving the forceps tip by actuators, intuitive operation is realized, compared with fully mechanical forceps. A compact and lightweight system is achieved since we adopt pneumatic actuators to drive the manipulator. In order to help the force sensing of the surgeon, the external force is measured from the air pressure and displayed in a visual way. Experimental comparison with a conventional handheld forceps and a teleoperation system is conducted and its results show the effectiveness of the proposed handheld forceps.**

I. Introduction

In recent years, the number of laparoscopic surgery has been increasing. During laparoscopic surgery, an endoscopic camera and several long tools are inserted into the patient's abdomen via small holes opened on the patient's skin. The surgeon conducts the operation such as cutting and suturing, viewing the image of the endoscopic camera. Since the incisions of the patient are smaller than conventional open surgery, recovery after the operation is earlier and thus the cost of hospital stay may be reduced.

However, advanced skills, originating from such new surgical procedures, are required for surgeons from the following factors. 1) It is impossible to approach the target from arbitrary angles since the motion of surgical tool is constrained at the insertion hole of the abdomen. In other words, only 4-DOF motions are allowed for surgical tools in the abdomen. 2) The operation is not intuitive because the motion of forceps tip and the human arm is opposite around the insertion point. 3) The surgeon is not able to feel the force because his/her hand and the tip of the forceps is separated about hundreds of millimeters.

It is necessary to develop a surgical tool which reduces the technical difficulty currently felt by surgeons. Development of handheld 4-DOF forceps and teleoperated surgical assist robot for laparoscopic surgery have been promoted all over the world [1-3]. Cambridge Endo developed a mechanical handheld forceps which enables the 4-DOF motion of gripper, 2-DOF flexible link, and rotation [4]. However, it is difficult to use this forceps as easily as surgical robot since the surgeon must apply a large force to its knob to bend the forceps tip.

Master-slave type surgical robot is an effective system to realize the intuitive laparoscopic surgery with multiple DOFs inside the abdomen, as if the surgeon's hand were inside the patient's body and directly manipulating the organs. The surgical robot "da Vinci" [5,6] developed by Intuitive Surgical Inc. is a master-slave type surgical robot, which can be intuitively operated [7] via the master console separate from slave surgical manipulators [8-10]. Though da Vinci is commercially successive, several problems still remain: Since the force sensing and feedback are not implemented, there is a risk of hurting organs or cutting suture threads by applying unnecessarily large force. Moreover, the system is too large and expensive for small hospitals without much budget and large operating rooms to introduce da Vinci. In addition, some doctors say that they want to conduct surgery nearby the patient so that they can directly monitor the conditions of the patients, which is difficult in master-slave teleoperation systems.

Haptic information is very important in surgery. Several works reported that haptic feedback to the operators in surgical robot systems contributes to accuracy and efficiency of operations [11-14]. Tadano et. al. developed a surgical robot system using pneumatic actuators with force sensing using air pressure [15,16]. However, the force required in laparoscopic surgery is about 0.5-2 N [17] and is similar to the resolution of the force sensing ability of the human hand (about 0.2-0.5 N). Thus force scaling, which magnifies the force information when displaying by the master arm, is necessary.

From the above discussions, very compact surgical robot with the function of display small reaction force of organs is needed for intuitive and efficient laparoscopic surgery. Jinno [18] et. al. developed a compact robotic forceps with a wrist joint. However, due to the weight of the drive unit including actuators, a support mechanism is required.

In this paper, we propose a wearable compact handheld forceps with the 2-DOF wrist joint. By using pneumatic actuators, which have high power-to-ratio, a compact and lightweight forceps is achieved. A motion sensor is adopted to measure the orientation of human wrist so that master-slave-like intuitive operation is realized. Since a non-contact sensor is used, a method to display the force information is required. The force is simply displayed visually.

The rest of this paper is as follows. Chapter 2 describes the overview of the developed system and a pneumatic driven forceps manipulator. Chapter 3 describes the position control system of the forceps manipulator and the master-slave control by capturing hand position using a motion sensor. Chapter 4 describes the methods of external force estimation and force display. Chapter 5 presents the experiment of block

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transfer by a medical student. Chapter 6 concludes this work.

