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Pneumatically-Driven Hand-held Forceps with Wrist Joint Operated by Built-in Master Controller

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***Abstract*— In this research, a compact surgical robot system is developed by using the existing skill of surgeons. The proposed system consists of forceps manipulator with a 2-DOF wrist joint and a 4-DOF passive holder supporting the forceps manipulator. The forceps manipulator is operated by a built-in master controller, integrated in the proximal side of the forceps. A master-slave type wrist joint, in which the master is integrated the hand-held forceps itself, is proposed. Moreover, intuitive operation is realized by an active transformation from the surgeon's wrist-rotation to the tip-rotation using an IMU and the pneumatic cylinders. The system provides surgeons with a compact system and an intuitive operation. Finally, we experimentally confirmed the joints and the tip rotation controls are satisfactory.**

***Index Terms*— Surgical Robot, Pneumatic Driven, Handheld Robot, Laparoscopic Surgery.**

I. INTRODUCTION

Laparoscopic surgery is one of the minimally invasive surgery procedures. An endoscope and several long forceps are inserted into the patient's abdominal cavity from small holes made on the skin. Though the postoperative recovery is earlier than conventional open surgery, superior skills are required for surgeons, 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-degree of freedom (DOF) motions are allowed for surgical tools in the abdomen[1,2].

A surgical robot enables an intuitive and dexterous operation in the abdominal cavity. It is generally a master-slave type robot and a surgeon operates the remote slave arm with a wrist joint via the master console. Several robotic systems have been developed [3,4], and da Vinci [5] surgical system is a commercially-successive one, already introduced in hundreds of hospitals in the world. In addition, development of various surgical robots, such as those with force feedback function and those which are applied to single-incision laparoscopic surgery (SILS) and natural orifice transluminal endscopic surgery (NOTES), are reported [7,8]. These system are suitable for intuitive operation and can be appliable to tele-surgery. However, they are robotic systems, requiring time-consuming setup procedures prior to clinical deployment, large workspace and expensive running cost for maintenance and consumables.

On the other hand, hand-held robotic forceps with a wrist joint have been developed [9,10]. Autonomy Laparo-angle [11] is one of the lightweight mechanically-driven forceps with wrist joint. 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. Kymerax is one of the robotic forceps which is actuated by electric motors [12]. Similarly, the other actuator-driven forceps have been developed [13][14]. However, these conventional robotic forceps are not intuitive due to the humble user-interface such as a joystick or a dial and the large weight of the drive unit.

Hence, it is necessary to develop robotic forceps for laparoscopic surgery, which is a compact and has an intuitive user-interface and wrist joint. In this paper, intuitive operation means that the motion of forceps tip is synchronized with the wrist motion of an operator, realizing the operation of wrist joint like a master-slave type robot. In contrast to the complexity of operating wrist motion, translation of the hand-held forceps can be easily operated by the surgeons trained to use conventional straight forceps.

In this study, a compact surgical robot system is developed by using the existing skill of surgeons. The proposed system consists of forceps manipulator with a 2-DOF wrist joint and a 4-DOF passive holder supporting the forceps manipulator. The forceps manipulator is operated by a built-in master controller, integrated in the proximal side of the forceps. Moreover, we prototype the pneumatically-driven robotic forceps with wrist joint operated by a built-in master controller. A surgeon operates the tip motion of the forceps, which require the dexterous operation, with the robotic system and the translational motion of the forceps with the surgeon's motion.

The rest of this paper is organized as follows. Section Ⅱ presents a concept of proposed surgical robot system mechanism of the developed forceps. Section Ⅲ shows a design of the developed robotic forceps system. Section I V presents the evaluation of position control performance. Section V concludes and discuss this paper.

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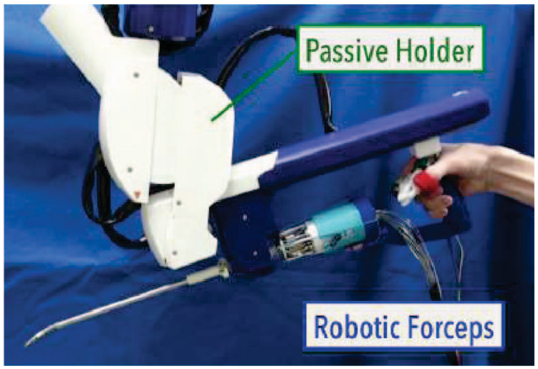

