Development of Multi Degrees-of-Freedom Haptic Forceps Robot with Three Actuated Fingers

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Surgical robots have been studied and developed to assist surgeons. Master-slave flexible forceps robots that are components of a flexible endoscopic surgical robot are useful to realize novel minimally invasive surgical procedures that are difficult for conventional rigid medical devices. Although driving force for the tip portion of a flexible forceps robot is mechanically transmitted by wires through the flexible portion, friction and backlash changed by the posture of the flexible portion make it difficult to realize precise end effector control. Furthermore, transmission of haptic sensation is necessary to realize safer operation. In this study, a multi degrees-of-freedom (DoF) haptic forceps robot with three fingers is presented as an end effector of a flexible forceps robot. Transmission of driving force in flexible structure that causes performance deterioration is eliminated by arranging motors near the end effector. To transmit haptic sensation to operators, bilateral control is implemented to a master-slave system composed of the haptic forceps robot and a multi DoF input device. Additionally, control on modal space is implemented to verify finger dexterity. The utility of the haptic forceps robot is experimentally validated.

Keywords: motion control, haptics, bilateral control, multi degrees-of-freedom robot, flexible forceps robot

1. Introduction

In the medical field, robotic technologies have been utilized to assist surgeons⁽¹⁾. Master-slave surgical robots for laparoscopic surgery have been studied and developed to reduce burden to patients and support surgeons⁽²⁾⁽³⁾. A surgeon teleoperates a slave robot (slave) by manipulating a master robot (master) in robotic operation, while receiving supports from the master-slave system such as hand shaking suppression and motion scaling.

In contrast to surgical robots with rigid medical tools for laparoscopy, flexible endoscopic surgical robots are the state of the art devices to realize novel procedures of minimally invasive surgery such as natural orifice transluminal endoscopic surgery (NOTES)⁽⁴⁾. Flexible endoscopic surgical robots have multi degrees-of-freedom (DoF) flexible forceps robots to conduct surgical tasks as hands of surgeons in addition to a flexible endoscope to obtain visual information. The structure of a flexible forceps robot inserted into a patient's body can be divided into a tip part and a flexible part. Driving force of actuators is transmitted from the outside of

the patient's body to the tip part through the inside of the flexible part. Wire driven mechanisms are widely used to transmit driving force in flexible structure⁽⁵⁾⁽⁶⁾. Elastic rods can transmit both of push and pull motion in narrow space⁽⁷⁾. However, friction and backlash depending on the posture and elasticity of the mechanical parts make it difficult to realize precise control of the tip part. In addition, haptic information obtained by the slave is deteriorated. The inability to transmit clear haptic sensation to operators is an issue of master-slave surgical robots⁽⁸⁾. Lack of haptic sensation causes some problems such as damage to objects and unintuitive teleoperation.

On the other hand, there are flexible forceps robots that have driving parts near the end effector. A surgical robot for NOTES that consists of multi DoF forceps robot with actuators near the end effector and an articulated flexible part was developed⁽⁹⁾. In order to transmit haptic sensation, a small gripping forceps unit was developed as the tip part of flexible forceps robots⁽¹⁰⁾. The arrangement of a motor on the tip part eliminated transmission of driving force in the flexible part that causes deterioration of the performance. Modularization of robots is other approach to construct multi DoF surgical devices for NOTES⁽¹¹⁾. The structure of the robot was composed of small versatile modules.

In this paper, a multi DoF haptic forceps robot with three actuated fingers is developed as the tip part of flexible forceps robots⁽¹²⁾. The haptic forceps robot is composed of a rotation module and a three fingered grasping module. Dexterous grasping motion can be realized by the fingers that are independently drivable. Besides, compound motion of the fingers can be defined as modes and controlled in modal space⁽¹³⁾. Transmission of driving force in flexible structure is

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Fig. 1. Concept of multi DoF haptic forceps robot composed of small modules incorporating driving parts

eliminated by arranging motors near the end effector. Modularized structure realizes various configuration depending on the purpose of tasks. In order to transmit haptic sensation, bilateral control is implemented to a master-slave system composed of the haptic forceps robot and a multi DoF input device. The utility of the developed haptic forceps robot is validated by experiments.