II. Handheld forceps system

Figure 1 shows the proposed handheld forceps system. This system consists of a forceps manipulator unit, a mounting holder and a motion sensor. A master-slave control is implemented between the non-contact motion sensor and the robotic forceps with a 2-DOF flexible link mechanism. The surgeon mounts the holder on their arm and manually moves the rest 4-DOF. Target angle of the forceps tip is calculated from the hand position and sent to a computer controlling the forceps.

A. Pneumatic Forceps Manipulator

The forceps manipulator shown in Fig. 2 in the system is a pneumatically-driven forceps with flexible joints developed in our previous work [19]. It consists of a driving unit and a tip unit. The driving unit consists of 4 super-elastic wires, 4 pneumatic cylinders, and 4 potentiometers measuring cylinder displacement. This unit drives the flexible joint of forceps tip through the wires. Output of the flexible joint is about 5N [19]. The gripper is driven by a small cylinder inside its base, without wire-transmission mechanism [20]. There are no interference between bending motion and opening/closing of the gripper. Pneumatically-driven forceps has several advantages for pneumatic driven forceps: compactness, less heating, cleanliness, and future MRI-compatibility. In addition, using high back-drivability of pneumatic actuators, it is possible to estimate the external force on the forceps tip.

B. Mounting Holder

The mounting holder shown in Fig.3 is attached to the surgeon's arm. Two stainless-pipe arms from the holder mount the forceps manipulator and the motion sensor. The weight of the holder itself is 0.35 kg, and the total weight including the forceps and the sensor is 0.60 kg. Although this weight is heavier than the conventional forceps, the fatigue of the surgeons is not too high because it is mounted on the surgeon's arm. It is designed reflecting the comments from a surgeon so that the axes of human arm and the forceps are on the same line. It is possible to mechanically feel the reaction force of the forceps tip.

C. Motion Sensor

Leap Motion [21], a motion sensor shown in Fig.4, captures the posture of the surgeon's hand. This sensor is capable of sensing hands at 120 fps and with resolution of 0.01 mm. The origin of the sensor coordinate locates at the center of the sensor and obtains position and orientation of each joint of fingers, the palm, and the wrist. We experimentally confirmed that the sensor is capable of capture the hand even when covered with a transparent sterilized sheet, required in operation rooms.

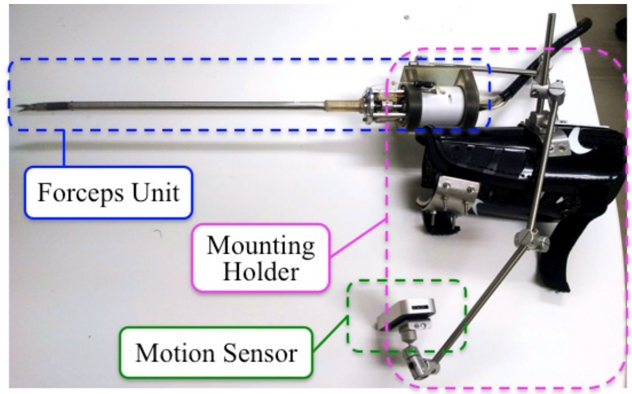

Figure 1. Proposed handheld forceps.

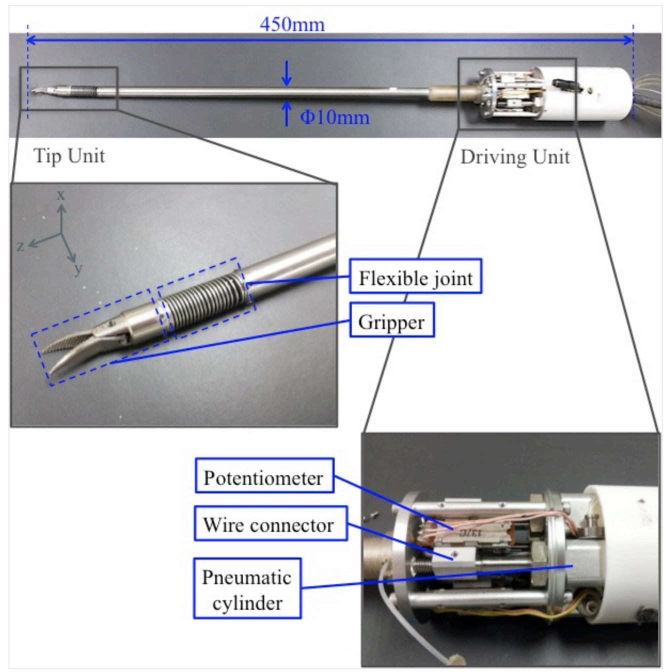

Figure 2. Pneumatically-driven forceps manipulator.

