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Development of a Multi DOF Haptic Robot for Dentistry and Oral Surgery

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Abstract— **There exist many dental surgery such as orthognathic surgery and an implant operation. Jaw deformity is one of the dental diseases such as an abnormality of occlusion and facial distortion in the shape. To treat jaw deformity, the osteotomy is carried out by human hands. However, drilling a jawbone accurately by oral surgeons is difficult. Recently, surgical robots are attracting attention in the medical field. The researches of surgery supporting systems have been carried out. They have possibilities to avoid unexpected accidents in the surgery, a hands shake and so on. The improvement of the minimally invasive surgery can be expected, thanks to robotic technology. The purpose of this research is the design and development of master-slave dentistry and oral surgery assisting robot. By implementing acceleration based bilateral control, haptic information can be communicated. Moreover, the proposed robot has the serial-parallel hybrid mechanism that can obtain the advantages of a serial mechanism and a parallel mechanism. In this paper, the mechanism of the proposed robot is explained and the performance of the proposed robot is validated by experiments.**

I. Introduction

Jaw deformity is a disease such as an abnormality of occlusion and a facial distortion. Although it is said that a genetic element is one of the causes of jaw deformity, the full details remain still unknown. Generally, to have orthodontic treatment is necessary . However, when the sympton of jaw deformity is terrible, in addition to the orthodontic treatment, jaw deformity must be cured by an osteotomy. Currently, the osteotomy in the field of oral surgery is carried out by human hands. However, drilling a jawbone accurately is difficult. Hence, the surgeons wish hand shake reduction, guided system, and so on. From the backgrounds, the development of the oral surgical robot is needed.

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Surgical robots have attracted attention in the medical field. In fact, the researches of surgery supporting systems have been carried out [1]– [3]. For example, "da Vinci Surgical System" is the famous commercialized surgical robot [4]. "da Vinci Surgical System" is an endoscopic surgical robot based on the master-slave system. A surgeon uses a master robot to operate a slave robot by remote control and treat a patient. The surgical robots can also be utilized in dentistry and oral surgery. Li *et al.* have developed a compact dental robotic system [5]. A soft bracing actuator is implemented at the end-effector part, therefore the system stiffness can be changed. Yeotikar *et al.* have developed an automation system of robotic arm for a dental implantation with a computer vision [6]. The computer vision has been used to establish a closed-loop feedback control system for the robotic arm, hence the end-effector of the robotic arm reaches the desired position for drilling a hole in jaw. Kim *et al.* have studied the design and simulation of assist-manipulator for implant surgery [7]. X. Duan *et al.* have developed a multi-arm maxillofacial surgical robot that has three serial link arms [8]. Yu *et al.* have developed the implant surgery supporting robot [9]. They proposed a guide system for a physician to achieve a correct start position with Lennard-Jones potential field-based force control. Moreover, they introduced an automatic stop system using bilateral control.

In a teleoperation system based on the master-slave system, the bilateral control is one of the control methods that communicates information between a master system and a slave system bidirectionally. There are many studies for the bilateral control. When only the position or force information is communicated between the master system and the slave system, this control method is called two-channel controller [10]. When the position and force information are communicated from each other between the master system and the slave system, this control method is called four-channel controller [11]. Acceleration based bilateral control (ABC) can achieve high-precision communication with the position and force information [12] [13]. ABC realizes the robust motion control by a disturbance observer (DOB) [14] and communicating the force information by a reaction force observer (RFOB) [15].

The purpose of this paper is the development of a novel oral surgery assisting robot. Multi DOF mechanisms are classified roughly into two types [16]. One is a serial mechanism and the other is a parallel mechanism. The serial mechanism has the structure that actuators are installed in