This paper is organized as follows: In section II, the mechanical design of the haptic forceps robot and the input device is presented. In section III, the control for the robots is explained. In section IV, the experiments are described. Finally, this paper is concluded in section V.

2. Mechanical Design

A master-slave system is a general configuration of teleoperation robots for surgery. In this paper, a multi DoF haptic forceps robot with three actuated fingers is developed as the tip part of flexible forceps robots⁽¹²⁾. Besides, a multi DoF input device that has the similar configuration of motors with the haptic forceps robot is utilized as the master.

2.1 Haptic Forceps Robot The concept of the multi DoF haptic forceps robot is shown in Fig. 1. The modularized structure composed of small haptic modules with different functions can be modified according to the purpose of tasks. Each module has driving parts composed of motors with encoders and backdrivable structure to obtain more precise haptic information. Driving force of motors is transmitted by rigid mechanical components. The electric wires of the motors and the encoders can be bended and inserted into the flexible part. The influence of flexible structure for transmission of the electric power and signals is ignorable.

The developed haptic forceps robot shown in Fig. 2 is composed of a rotation module and a grasping module. Both modules are a cylindrical device having a diameter of 15 mm. The rotation module includes a rotary motor and rotates components mounted on the moving part of the rotation module. The grasping module has three finger submodules arranged at 120 degrees interval. The submodules have the identical structure composed of a rotary motor with a bevel gear and a jaw. A bevel gear attached to the rotary motor transmits rotary motion to the jaw with a gear-shaped part. All of four

(a) Haptic forceps robot with a flexible tube

(b) Mechanical design

Fig. 2. Multi DoF haptic forceps robot composed of rotation module and three fingered grasping module

Fig. 3. Multi DoF input device with the similar configuration of motors with haptic forceps robot

rotary motors used for the haptic forceps robot are constituted by a brushless DC motor (EC6, Maxon motor AG) with a planetary gear head and an incremental rotary encoder. The resolution of the encoders is 256 pulses/revolution.

2.2 Input Device A simple configuration of master-slave systems is that the master has the same structure with the slave. The input device shown in Fig. 3 has the similar configuration with the haptic forceps robot. The structure of the input device is composed of a rotation part and a grasping part. The rotation part has a DC rotary motor with a planetary gear head and an incremental rotary encoder and rotates the grasping part mounted on the moving part. The resolution of the rotary encoder is 1024 pulses/resolution.

The voice coil motor (VCM) that is a direct drive motor with high backdrivability is used as the master for each finger submodule of the slave. Three VCMs are placed at the grasping part at 120 degrees interval. A finger hole is attached to the moving part of each VCM as the end effector of the master. The displacement of the coils is measured by incremental linear encoders. The resolution of the linear encoders is $0.4 \mu\text{m}$.

3. Control

3.1 Motion Control of Each Joint Position/angle and force/torque are the typical variables to express motion of motors. Position and force information of the motors installed in the robots are defined as follows.

$$\mathbf{X}_{fr} = [\theta_{fr} \quad \mathbf{X}_{fr}^T]^T, \dots \quad (1)$$

$$\mathbf{F}_{fr} = [T_{fr} \quad \mathbf{F}_{fr}^T]^T, \dots \quad (2)$$

$$\mathbf{X}_{id} = [\theta_{idR} \quad \theta_{idF1} \quad \theta_{idF2} \quad \theta_{idF3}]^T, \dots \quad (3)$$

$$\mathbf{F}_{id} = [T_{idR} \quad T_{idF1} \quad T_{idF2} \quad T_{idF3}]^T, \dots \quad (4)$$

θ , $\mathbf{X}$, T , and $\mathbf{F}$ are angle, position, torque, and force, respectively. The subscripts fr, id, R, F1, F2, and F3 denote the haptic forceps robot, the input device, rotation, finger 1, finger 2, and finger 3, respectively. The variables of the grasping module of the haptic forceps robot $\mathbf{X}_{frF}$ and $\mathbf{F}_{frF}$ are given by,

$$\mathbf{X}_{frF} = [X_{frF1} \quad X_{frF2} \quad X_{frF3}]^T, \dots \quad (5)$$

$$\mathbf{F}_{frF} = [F_{frF1} \quad F_{frF2} \quad F_{frF3}]^T, \dots \quad (6)$$