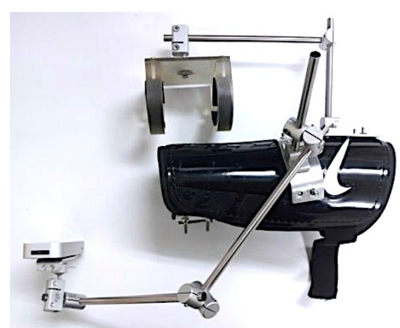
Figure 3. Mounting holder

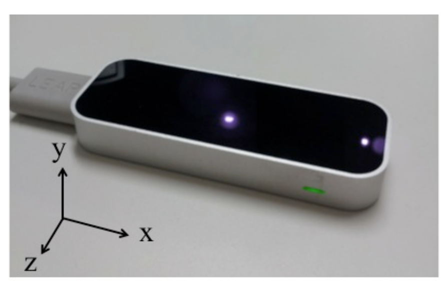

Figure 4. Motion sensor.

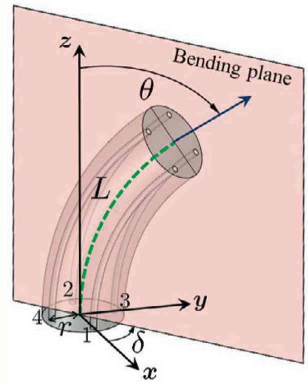

Figure 5. Nomenclature and a reference frame on the flexible joint.

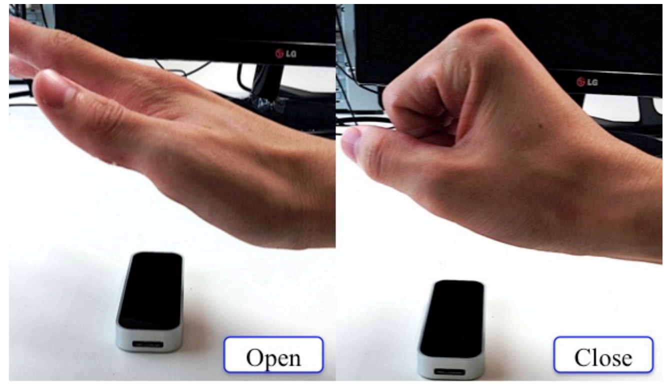

Figure 6. Hand gripping motion.

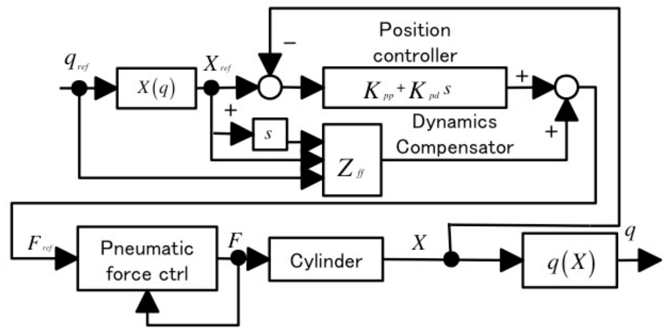

Figure 7. Block dialog of the control system of the forceps.

III. Position Control

The position control system of the forceps manipulator and the master-slave control by capturing hand position using a motion sensor is described in this section. This handheld forceps is a kind of master-slave system in which the master is a motion sensor and the slave is a forceps tip. Target position of the slave manipulator is calculated from the sensor data, and it is sent to the PC controlling the forceps. Slave manipulator has 3-DOF, bending angle θ ($0<\theta<\pi/2$) and bending direction δ ($-\pi<\delta<\pi$), and gripper open/close state (0 or 1). Definitions of these variables are shown in Fig.5.

A. Calculation of Reference Position

First, the positions of wrist and palm of the operator are captured using the motion sensor. The relative position of the palm from the wrist is transformed to the direction so that the orientation of the hand and that of the forceps tip correspond.