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series between the base and the end-effector by links. As characteristics, workspace is large, therefore the serial mechanism can correspond to various works flexibly. However, there are disadvantages that are low-rigidity, low-speed, and so on. On the other hand, the parallel mechanism has the structure that actuators are installed in parallel between the base and the end-effector by links and passive joints. As characteristics, there are high-accuracy, high-speed, high-rigidity, and so on. However, there are disadvantages that are workspace is small. A hybrid mechanism is a combination of the serial mechanism and the parallel mechanism. The hybrid mechanism can obtain the advantages of both mechanisms. In the base side of the proposed robot, the error affects a tip side significantly and a high-rigidity is needed to support the tip side. Hence, the base side of the proposed robot implements the parallel mechanism. In the tip side of the proposed robot is needed a high-precision and a large workspace. Therefore, the tip side of the proposed robot implements the serial mechanism. Moreover, remote center of motion (RCM) mechanism is implemented in the serial mechanism. RCM mechanism can decide the posture of the end effector without changing the position. Furthermore, the proposed robot is the master-slave system and ABC is implemented to communicate haptic sensation.

This paper consists of five sections. In section II, the mechanism of the proposed robot is explained. In section III, the motion control is explained. In section IV, the experiment is carried out to validate the performance of the proposed robot. Finally, in section V, this paper is summarized.

II. Proposed Robot

The proposed robot is the master-slave system. Moreover, the master robot and the slave robot are the same structure. Therefore, the structure of one robot is explained.

Fig. 1 shows the overview of the proposed robot. The proposed robot has a parallel link part and an end-effector part. The parallel mechanism can achieve multi DOF motion without motors that are installed near the end-effector. The parallel link part has three DOF that are heaving, pitching, and yawing. The position and posture of the end-effector part are decided by the parallel link part. The end-effector part has three DOF that are rolling, RCM, and linear motion. RCM mechanism can decide the posture of end-effector without changing the position of the end-effector. The linear motion can be utilized for avoiding the drill stuck. Each part has three DOF and the proposed robot has six DOF totally. In the proposed robot, force information is obtained by Reaction Force Observer (RFOB) [15], therefore the proposed robot has no force sensor. Hence, the size of the robot can be reduced and it is possible to reduce cost.

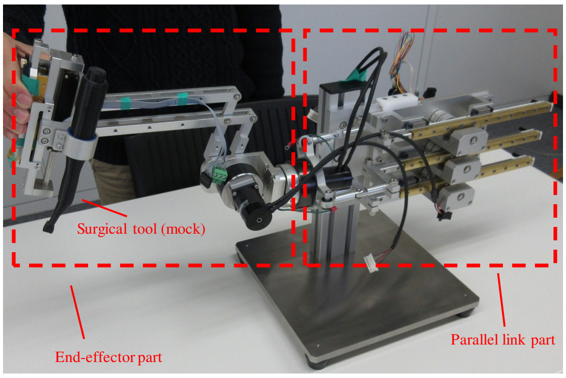


Fig. 1. Overview of proposed robot.

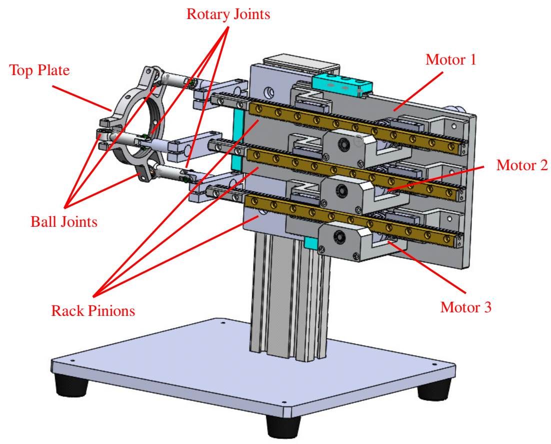


Fig. 2. Design of parallel link part.

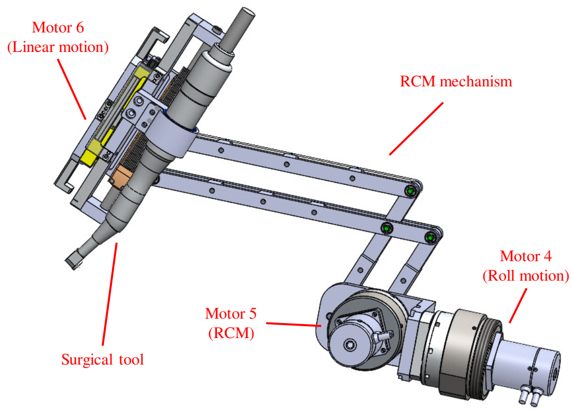


Fig. 3. Design of end-effector part.