Reduction ratio of the gear head equipped with the rotary motors is given by,

$$\mathbf{G} = \text{diag}(G_R, G_{F1}, G_{F2}, G_{F3}), \dots \quad (7)$$

G denotes value of reduction ratio. Variables of a motor on the motor space are converted into variables of the output shaft of a gear head on the joint space. The relation of the motor space and the joint space is given by,

$$\mathbf{X}_j = \mathbf{G}^{-1} \mathbf{X}_a, \dots \quad (8)$$

$$\mathbf{F}_j = \mathbf{G} \mathbf{F}_a, \dots \quad (9)$$

The subscripts a and j denote the motor space and the joint space.

Both of position control and force control are based on acceleration control with Disturbance Observer (DOB) that realizes robust motion control of motors⁽¹⁴⁾. Velocity information used for PD position control and DOB is calculated by pseudo differential of position information. Since force/torque sensors are not installed to the robots, force information used for P force control is estimated by Reaction Force Observer (RFOB)⁽¹⁵⁾. By applying force sensorless control, robots can be simplified and miniaturized.

3.2 Bilateral Control A method to configure master-slave systems is bilateral control. In particular, the acceleration based four-channel bilateral control can transmit clear haptic sensation between a master and a slave⁽¹⁶⁾. In case of the master-slave system described in Section 2, the control goals of the bilateral control are given as follows.

Fig. 4. Schematic diagram of four-channel bilateral control

Fig. 5. Front view of grasping module and composition of modes

$$\mathbf{X}_{jid} - \alpha \mathbf{X}_{jfr} = 0, \dots \quad (10)$$

$$\mathbf{F}_{jid} + \beta \mathbf{F}_{jfr} = 0, \dots \quad (11)$$

The scaling values α and β that can amplify haptic sensation are expressed by,

$$\alpha = \text{diag}(\alpha_R, \alpha_{F1}, \alpha_{F2}, \alpha_{F3}), \dots \quad (12)$$

$$\beta = \text{diag}(\beta_R, \beta_{F1}, \beta_{F2}, \beta_{F3}), \dots \quad (13)$$

α and β are position scaling and force scaling. The linear actuators are used for grasping motion of the master, although the rotary actuators are used for grasping motion of the slave. Therefore, the scaling values convert rotary motion of the slave into linear motion of the master. The schematic diagram of the bilateral control is shown in Fig. 4. $\hat{\partial}$, the superscripts ref and res denote estimated values, reference values of the acceleration control, and response values measured by sensors, respectively. To improve the performance of the bilateral control with scaling using the different mass master-slave system, the oblique coordinate control is utilized⁽¹⁷⁾.

3.3 Control in Modal Space The grasping module of the haptic forceps robot has three motors to conduct grasping motion. On the other hand, three modes can be defined by compounding motion of three motors⁽¹³⁾. The front view of the haptic forceps robot and schematic drawings are shown in Fig. 5. Unlike two fingered grippers that are generally applied for forceps, the finger submodules arranged at 120 degrees interval can be used for X direction manipulation and Y direction manipulation. Therefore, in this paper, three modes

Fig. 6. Schematic diagram of acceleration control of haptic forceps robot in modal space

that consist of the grasping mode, the X manipulation mode, and the Y manipulation mode are defined.

Position information in the modal space is given as,

$$X_{mfr} = [X_g \quad X_x \quad X_y]^T. \quad (14)$$

X_g , X_x , and X_y denote the grasping mode, the X manipulation mode, and the Y manipulation mode, respectively. Position information in the joint space is converted by modal transformation matrix T_m given by,

$$X_{mfr} = T_m X_{jfr}, \quad (15)$$

$$T_m = \begin{bmatrix} 2 & 1 & 1 \\ 0 & -1 & 1 \\ 2 & -1 & -1 \end{bmatrix}. \quad (16)$$

The inverse transformation matrix is given as,

$$T_m^{-1} = \begin{bmatrix} 0.25 & 0 & 0.25 \\ 0.25 & -0.5 & -0.25 \\ 0.25 & 0.5 & -0.25 \end{bmatrix}. \quad (17)$$

The schematic diagram of acceleration control in the modal space is shown in Fig. 6. The PD position control or the P force control is applied to each mode.