The bending angle θ and direction δ are calculated as follows:

$$\theta = \beta \times \cos^{-1}\left(\frac{|Pz - Wz|}{h}\right) \tag{1}$$

$$\delta = \tan^{-1}\left(\frac{Py - Wy}{Px - Wx}\right) \tag{2}$$

$$h = \sqrt{(Px - Wx)^2 + (Py - Wy)^2 + (Pz - Wz)^2} \tag{3}$$

where *Px, Py,* and *Pz* are the positions of the palm in sensor coordinates. *Wx, Wy,* and *Wz* are the positions of the hand wrist in the sensor coordinates. The movable range of the human hand is smaller than that of the forceps tip. We introduce a scaling factor $\beta = 1.1$ to magnify the human wrist motion.

The hand position data are smoothed to reduce noise by a simple moving average of 10 frames (about 0.082 sec). The gripper state of the forceps is determined by the hand grabbing state (Fig.6), which can be obtained via Leap Motion SDK. In order to prevent chattering, gripper state changes only when the hand grabbing state keeps the same value for 0.17 s after state change.

B. Forceps Manipulator Control System

Fig.7 shows the block diagram of control system of the forceps manipulator.

Reference values of θ and δ are given by eq. (1) and (2), which are transformed to the positions of pneumatic cylinders by solving inverse kinematics. As for inverse kinematics of the flexible joint, please refer to [19].

PD-based position controller is implemented. Target driving force of the pneumatic cylinders are calculated as the sum of the feedback terms and the feedforward terms to compensate for the dynamics such as frictions [18]. K_{pp} is the proportional gain set to 5.0 N/mm and K_{pd} is the differential gain set to 0.04 Ns/mm.

In order to follow the target driving force in such a pneumatic system, the error between target pressure and measurement values from pressure sensors are feed back to the controller and PID control is implemented. The control inputs are the voltage of servo valves. Control interval of the system is 1 ms, which is fast enough to drive and control the position of the forceps manipulator.

C. Experimental Results

Control performance of the proposed system is confirmed in this section. Figs.8 and 9 show the bending angle θ and direction δ respectively. The blue line is the target value and the red line is the measured value by the potentiometer. From the experimental result, the response of the bending angle and direction is confirmed to be fast enough.

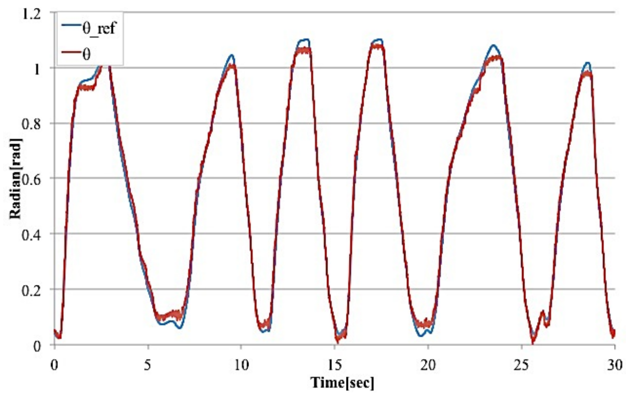

Figure 8. Position control performance (bending angle).

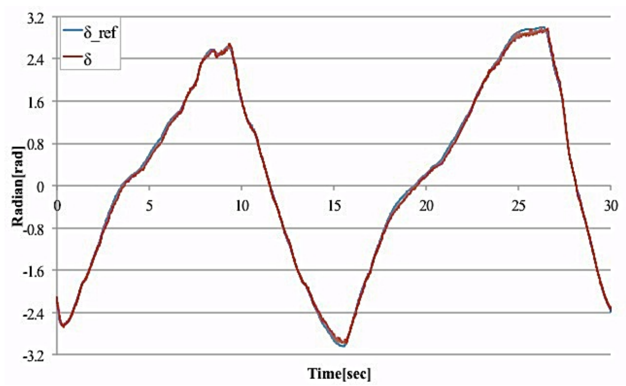

Figure 9. Position control performance (bending direction).