A. Parallel Link Part

Fig. 2 shows the design of the parallel link part. The parallel mechanism can achieve multi DOF motion without motors that are installed near the end-effector and has some advantages such as high-rigidity, high-accuracy, and so on. The parallel mechanism is designed by three arms. Each arm has a rack pinion, a rotary joint, and a ball joint. These arms are connected to a top plate and shifted by 120 degrees. The rotary motors (Faulhaber, 2057S024B) for pinions are used. Moreover, the optical rotary encoders (Faulhaber, IE2-1024) are installed in all rotary motors to obtain the information of angle response.

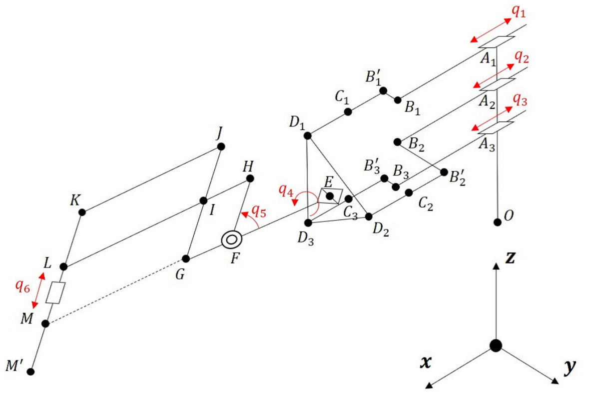


Fig. 4. Schemtic drawing of proposed robot.

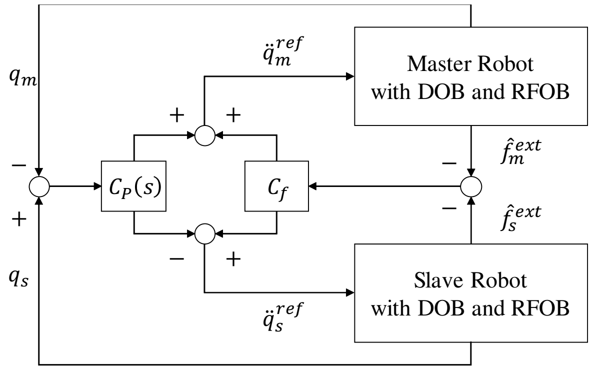
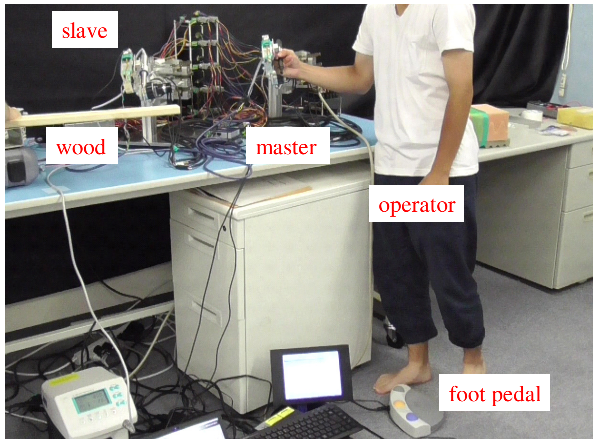
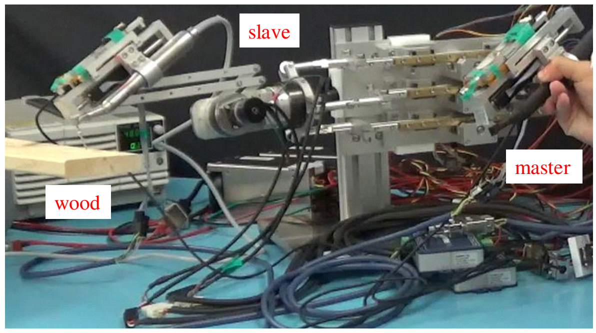


Fig. 5. Block diagram of acceleration based bilateral control.