4. Experiment

Bilateral teleoperation of the master-slave system (experiment 1) and control of the haptic forceps robot in the modal space (experiment 2) were conducted to verify the performance of the haptic forceps robot. In both experiments, the sampling time of the control was set at 0.1 ms. The signal of the encoders was multiplied by four to enhance the resolution. The parameters used in the experiments are shown in Table 1. The force controller of the bilateral controller used in the experiment 1 derived force reference values that is converted to acceleration reference values by nominal mass, while acceleration reference values were directly derived by the force control in the modal space in the experiment 2. Therefore, the force gain in the experiment 2 was much larger than the one in the experiment 1.

4.1 Experiment 1: Bilateral Teleoperation

4.1.1 Experimental Setup The bilateral control was implemented to the master-slave system. The resolution of the encoders of the master was different from one of the slave. Since motion of the motors with the encoders was converted by the reduction gear mechanisms, the master and the slave had the resolution of 5939.2 pulse/rev and 14592 pulse/rev

Fig. 7. Experimental setup

Fig. 8. Objects for experiment 1

for rotational motion in the joint space. The encoders for grasping motion had also high resolution in the joint space. Besides, the signal of the encoders was multiplied by four. Since the resolution was sufficient to transmit haptic sensation to operators in this experiment, the influence of the difference of the resolution between the master and the slave was ignored. The rotational motion of the master and the slave was synchronized by setting the position scaling as in Table 1, while the movable range of a VCM that is 10 mm in the master corresponded to the rotation range of $4/\pi$ rad of a finger in the slave. The force scaling β was decided based on the ratio of the maximum force or torque of the master and the slave and empirically adjusted. The maximum force or torque of the robots is calculated by the reduction ratio and the output of actuators considering the output of power sources and motor drivers. The experimental setup is shown in Fig. 7. The rotation module of the haptic forceps robot was fixed vertically on a stand. Free motion, contact motion to a soft object, and contact motion to a hard object were conducted. The objects used in contact motion are shown in Fig. 8. In free motion, the master-slave system was moved without contacting objects. In contact motion to the soft object, the haptic forceps robot grasped and rotated a balloon fixed at the table. In contact motion to the hard object, the haptic forceps robot grasped a screw.

4.1.2 Experimental Results The experimental results of rotational motion are shown in Fig. 9. In the angle response of rotational motion shown in (a), (b), and (c), response values of the slave drawn by the red lines followed response values of the master drawn by the green lines. In the torque response of rotational motion shown in (d), (e), and (f), the absolute values of estimated torque of the master drawn by the green lines were the almost same with the

Table 1. Parameters in experiments

Parameters	Master in experiment 1		Slave in experiment 1		Slave in experiment 2
	Rotation	Fingers	Rotation	Fingers	
Reduction ratio	5.800	1.000	57.00	182.4	182.4
Position gain	$3.600 \times 10^3 \text{ s}^{-2}$	$6.400 \times 10^3 \text{ s}^{-2}$	$3.600 \times 10^3 \text{ s}^{-2}$	$6.400 \times 10^3 \text{ s}^{-2}$	$1.000 \times 10^4 \text{ s}^{-2}$
Velocity gain	120.0 s^{-1}	160.0 s^{-1}	120.0 s^{-1}	160.0 s^{-1}	200.0 s^{-1}
Force gain	0.8000	0.8000	0.8000	0.8000	$9.000 \times 10^4 \text{ kg}^{-1} \cdot \text{m}^{-2}$
Cutoff frequency of DOB and RFOB	200.0 rad/s	200.0 rad/s	200.0 rad/s	200.0 rad/s	300.0 rad/s
Cutoff frequency of pseudo differential	400.0 rad/s	400.0 rad/s	400.0 rad/s	400.0 rad/s	600.0 rad/s
Position scaling α	-	-	1.000	$1.270 \times 10^{-2} \text{ m}$	-
Force scaling β	-	-	9.750	54.75 m^{-1}	-

Fig. 9. Results of experiment 1 (rotational motion in transmission of haptic sensation)

Fig. 10. Results of experiment 1 (grasping motion in transmission of haptic sensation)

absolute values of amplified torque of the slave. Therefore, the control goals of the scaling bilateral control given by (10) and (11) were achieved and haptic sensation in rotational motion was transmitted to the master. The same results were obtained in the experimental results of grasping motion shown in Fig. 10. The displacement in the positive direction denotes opening of the fingers.

