2P4-10

Haptic device using an ultrasonic motor with an elastic mechanism

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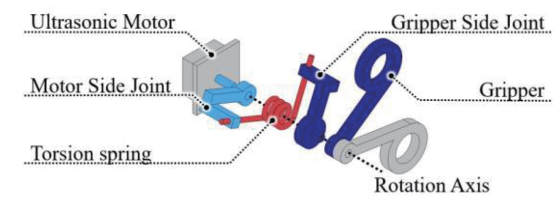
1. Introduction

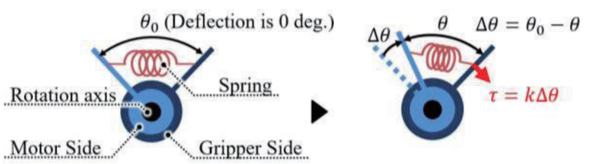
Haptic feedback in remote surgery has the potential for overcoming problems such as prolonged surgical procedures, decreased tactile precision, and tissue or organ damage[1)]. Ultrasonic motors are expected to be suitable for haptic feedback in the robotic surgery because of their excellent positional precision, responsiveness, and non-magnetic properties which make them compatible with MRI environments. However, due to their high holding torque, ultrasonic motors lack flexibility, and particularly in torque control, significant torque errors occur when the rotation direction is reversed[2)]. These errors can be reduced by introducing an elastic element between the ultrasonic motor's shaft and target object[3)]. An important finding was the rate of the error reduction and the response time of the system have a trade-off depending on the spring constant of the elastic element[3)]. Therefore, in this study, the effect of the spring constant on the torque errors and the response time were investigated for haptic feedback applications.

2. Elastic mechanism

Fig. 1 shows an elastic mechanism introduced between the output shaft of the ultrasonic motor and the gripper operated by the surgeon to improve the torque control. By driving the ultrasonic motor to change the angular gap between the two arms of the spring, the spring is deformed. When the deflection angle is $\Delta\theta$, the spring with a spring constant of k transmit a torque of $T = k\Delta\theta$ to the gripper.



(a)



(b)

Fig. 1 Elastic mechanism, (a) Conceptual structure, (b) System of outputting the torque.

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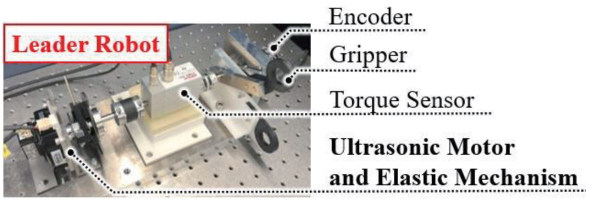
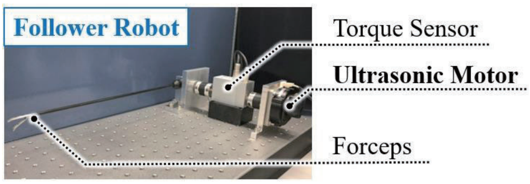
3. The prototype of a teleoperated surgical robot

Using the elastic mechanism, a prototype of a 1-DOF teleoperated surgical robot with haptic feedback was developed (**Fig. 2**). This robot consists of a leader robot operated by the surgeon and a follower robot providing the medical treatment to the patient. Regarding the positional control of the forceps, when the surgeon grasps the leader's gripper, the follower's motor rotates to open and close the forceps coincident with the gripper's movement. Concerning the feedback force control, the leader's motor rotates to transmit a torque equal to the measured torque of the follower's motor to the gripper, tracking the gripper's movement.



(a)



(b)

Fig. 2 Teleoperated surgical robot, (a) Leader robot, (b) Follower robot.

4. Torque control experiment

For designing a haptic device, the feedback force resolution, the response time, and the representable impedance should be considered. Measurements were conducted on the error in feedback torque during operation which influences the resolution, and the response time. For these experiments, two types of springs with different spring constants were prepared. In addition, a servo motor was connected to the ultrasonic motor and elastic mechanism in place of the gripper to replicate the movement of the surgeon's operation of the gripper.