(a) Over view.



(b) Enlarged view.

Fig. 6. Experimental setup.

B. End-effector Part

Fig. 3 shows the design of the end-effector part. End-effector part has two rotary motors with the rotary encoders (Microtech Laboratory Inc., MDH-3018-108KE) and a linear motor (Faulhaber, LM1483-040-11). Two rotary motors are used for rolling and RCM. RCM mechanism can decide the posture of end effector without changing the position. The rotary motors are connected to the top plate of the parallel link part. An optical linear encoder (Technohands Co., Ltd., TA-200) is installed in the linear motor to obtain the information of position response.

C. Description of motion

Fig. 4 shows a schematic drawing of the proposed robot. In Fig. 4, q_i shows a displacement of motor i. The rack pinions driven by motor 1, motor 2, and motor 3 are simplified as the linear motors.

When motor 1, motor 2, and motor 3 that are point A_1, A_2, and A_3 move in the same direction, the top plate that is point E performs heave motion. When motor 2 is fixed and the others move in the different direction from each other, the top plate performs pitch motion. When motor 2 moves and the others move in the different direction from motor 2, the top plate performs yaw motion. Next, when motor 4 rotates, point F performs roll motion. Point F, G, H, I, J, K, and M show the RCM mechanism and the posture of the end-effector that is point M changes without changing the position of the end-effector when motor 5 rotates. Finally, when motor 6 performs linear motion that is used for avoiding drill stuck, the end-effector moves from point M to point M'.

III. Motion Control

ABC that has DOB and RFOB is implemented for the proposed robot. DOB can estimate the disturbance from a calculation and suppress the effect of disturbance by applying the compensation current. RFOB can estimate the reaction force by subtracting friction effect and internal interactive force from the disturbance estimated by DOB. DOB and RFOB can realize the force sensorless control.

Fig. 5 shows the block diagram of ABC. The control target of bilateral control is simultaneously achieving position tracking and the law of action and reaction as follow:

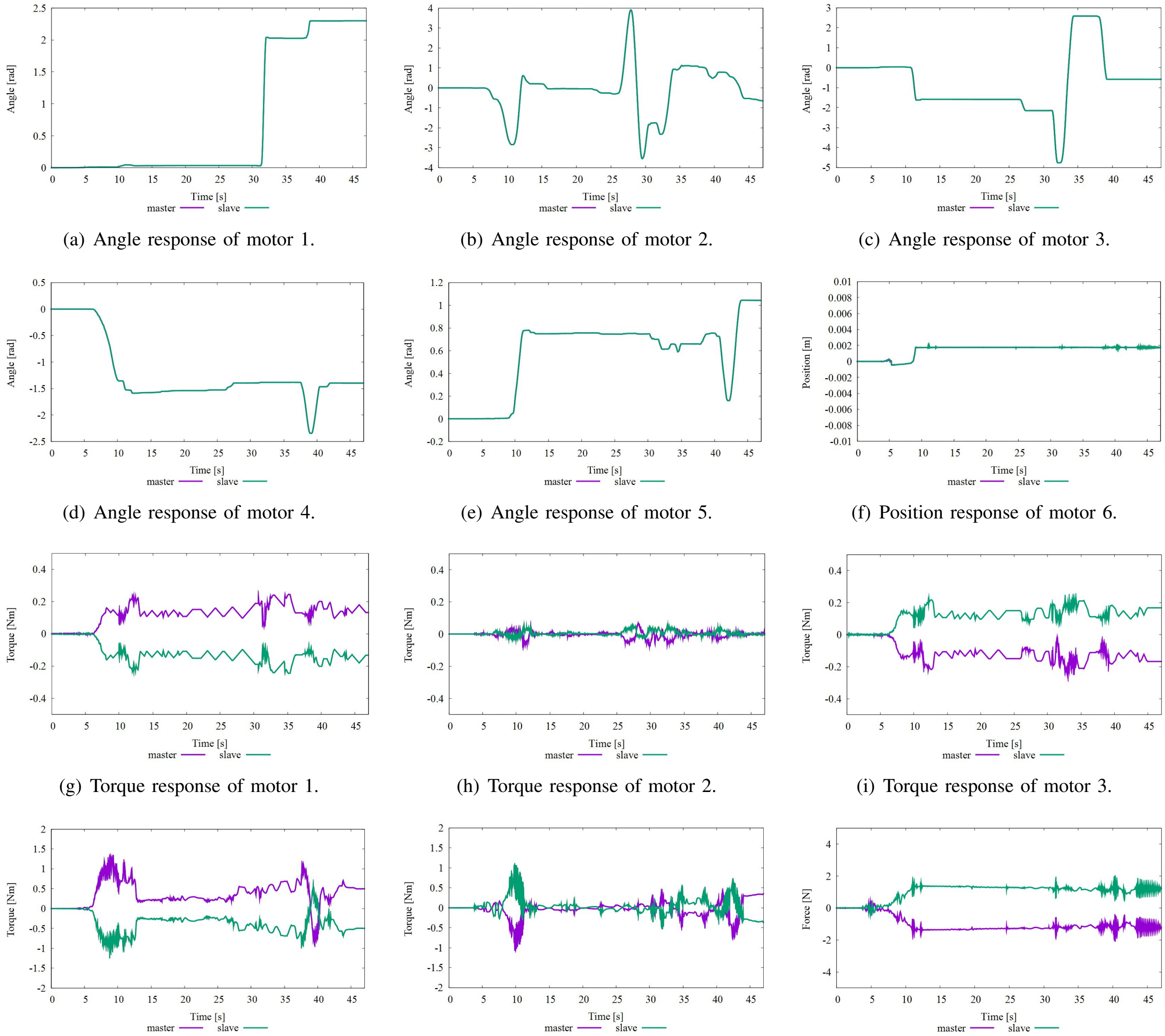
$$q_m - q_s = 0 \tag{1}$$

$$f_m + f_s = 0 \tag{2}$$

where, q shows the positon and f shows the reaction force. The subscripts m, s show master and slave. Handling the position control and the force control severally is difficult. However, the target of position control and the target of force control can be achieved simultaneously by the high-precision acceleration control using DOB. The acceleration references

TABLE I
PARAMETER OF EXPERIMENTAL SYSTEM

Description	Parameter	q_1, q_2, q_3	q_4	q_5	q_6
Nominal inertia (mass)	$J_n(M_n)[\mathrm{mgm}^2(\mathrm{kg})]$	0.4	100	150	0.035
Nominal thrust constant	$K_{tn}[\mathrm{mNm/A}]$	8.54	65.0	65.0	12.44
Position gain	$K_p[1/\mathrm{s}^2]$	10000	10000	6400	6400
Velocity gain	$K_v[1/\mathrm{s}]$	200	200	160	160
Force gain	$K_f[1/\mathrm{kgm}^2(1/\mathrm{kg})]$	50000	20	200	10
Cut-off frequency of DOB	$g^{dis}[\mathrm{rad/s}]$	600	600	600	300
Cut-off frequency of RFOB	$g^{rfob}[\mathrm{rad/s}]$	600	600	600	300



(a) Angle response of motor 1. (b) Angle response of motor 2. (c) Angle response of motor 3.

(d) Angle response of motor 4. (e) Angle response of motor 5. (f) Position response of motor 6.

(g) Torque response of motor 1. (h) Torque response of motor 2. (i) Torque response of motor 3.

(j) Torque response of motor 4. (k) Torque response of motor 5. (l) Force response of motor 6.