In free motion, manipulation force to move the fingers that is undesirable force in bilateral teleoperation was small. On the other hand, manipulation force of the rotation module was not ignorable, because FFC cables of the motors in the grasping module were twisted and contacted to the internal

structure of the rotation module. In contact motion to the soft object, reaction torque generated by the balloon changed according to movement of the rotation module and the finger 1 of the grasping module due to low stiffness of the object. Since stiffness of the screw is large, position of the fingers in contact motion to the hard object was almost constant after grasping the object regardless of force variation.

4.2 Experiment 2: Control in Modal Space

4.2.1 Experimental Setup The haptic forceps robot fixed vertically on the stand was controlled in the modal space. The force control was applied to the grasping mode. The position control was applied to the X and Y manipulation

Fig. 11. Results of experiment 2 (control in modal space)

mode. The motion in the modal space was switched every five seconds. First, constant command values were input to all modes. A resin rod that has a diameter of 10 mm was held by the fingers by setting the force command value of the grasping mode at -0.05 N. Second, a sinusoidal command value was input to a mode, while constant command values were input to the others. The command was fluctuated in the order of the grasping mode, the X manipulation mode, and the Y manipulation mode. The rotation module was not used in this experiment.

4.2.2 Experimental Results The experimental results of control in the modal space are shown in Fig. 11. In each result, angle or torque response followed the command. The displacement of the X and Y manipulation mode was ignorable, while the sinusoidal force command of the grasping mode was input. Although estimated force of the grasping mode was fluctuated from 10 seconds to 20 seconds, the magnitude of force was small. Therefore, three DoF motion that consists of the grasping mode and the two DoF manipulating modes was realized by the three fingers of the haptic forceps robot.

5. Conclusion

This paper presented the multi DoF haptic forceps robot with three actuated fingers as an end effector of flexible forceps robots. The haptic forceps robot composed of the small cylindrical modules with backdrivable structure was developed to conduct rotational motion and dexterous grasping motion using the fingers in narrow space. Transmission of driving force in flexible structure, which causes deterioration of the performance of flexible forceps robots, was eliminated by installing motors in the modules. In the experiments, the master-slave system was composed of the haptic forceps robot and the multi DoF input device. Haptic sensation was transmitted by the master-slave system implementing the bilateral control with scaling. Besides, the three modes were defined by compound motion of the fingers of the grasping module that are independently drivable. Dexterity of the three fingered grasping module was confirmed by conducting grasping motion and manipulation on the modal

space. Therefore, the utility of the developed haptic forceps robot was demonstrated.

The developed haptic forceps robot has the diameter of 15 mm to incorporate three commercially available actuators with the diameter of 6 mm in grasping module. The diameter of some prototypes of flexible endoscopic surgical robots in references is from 12 mm to 16 mm⁽⁶⁾⁽⁷⁾⁽¹¹⁾. The size of the haptic forceps robot may not be sufficiently small for realization of more dexterous surgical operations. It is necessary to miniaturize the modules by applying smaller actuators and mechanical components to extend the utility of the haptic forceps robot. In medical tasks, the performance of the master-slave system is influenced by the usability of the input device. In this paper, the grasping motion using the fingers of the haptic forceps robot was converted into three modes and controlled in modal space. Therefore, input devices not only with the similar configuration of actuators with the slave, but also with motion corresponds to the modes of the slave can be utilized. The configuration of the master that is suitable for medical tasks using haptic forceps robots must be considered in future works.