IV. EXTERNAL FORCE ESTIMATION AND FORCE DISPLAY

Due to the intervening mechanism between the surgeon's hand and the organ, force sensing ability of the surgeon in laparoscopic surgery degrades compared with open surgery. Since the forceps manipulator in this work has the ability of force estimation as fine as human hand, we consider enhancing the force sensing of the surgeon by designing a simple force display.

Minimum detectable external force of the pneumatic forceps is 0.25 N [19]. This deadband is mainly caused by the friction of wire-transmission mechanism and the resolution of force estimation is smaller if the force is larger than 0.25 N.

Surgeons always view the image from endoscopic camera during surgery and force value can be presented by drawing some information near the display of the endoscopic image. An appropriate method of showing the force value, however, should be designed. It is difficult for surgeons to read numerical value or graph instantaneously. Thus we implemented a force display using the color. This method displays the small reaction force from organs less than 2.0 N, which is difficult to be felt by surgeons. Larger force than 2.0 N is not displayed because the operator can physically feel it due to the direct coupling of the human arm and the forceps manipulator.

In addition, in order to avoid hurting organs by the forceps, control gain is dynamically changed when the forceps is in contact with environment. The gain is reduced when the contact force is large as described later.

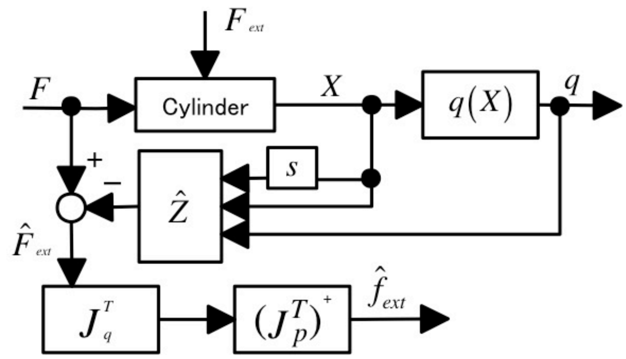

Figure 10. Block dialog of external force estimation.

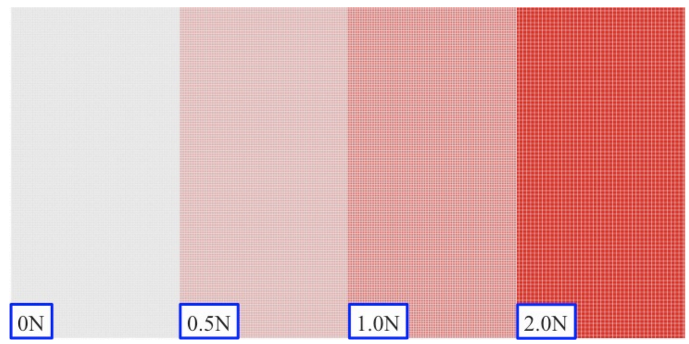

Figure 11. Displaying the external force visually.

A. *Estimating External Force System*

Fig.10 shows the block dialog of the external force estimator [19]. The external force components can be estimated by subtracting the mechanical impedance from the total cylinder driving force. The mechanical impedance contains coulomb and viscous friction in wire-transmission mechanism and the spring force of the flexible joint. Then the subtracted value is converted to the force of the forceps tip using the Jacobian matrix which describes the relationship between the cylinder velocity and the angular velocity of the forceps tip.

B. *Force Display in the Visual Way*

In order to display smaller force than the operator's perceptional limitation, a force display using a color is proposed. In the proposed method, force between 0 N and 2 N is represented by color determined by the following:

$$S_{\text{disp}} = \frac{255}{2}\left|\hat{f}_{ext}\right|, \qquad (4)$$
$$\left|\hat{f}_{ext}\right| = \sqrt{(RFx)^2 + (RFy)^2 + (RFz)^2},$$

where $0 \le S_{\text{disp}} \le 255$ is the saturation (vividness) of the color. Therefore, the larger this value, the more vivid color is displayed. *RFx, RFy,* and *RFz* are the external force in each direction. Estimated force is sent from the forceps controller to a PC for displaying the result of eq. (4) via the UDP communication. Fig.11 shows the example of the force display when the force is 0 N, 0.5 N, 1 N, and 2 N. When the external force is larger than 2 N, the saturation is defined as $S_{\text{disp}} = 255$.