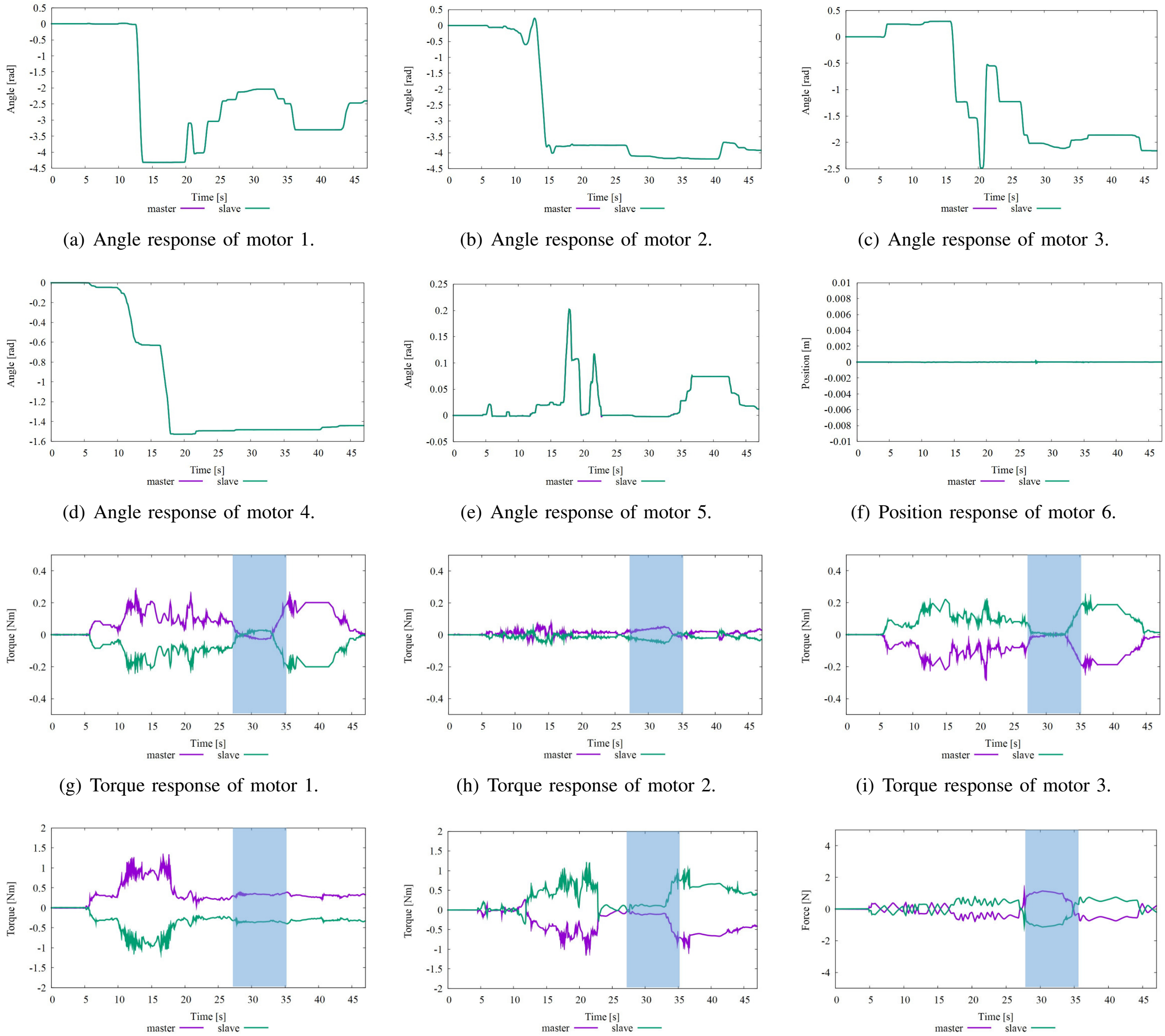
Fig. 7. Experimental results in free motion.

$\ddot{q}_m^{ref}$, $\ddot{q}_s^{ref}$ are calculated as follow:

$$\ddot{q}_m^{ref} = C_p(s)(q_s - q_m) - C_f\left(\hat{f}_s^{ext} + \hat{f}_m^{ext}\right) \quad (3)$$

$$\ddot{q}_s^{ref} = C_p(s)(q_m - q_s) - C_f\left(\hat{f}_m^{ext} + \hat{f}_s^{ext}\right) \quad (4)$$

where, $\hat{f}_m^{ext}$, $\hat{f}_s^{ext}$ are the reaction force of the master-slave system that are estimated by RFOB. $C_p(s)$ is a position controller that consists of position gain K_p and velocity gain K_v, and C_f is a force controller that consists of force gain



(a) Angle response of motor 1. (b) Angle response of motor 2. (c) Angle response of motor 3.