Fig. 1. Proposed surgical robotic system

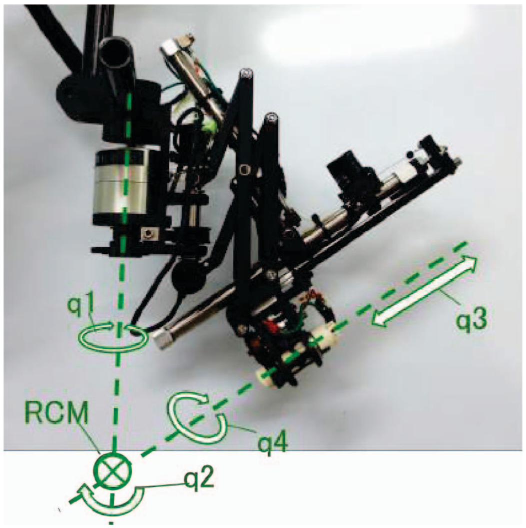

Fig. 2. Passive holder which removed exteriors.

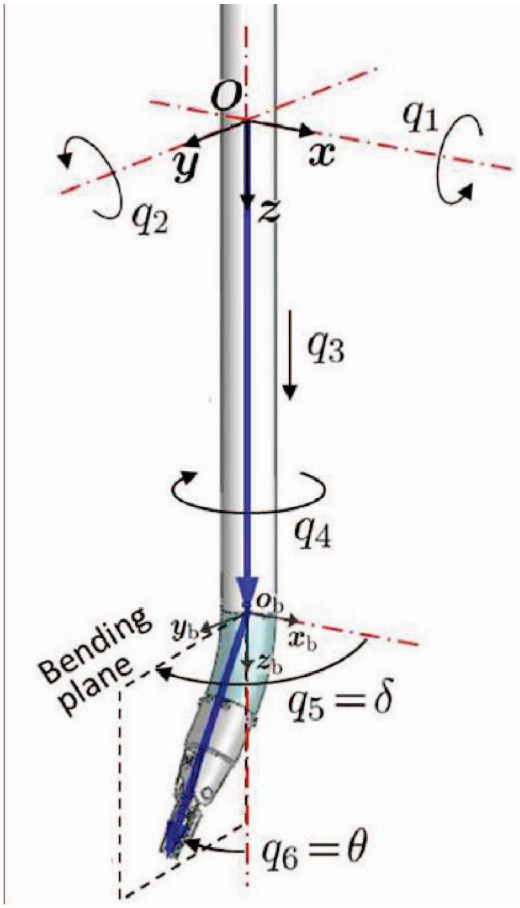

Fig. 3. Nomenclature and coordinates of the forceps[19]

II. PROPOSED SURGICAL ROBOTIC SYSTEM

Fig.1 shows the proposed surgical robotic system which consists of pneumatically-driven hand-held robotic forceps with 2-DOF wrist joint and a 4-DOF passive holder the forceps [15]. The passive holder has the remote center of motion(RCM) mechanism designed to have the forceps insertion point as fixed point. Note that, the holder has actuators, however, in this research, we use the holder as the passive holder by deactivating the actuators. A surgeon operates the tip motion of the forceps which require dexterous operation with the robotic system and the translational motion of the forceps with the surgeon's motion.

Fig.3 shows the coordinates of the forceps in abdominal cavity where a point O denotes the insertion point. In this system, a surgeon operates the wrist joint (q_5, q_6) by a controller integrated in the proximal end of the forceps. Note that, we defined the wrist joint posture as bending direction $\delta\,(= q_5)$ and bending angle $\theta\,(= q6)$. In addition, the surgeon directly operates the rotational motions of the forceps, i.e., rotational motion (q_1, q_2, q_4) and linear motion (q_3) around insertion point O as in the conventional laparoscopic surgery. When performing rotational motion $(q1, q2)$, the motion of forceps tip and of surgeon's hand are inverted around the fixed point. However, it is possible to overcome by the training.

In laparoscopic surgery, a needle used for suturing organs and blood vessels is a curved needle. Therefore, the wrist-joint and the rotation about the bent forceps tip are important for an efficient and safe suturing. However, the proposed robotic forceps does not have tip-rotation DOF on the forceps tip. Therefore, we proposed the control method of realizing tip-rotation using the surgeon's wrist rotation.

Usually, when the operator rotate own wrist with the forceps by $\delta_h\,(= q4)$ angle (see fig.4 (a)(b)), the bending direction of the forceps tip is rotated by δ_h from initial angle δ_0. In this case, when the bending direction is modified to cancel δ_h by setting the bending direction as $\delta_0 - \delta_h$, the forceps tip rotate by δ_h angle on the spot with maintained the tip direction (see fig.4 (d)). Thus, tip rotation is achieved in response to wrist rotation.