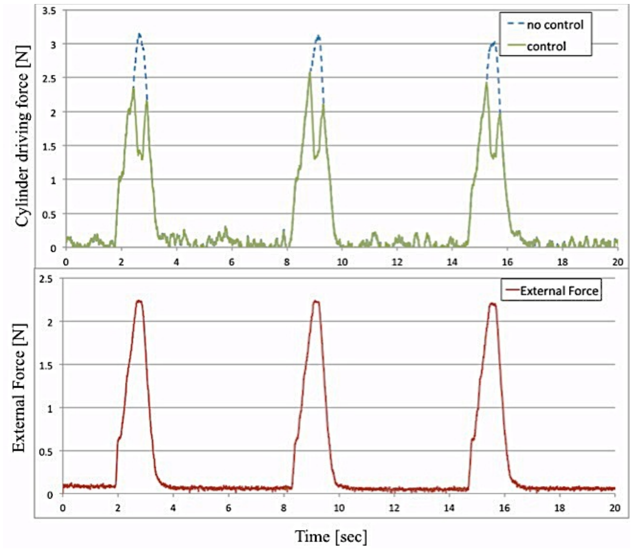

Figure 12. Cylinder driving force and external force.

C. Estimating External Force System

In order to avoid damaging the organs by applying unnecessarily large force, the proportional gain of the position control is dynamically changed according to the external force. When external force is larger than 2.0 N, control gain K_{pp} is adjusted as follows:

$$\overline{K_{\mathrm{pp}}} = K_{\mathrm{pp}} - |\hat{f}_{\mathrm{ext}}|, \tag{6}$$

where $\overline{K_{\mathrm{pp}}}$ is the modified proportional gain. The lower diagram of Fig.12 represents the external force. The upper diagram of Fig.12 shows the cylinder driving force of the PD control. The green line shows the result using the proposed control method and the blue dotted line shows that without using the method. It is confirmed that the cylinder driving force is reduced according to the external force.

V. Evaluation Experiment

We conducted experiments to compare the proposed interface with existing ones. We compared the following tools: 1) Conventional forceps in both hands. 2) Teleoperated surgical robot [22]. 3) The proposed system on the right hand and normal forceps on the left hand. Each experimental setup is shown in Fig. 14. Haptic devices (3D Systems Inc. PHANTOM Desktop) is used as master arms for teleoperation. The forceps tip of the proposed system is limited to 1-DOF in this experiment in order to reduce the effect of measurement noise. We adopted the block transfer task, which is a standard training task for laparoscopic surgery. Dexterity Block (Fig.15) by VTi medical Inc. is set in a drybox in which forceps and endoscopic camera are inserted. Endoscopic camera is a 3D endoscope camera of Olympus Inc.

The time to finish the following task is measured: 1) Pick a triangle block on the left side by the left forceps. 2) Pass the block to the right forceps. 3) Place the block on the right side with the corresponding number. 4) Do the same procedure for five blocks.

Fig.16 shows the result of the experiments. Average and standard deviation of task completion time are shown. The completion time using the surgical robot was the fastest. The time was almost the same with conventional forceps and with the proposed system. The advantage of proposed system is not confirmed only from the task completion time. However, as for standard deviation, the surgical robot and the proposed system have smaller values than conventional forceps. The standard deviation was almost the same with surgical robot and with the proposed system. From above, the proposed system can be operated as stably as the surgical robot. In addition, the forceps tip was limited to 1-DOF in this experiment. The completion time may be shorten if the tip of forceps has 2-DOFs.

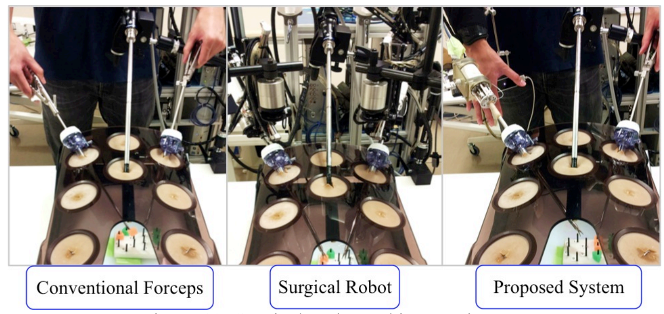

Figure 13. Surgical tools used in experiments.