(d) Angle response of motor 4. (e) Angle response of motor 5. (f) Position response of motor 6.

(g) Torque response of motor 1. (h) Torque response of motor 2. (i) Torque response of motor 3.

(j) Torque response of motor 4. (k) Torque response of motor 5. (l) Force response of motor 6.

Fig. 8. Experimental results in drill motion.

TABLE II

AVERAGE ERROR OF EXPERIMENT

	free motion		drill motion	
	e_q [rad (m)]	e_f [Nm (N)]	e_q [rad (m)]	e_f [Nm (N)]
motor 1	7.8×10^{-6}	3.3×10^{-6}	3.7×10^{-6}	8.1×10^{-5}
motor 2	1.2×10^{-6}	3.6×10^{-6}	1.5×10^{-6}	1.9×10^{-4}
motor 3	5.6×10^{-6}	3.5×10^{-6}	2.9×10^{-6}	7.3×10^{-6}
motor 4	3.1×10^{-6}	1.7×10^{-4}	2.2×10^{-6}	6.9×10^{-4}
motor 5	2.8×10^{-6}	4.7×10^{-4}	9.2×10^{-6}	5.3×10^{-3}
motor 6	3.2×10^{-7}	8.1×10^{-6}	7.1×10^{-8}	1.6×10^{-5}

K_f as follow:

$$C_p(s) = K_p + K_v s \tag{5}$$

$$C_f = K_f. \tag{6}$$

IV. EXPERIMENT

By using the proposed robot that implements ABC, the performance of the proposed robot is validated by the experiment. The experiment is carried out in a free motion and a drill motion. In the free motion, the end-effector of the slave robot has no contact with the object. In the drill motion that the end-effector of the slave robot drills the wood instead of the bone, the force matching that occurs between the master robot and the slave robot is verified.

Fig. 6 shows the experimental setup. The master robot has a drill mock made by the 3D printer and the slave one has a dental drill as the end-effector. The operator grasps the drill mock and drills the wood by remote control. The dental drill drives by a foot pedal and rotates 800 rpm. Table I shows parameters of the experimental system. Each parameter is decided experimentally. Fig. 7 shows the experimental results of angle responses and torque responses in free motion. Fig.

8 shows the experimental results of angle responses and torque responses in the drill motion.

From Fig. 7 and Fig. 8, each angle response of the slave robot follows each angle response of the master robot. Besides, each torque response of the slave robot and the master robot are following the law of action and reaction. Hence, the control target of ABC was achieved.

In the free motion that is shown in Fig. 7, except motor 2, large torque caused by the gravity effect was generated. The torque for supporting the gravity of robot occurs. Motor 2 is not relative to gravity because motor 2 is used for a horizontal direction. Hence, the torque of motor 2 caused by the gravity is almost zero. In the drill motion that is shown in Fig. 8, the reaction force can be observed at motor 1 and motor 3 in a period from 27.0 s to 35.0 s. Motor 1 and motor 3 are used for the pitch motion and the slave robot drills the wood from above. Therefore, the reaction force is received by motor 1 and motor 3. The other motors are not relative to pitch motion. Table II shows the average errors of master and slave responses in the free motion and the drill motion. Let e_q and e_f be the error of the position response and the error of force response, respectively. All average errors are small enough, therefore it is confirmed that the developed robot can transmit the haptic sensation well. The utility is validated.

V. Conclusions

In this paper, a haptic robot using bilateral control for assisting dental surgery was developed. The proposed robot has two parts, one is the parallel link part and the other is the end-effector part. The parallel link part has three DOF (heaving, pitching and yawing). The parallel mechanism can achieve multi DOF without many motors that are installed near the end-effector. The end-effector part has three DOF (rolling, RCM, and linear motion). The proposed robot is the master-slave system and ABC is implemented. In the experiment, the control target of ABC could be achieved and haptic sensation between the master robot and the slave robot could be communicated. The utility of the proposed robot was confirmed from the results. As future works, ABC in the workspace is implemented and the navigation system is developed.

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