III. DEVELOPMENT OF ROBOTIC FORCEPS

Fig.5 shows the developed robotic forceps and Fig.6 shows a schematic diagram of the control system. Note that, forceps

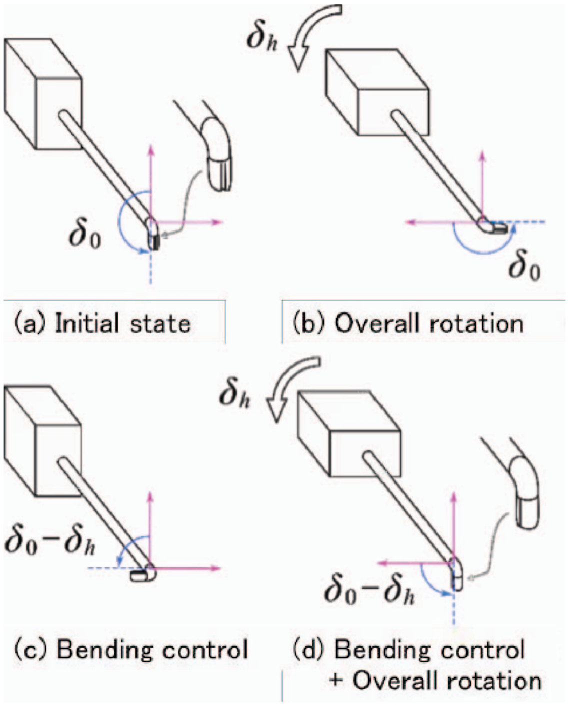

Fig. 4. Algorithm of the tip rotation control

unit in Fig.6 is a schematic figure of only an 1-DOF tendon-drive mechanism. The robotic forceps consists of an operation unit for operating the forceps tip and a forceps unit working in the abdominal cavity. The desired bending motion of wrist joint and grasping motion are realized by the precision pneumatic control at the forceps unit in response to the input by the operation unit.

A. *Operation unit*

The forceps are operated by the operation unit (see fig.5) which consists of a stick controller (Alps Electric Co., Ltd., RKJXK122000D), which mounted on the base of the gripper, to operate forceps wrist joint, an inertial measurement unit (IMU) (Invensense Inc., MPU-6050) to estimate the operator's wrist-rotation angle and a potentiometer (Alps Electric Co., Ltd., RDC1010A12), which mounted in the gripper, to operate forceps grasper. The grasper of the forceps operated by opening and closing of the master gripper and the wrist joint operated by bending the master gripper. The gripper is managed by thumb and index finger of the operator [16].