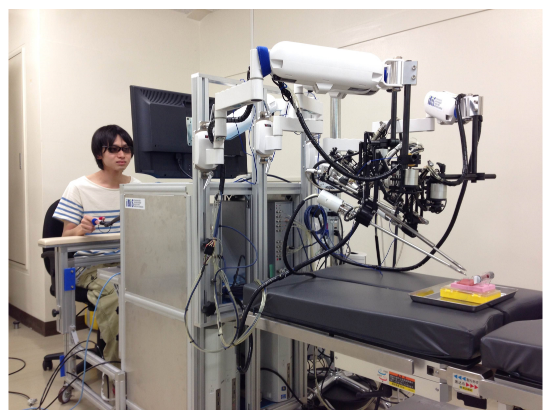

Figure 14. Teleoperated Surgical Robot.

Figure 15. Dexterity Block.

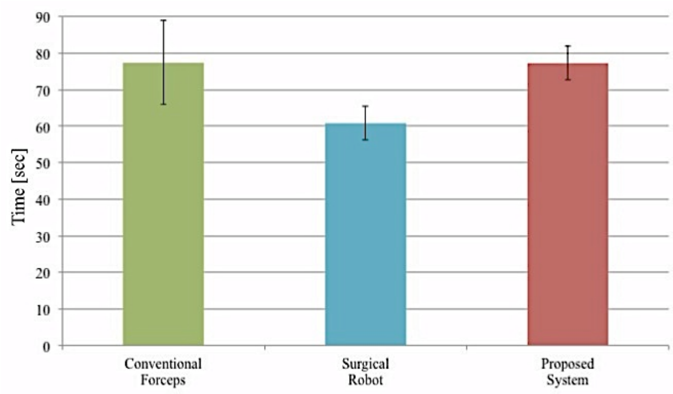

Figure 16. Experiment result.

VI. CONCLUSION

We proposed a wearable compact handheld forceps with 2-DOF robotic joint operated by a motion sensor. We adopted pneumatically-driven forceps with high power-to-weight ratio in order to reduce the weight. A master-slave control between the motion sensor and the pneumatic wrist joint is implemented. A motion sensor is used as the master interface so that the system is lightweight without link mechanism.

In addition, mechanical force transmission to the surgeon may not be sufficient in laparoscopic surgery because the laparoscopic surgery requires as fine force as the sensing ability of human hand. To overcome this problem, we made use of the reaction force estimation function of pneumatic forceps manipulator with high back-drivability. A system to visually display small force is constructed. In order to avoid hurting organs by the forceps, we also implemented a control method, which reduces the proportional control gain according to the reaction force.

We conducted experiments to compare the proposed interface with conventional forceps and a teleoperated surgical robot by the block transfer task. The result could not confirm the advantage of proposed system only from the working time. However, the standard deviation of task completion time using the proposed system is similar to the robot and the surgeon can conduct operations as stably as teleoperated robots.

Future works are the improvement of control performance in 2-DOF motion. In addition, experiments by surgeons with practical tasks using biological model, and experiments using the proposed hand-held system in both hands.