References

- (1) R.H. Taylor and D. Stokanovici: "Medical Robotics in Computer-Integrated Surgery", *IEEE Transactions on Robotics and Automation*, Vol.19, No.5, pp.765–781 (2008)
- (2) G.S. Guthart and J.K. Salisbury, Jr.: "The Intuitive™ Telesurgery System: Overview and Application", in *Proceedings of 2000 IEEE International Conference of Robotics and Automation*, pp.618–621 (2000)
- (3) M. Ghodoussi, S.E. Butner, and Y. Wang: "Robotic Surgery—The Transatlantic Case", in *Proceedings of 2002 IEEE International Conference on Robotics and Automation*, pp.1882–1888 (2002)
- (4) L.L. Swanstrom: "NOTES: Platform Development for a Paradigm Shift in Flexible Endoscopy", *Gastroenterology*, Vol.13, No.4, pp.1150–1154 (2011)
- (5) D.J. Abbott, C. Becke, R.I. Rothstein, and W.J. Peine: "Design of an Endoluminal NOTES Robotic System", in *Proceedings of 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.410–416 (2007)
- (6) S.J. Phee, S.C. Low, V.A. Huynh, A.P. Kencana, Z.L. Sun, and K. Yang: "Master And Slave Transluminal Endoscopic Robot (MASTER) for Natural Orifice Transluminal Endoscopic Surgery (NOTES)", in *Proceedings of the 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp.1192–1195 (2009)
- (7) J. Zhao, X. Zheng, M. Zheng, A.J. Shih, and K. Xu: "An Endoscopic Continuum Testbed for Finalizing System Characteristics of a Surgical Robot for NOTES Procedures", in *Proceedings of 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp.63–70 (2013)
- (8) A.M. Okamura: "Methods for Haptic Feedback in Teleoperated Robot-Assisted Surgery", *Industrial Robot*, Vol.31, No.6, pp.499–508 (2004)
- (9) C.M. Seow, W.J. Chin, C.A. Nelson, A. Nakamura, S.M. Farritor, and D. Oleynikov: "Articulated Manipulator With Multiple Instruments for Natural Orifice Transluminal Endoscopic Surgery", *ASME Journal of Medical Devices*, Vol.7, No.4, pp.041004-1–041004-10 (2013)
- (10) T. Matsunaga, D. Tomizuka, T. Nozaki, Y. Saito, K. Ogawa, K. Ohnishi, N. Wada, and Y. Kitagawa: "Development of Miniature Haptic Forceps for Flexible Endoscope", *Journal of Japan Society of Computer Aided Surgery*, Vol.19, No.3, pp.123–130 (2017)
- (11) G. Tortora, P. Dario, and A. Menciassi: "Array of Robots Augmenting the Kinematics of Endocavitary Surgery", *IEEE/ASME Transactions on Mechatronics*, Vol.19, No.6, pp.1821–1829 (2014)
- (12) T. Matsunaga, T. Shimono, and K. Ohnishi: "Development of Multi Degree of Freedom Haptic Forceps Robot with Multi Actuated Fingers", in *Proceedings of the 5th IEEE International workshop on Sensing, Actuation, Motion Control, and Optimization*, pp.1–4 (2019)
- (13) T. Tsuji, K. Ohnishi, and A. Sabanovic: "A Controller Design Method Based on Functionality", *IEEE Transactions on Industrial Electronics*, Vol.54, No.6, pp.3335–3343 (2007)
- (14) K. Ohnishi, M. Shibata, and T. Murakami: "Motion Control for Advanced Mechatronics", *IEEE/ASME Transactions on Mechatronics*, Vol.1, No.1,

pp.56–67 (1996)

- (15) T. Murakami, F. Yu, and K. Ohnishi: “Torque Sensorless Control in Multidegree-of-Freedom Manipulator”, *IEEE Transactions on Industrial Electronics*, Vol.40, No.2, pp.259–265 (1993)
- (16) W. Iida and K. Ohnishi: “Reproducibility and Operationality in Bilateral Teleoperation”, in *Proceedings of the 8th IEEE International Workshop on Advanced Motion Control*, pp.217–222 (2004)
- (17) S. Sakaino, T. Sato, and K. Ohnishi: “Multi-DOF Micro-Macro Bilateral Controller Using Oblique Coordinate Control”, *IEEE Transaction on Industrial Informatics*, Vol.7, No.3, pp.446–454 (2011)

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