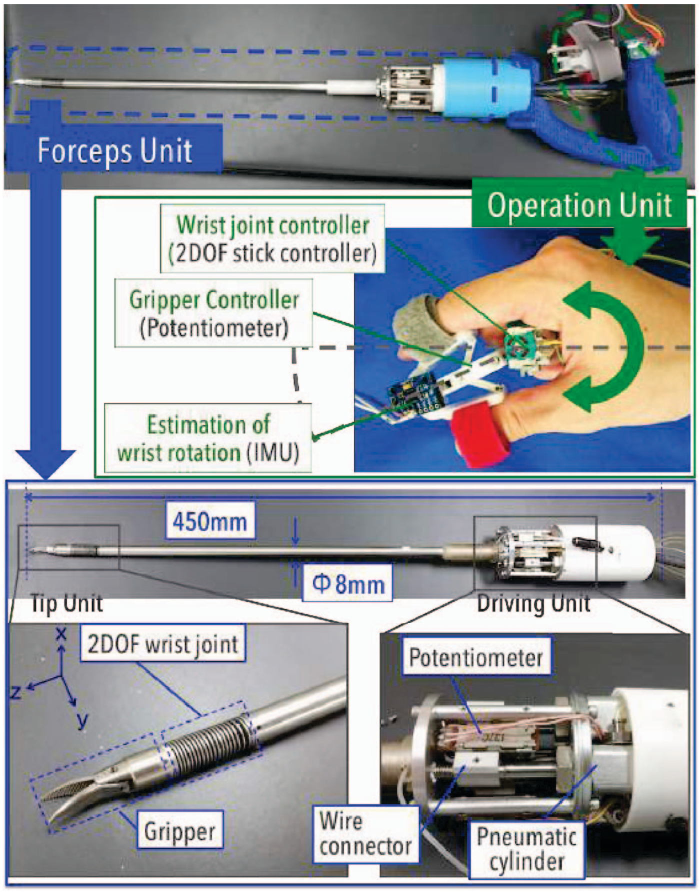

Fig. 5. Overview of robotic forceps

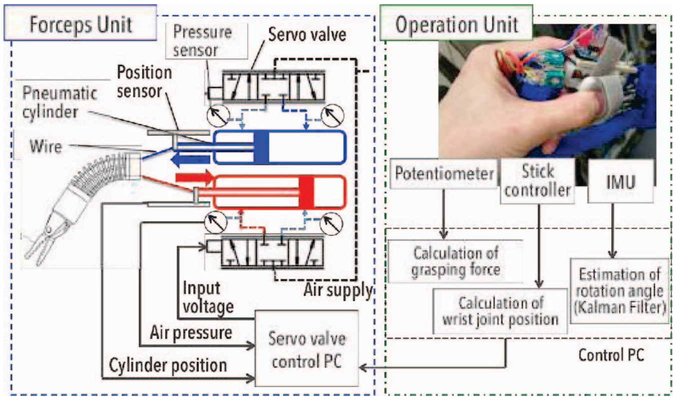

Fig. 6. Schematic diagram of the control system

The stick controller is a 2-DOF variable resistor. The relationship between the bending angle of the stick controller and the voltage shift was determined experimentally. Fig.7 shows an experimental environment that the bending angle measured by a motion sensor (Leap Motion, Inc, Leap Motion) [17] and the voltage shift measured by a single board microcomputer (Arduino, Arduino Uno R3). Fig.8 shows the result, where the supply voltage to the sensor is 5V.

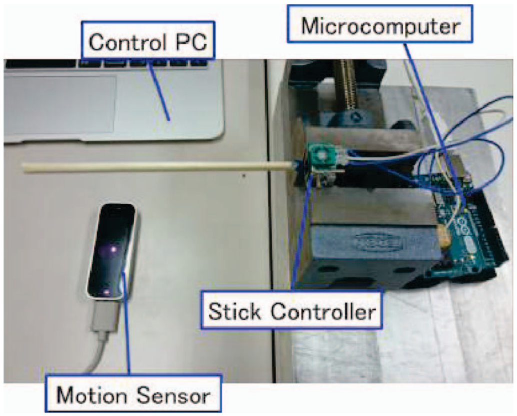

Fig. 7. Experiment environment

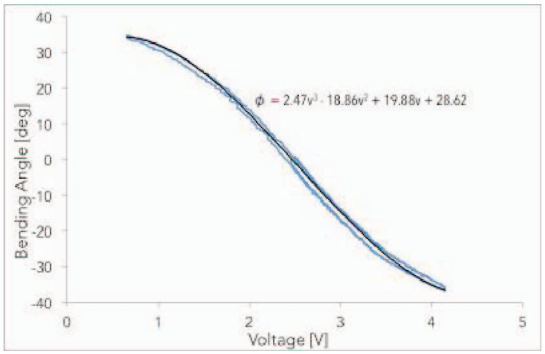

Fig. 8. Relationship between the bending angle and the voltage of the stick controller

The relationship between the bending angle ϕ_i and the voltage v is approximated by the following polynomial:

$$\phi_{1,2} = 2.47v^3 - 18.86v^2 + 19.88v + 28.62 \tag{1}$$

Equation (2) transforms $\phi_{1,2}$ into the bending direction δ and angle θ.

$$q(\phi) = \begin{bmatrix} \delta \\ \alpha\theta \end{bmatrix} = \begin{bmatrix} \tan^{-1}(\phi_2/\phi_1) \\ \alpha\sqrt{{\phi_1}^2 + {\phi_2}^2} \end{bmatrix} \tag{2}$$

α denotes a scaling constant of bending motion between the operation unit and the forceps unit. In this research, α is set 1.8. To estimate the wrist rotation angle, we applied a Kalman filter [18] to the measurements from the IMU that consists of a gyroscope and an accelerometer.