4.1 Torque error measurement

Supposing the situation where the surgeon operates the gripper, a sinusoidal rotational motion generated using a servo motor. A constant target torque of 0.2 Nm was commanded, and the ultrasonic motor was controlled to rotate by keeping the constant spring deflection outputing the target torque. The maximum error between the feedback torque and the target torque was measured. As a comparison, the same experiment was also conducted with a direct drive of the ultrasonic motor without the elastic mechanism.

The results are shown in **Fig. 2**. Torque errors were mitigated with the introduction of the elastic mechanism. Moreover, it was observed that torque errors are reduced when using a smaller spring constant. At a minimum, 125 % of the required resolution of 10 mNm was achieved in this experiment.

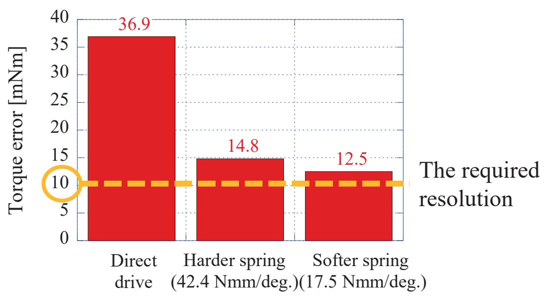


Fig. 2 Result of the torque error

4.2 Response time measurement

As for the response time, the rise time of the step response to a target torque was evaluated. Consider the time Δt required to response a step-like target torque change from T_1 to T_2. In that case, the ultrasonic motor rotates to change the deflection angle from θ_1 to θ_2. Assuming the non-linear torque-speed relationship of the ultrasonic motor as $v_{deg./s} = f(T)$ and the angle-torque relationship for the elastic mechanism as $T = g(\theta)$, a following equation can be obtained:

$$v_{deg./s} = \frac{d\theta}{dt} = f\{g(\theta)\} \tag{1}$$

By separating variables and performing definite integrals on both sides, Δt can be expressed as follows:

$$\Delta t = \int_{\theta=\theta_1}^{\theta=\theta_2} \frac{1}{f\{g(\theta)\}} d\theta \tag{2}$$

Using equation (2), the relationship between the spring constant and the rise time was calculated for the case of a torque change from 0 Nm to 0.2 Nm.

Both calculation and experimental results are shown in **Fig. 3**. Experimental results were agreed with the calculated results. A delay time of less than 50 ms, necessary to avoid distorting the perception of the grasped object's stiffness[1], was achieved.

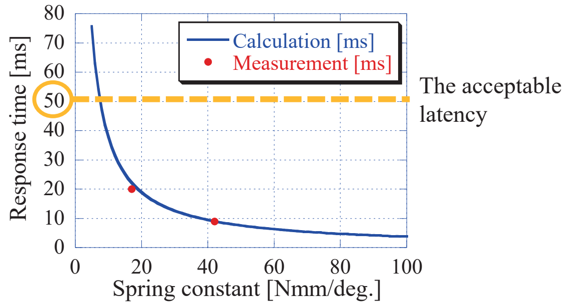


Fig. 3 Result of the response time

5. Haptic feedback experiment

Using the surgical robot, the accuracy of impedance represented by the elastic mechanism with the measured torque error and response time was evaluated. Three different materials; sponge, styrofoam, and iron were grasped using the forceps of the robot. By linearly approximating the curves of the rotational angle of the gripper and the output torques, the perceived hardness of the material by the follower and that by the surgeon at the leader were measured.

As shown in **Table I**, when grasping the iron, the error in perceived hardness by the surgeon was quite large because of the ultrasonic motor's holding torque.

Table I Result of the haptic feedback experiment

	Leader [Nmm/deg.]	Follower [Nmm/deg.]	Error [%]
Sponge	3.12	3.10	0.65
Styrofoam	30.0	28.7	4.50
Iron	47.0	59.8	21.4

6. Conclusion

In this study, the torque error and response time were evaluated by introducing an elastic mechanism to the ultrasonic motor. Additionally, using the teleoperated surgical robot, the evaluation of the accuracy of the hardness of the grasped material feedbacked to the surgeon was conducted.

Acknowledgment
This work was supported by Shinsei Corporation and Nachi-Fujikoshi Corporation.

References

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