REFERENCES

[1] B.L. Davies, “A review of robotics in surgery,” Journal of Engineering in Medicine, Vol. 213, pp. 129-140, 2000.
[2] Russell H. Taylor and Dan Stioianovici, “Medical robotics in computer-integrated surgery,” IEEE Transactions on Robotics and Automation, Vol. 19, No. 5, pp. 765–780, 2003.
[3] Garth H. Ballantyne, Jacques Marescaux, and Pier Cristoforo Giulianotti, editors, “Primer of Robotic & Telerobotic Surgery,” LIPPINCOTT WILLIAMS & WILKINS, 2004.
[4] http://cambrigeendo.com/.
[5] http://www.intuitivesurgical.com/.
[6] G.S. Guthart and J.K. Salisbury Jr, “The intuitiveTM telesurgery system: overview and application,” In Robotics and Automation, 2000. Proceedings. ICRA’00. IEEE International Conference on, Vol. 1, pp. 618–621. IEEE, 2000.
[7] A.R. Lanfranco, A.E. Castellanos, J.P. Desai, and W.C. Meyers, “Robotic surgery: a current perspective,” Annals of Surgery, Vol. 239, No. 1, p. 14, 2004.
[8] J. Arata, H. Takahashi, P. Pitakwatchara, S. Warisawa, K. Tanoue, K. Konishi, S. Ieiri, S. Shimizu, N. Nakashima, K. Okamura, Y. Fujino, Y. Ueda, P. Chotiwan, M. Mitsuishi, and M. Hashizume, “A remote surgery experiment between japan and thailand over internet using a low latency codec system,” In Robotics and Automation, 2007 IEEE International Conference on, pp. 953 –959, april 2007.
[9] H.H. King, K. Tadano, R. Donlin, D. Friedman, M.J.H. Lum, V. Asch, Cong Wang, K. Kawashima, and B. Hannaford, “Preliminary protocol for interoperable telesurgery,” In Advanced Robotics, 2009. ICAR 2009. International Conference on, pp. 1 –6, june 2009.
[10] K. Onda, T. Osa, N. Sugita, M. Hashizume, and M. Mitsuishi, “Asynchronous force and visual feedback in teleoperative laparoscopic surgical system,” In Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on, pp. 844 –849, oct. 2010.
[11] C.R. Wagner, N. Stylopoulos, and R.D. Howe, “The role of force feedback in surgery: analysis of blunt dissection, In 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Vol. 2002. Citeseer, 2002.
[12] C.R. Wagner, N. Stylopoulos, and R.D. Howe, “The role of force feedback in surgery: analysis of blunt dissection, In 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Vol. 2002. Citeseer, 2002.
[13] D. Morris, H. Tan, F. Barbagli, T. Chang, and K. Salisbury, “Haptic feedback enhances force skill learning,” In EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint, pp. 21–26. IEEE, 2007.
[14] James C. Gwilliam, Mohsen Mahvash, Balazs Vagvolgyi, Alexander Vacharat, David D. Yuh, and Allison M. Okamura, “Effects of haptic and graphical force feedback on teleoperated palpation,” In IEEE International Conference on Robotics and Automation, pp. 677–682, 2009..
[15] K. Tadano and K. Kawashima, “Development of 4-dofs forceps with force sensing using pneumatic servo system,” In IEEE International Conference on Robotics and Automation, pp. 2250–2256, 2006.
[16] K. Tadano and K. Kawashima, “Development of 4-dofs forceps with force sensing using pneumatic servo system,” In IEEE International Conference on Robotics and Automation, pp. 2250–2256, 2006.
[17] Masaya Kitagawa, AllisonM. Okamura, BrianT. Bethea, VincentL. Gott, and WilliamA. Baumgartner, “Analysis of suture manipulation forces for teleopera- tion with force feedback,” Takeyoshi Dohi and Ron Kikinis, editors, Medical Image Computing and Computer-Assisted Intervention — MICCAI 2002, 第 2488 巻 of Lecture Notes in Computer Science, pp. 155–162. Springer Berlin Heidelberg, 2002.
[18] Nobuto Matsuhira, Makoto Jinno, Toyomi Miyagawa, Takamitsu Sunaoshi, Take- hiro Hato, Yasuhide Morikawa, Toshiharu Furukawa, Soji Ozawa, Masaki Kita- jima, and Kazuo Nakazawa, “Development of a functional model for a master-slave combined manipulator- for laparoscopic surgery,” Advanced Robotics, Vol. 17, No. 6, pp. 523–539, 2003.
[19] Daisuke Haraguchi, Kotaro Tadano, and Kenji Kawashima, "Development of a Pneumatically-Driven Forceps Manipulator Using a Flexible Joint," *Symposium on Fluid Power*. Vol. 2011.
[20] Kotaro Tadano, Kenji Kawashima, Kazuyuki Kojima, and Naofumi Tanaka. De- velopment of a pneumatic surgical manipulator ibis iv. Journal of Robotics and Mechatronics, Vol. 22, No. 2, pp. 179–188, 2010.
[21] https://developer.leapmotion.com/.
[22] Kotaro Tadano, Kenji Kawashima, “Development of a Master Slave System with Force-Sensing Abilities Using Pneumatic Actuators for Laparoscopic Surgery,” Advanced Robotics, Vol.24, No.12, pp.1763-1783, 2010.