B. Forceps unit

We adopt a pneumatic forceps manipulator [19] of a master-slave type surgical robot which is originally by Haraguchi as the forceps unit. The forceps consists of the 2-DOF tendon-driven wrist joint and the grasper. The diameter of the insertion portion into the abdominal is 8 mm. The driving unit of the wrist joint consists of 4 pneumatic cylinders (SMC, CJ2QB10-15), 4 Ni-Ti super-elastic wires and 4 potentiometers (Alps Electric Co., Ltd., RDC1010A12) which measures each displacement of the cylinder. The wires are attached to the wrist joint of stainless steel spring. The wires go through the shaft and are fastened to the pneumatic cylinders. The 2-DOF bending motion is achieved by driving the spring via the wires by the cylinders The wrist joint posture is defined as bending direction $\delta\,(-180^\circ \leq \delta \leq 180^\circ)$ and bending angle $\theta\,(0^\circ \leq \delta \leq 60^\circ)$. The grasper has a link mechanism and is driven by built-in small pneumatic cylinder at the forceps tip [15].

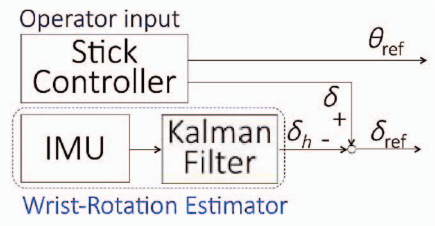

Fig. 9. Operation control system

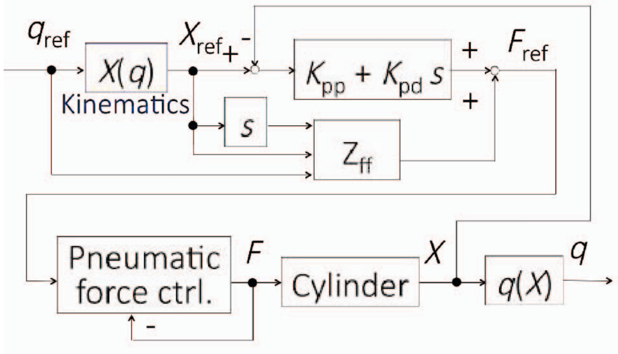

Fig. 10. Position control system

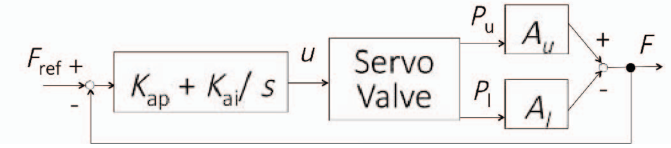

Fig. 11. Pneumatic force control system

C. Control system

Fig. 9,10,11 show developed control systems. In operation side (see fig.9), bending angle θ_{ref} and bending direction δ_{ref} are the target value of the position control. Operator's input to the stick controller provides θ_{ref} and δ_0. To realize the tip-rotation in response to wrist-rotation, θ_{ref} is modified by adding δ_0 to the wrist-rotation angle δ_h to cancel the rotation about the sheath axis. We adopt the UDP communication between the position control side and the operation side.

In position control side (see Fig.10), cascade control, which is the PD-based position controller that encloses the PI-based pneumatic force controller (see Fig.11), is implemented. The main loop consists of the PD-based cylinder position controller and feedforward compensation based on dynamics model Z_{ff}.

TABLE I

CONTROL GAIN

Parameter	Gain
K_{pp}	5.0[N/mm]
K_{pd}	0.04[Ns/mm]
K_{ap}	2.0[V/N]
K_{ai}	0.001[V/Ns]

The minor loop is the PI-based pneumatic cylinder driven force controller. F donates the cylinder's driving force. P shows air pressure measured by a pressure sensor (SMC, PSE540-01). A is a pressure-receiving area of the cylinder. u is the input voltage to the servo valve (FESTO, MPYE-M5-B). We decide control parameters of the control system as Table1.

IV. EVALUATION OF POSITION CONTROL PERFORMANCE

We experimentally confirmed the position control performance of developed robotic system. First, position controlling performance of the forceps tip is evaluated by operating the master-gripper. Fig. 12 shows the result of position control, where the upper figure shows the bending angle position and the lower figure shows the bending direction position. In Fig.12, the broken lines represent a target value given from the operation unit, the solid lines shows the forceps tip position calculated from the measured cylinder displacement and kinematics. We confirmed a good tracking performance and response performance.

Next, we evaluate the tip rotation control performance when the operator rotates the wrist while inputting the constant bending angle θ. Fig. 13 shows the performance of the tip rotation control, where the upper figure shows the bending angle position and the lower figure shows the bending direction position. In Fig.13, δ_h shows the estimate of wrist-rotation angle, δ_{ref} shows the target bending direction and δ shows the measured bending direction. We confirmed reference bending angle δ_{ref} modified by in response to wrist-rotation angle δ_h.

However, when we focus attention on the tracking performance of the bending direction, we find the bending angle of Fig.13 is weaker than Fig.12. The proposed control method, which realizes tip-rotation, require good dynamic characteristics and more precise control of cylinders in response to wrist-rotation than basically bending control. We considered that the bending angle of Fig.13 is weaker than Fig.12 is attributed to the delay of the position control of cylinders. Therefore, we should revise the dynamics model and parameter to improve the dynamic characteristics of the forceps. Moreover, we consider that the estimation error of the rotation angle measured by the IMU and the effect of friction of the cylinder.

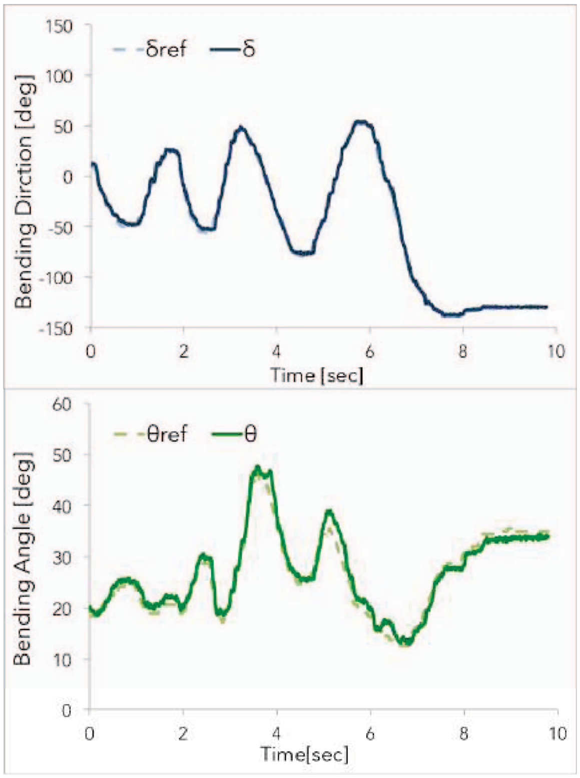

Fig. 12. Experiment of position control performance

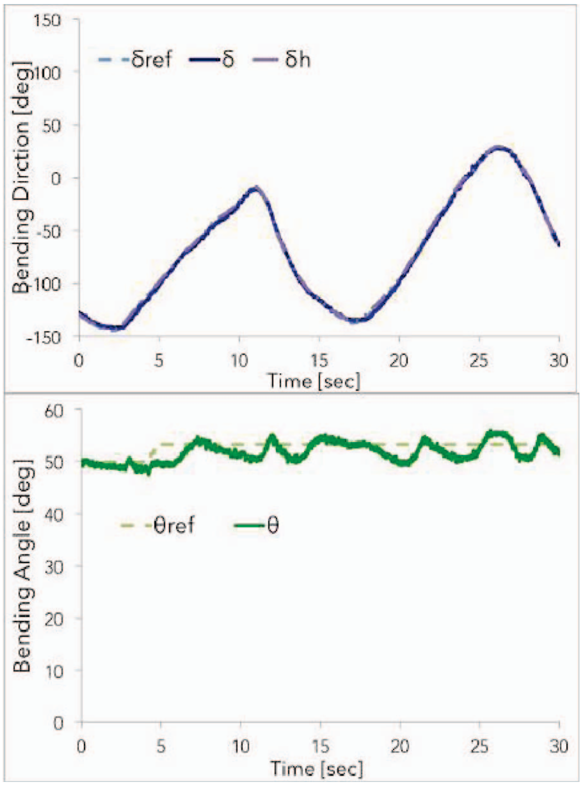

Fig. 13. Experiment of tip rotation performance

V. CONCLUSION

In this study, a compact surgical robot system is developed by using the existing skill of surgeons. The proposed system consists of forceps manipulator with a 2-DOF wrist joint and a 4-DOF passive holder supporting the forceps manipulator. The forceps manipulator is operated by a built-in master controller, integrated in the proximal side of the forceps.

Moreover, we prototype the pneumatically-driven robotic forceps with wrist joint operated by a built-in master controller. In addition, the surgeon's wrist rotation is measured by an IMU and the tip attitude is controlled so that the rotation about the gripper axis is realized, keeping the gripper direction. Finally, We confirmed that controlling performance of the forceps tip position.

Future works are improvement of the dynamic characteristics of the forceps and evaluation by suturing task.

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