Control of haptic master – slave robot system for minimally invasive surgery (MIS)

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Abstract. In this work, 4 degrees-of-freedom (DOF) haptic master featuring electrorheological (ER) fluid is proposed and integrated with a slave. Using an ER fluid, the haptic master is devised which can generate a repulsive force/torque with the 4-DOF motion and provide stimulus information to operator. For realization of master-slave MIS system, an encoder is installed with the ER haptic master to establish the MIS master system. The motion command of the haptic master is realized by slave surgery robot. In order to follow the motion of the haptic master, the mechanism of slave surgery robot is devised. Accordingly, the haptic master-slave system is established by incorporating the slave robot with the haptic master device in which the repulsive force/torque and desired position are transferred to each other. In order to obtain the desired torque trajectories, a sliding mode controller (SMC) is designed and implemented. It has been demonstrated that the desired effective torque tracking control performance is well achieved using the proposed master-slave system.

1. Introduction
Recently, it is very popular to apply robotic technology to modern medical industry, such as minimally invasive surgery (MIS) [1]. Typically, the MIS needs the robot to perform surgery through the usage of long surgical instruments that are inserted through incision points. From the patient’s point of view, the advantages of the MIS are less injury to tissue, higher accuracy rate, shorter hospital stay and less pain. But, from the viewpoint of surgeon, the MIS systems only send back visual information and cannot provide information about viscosity and stiffness of the touched tissue or organ. This causes the surgeon not to feel what is happening inside abdomen of patient. Therefore, it is very important to develop the haptic master robot system.

Several medical haptic devices featuring kinesthetic force feedback have been researched and developed for the medical training environment using a simulator and virtual reality, in which a haptic system provides kinesthetic force information of virtual patients to a doctor. Among them, two types of actuation mechanism are common: passive and active types. Although the passive type is known to be safe, the active type using electric motor is widely used as a repulsive force or torque generating actuator. However, it has a complicated mechanism, safety problem and difficulty in continuous force control [2, 3]. In order to adopt a medical haptic master in a real operation room, these problems

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should be solved. Subsequently, diverse researches about haptic master using smart materials such as
electrorheological (ER) fluid have been researched. ER fluid is able to change their rheological
properties such as yield stress by applying electric field. The advantages of ER fluid are also fast
response, simple mechanism, continuous force and high stability. These features are ideal properties
for haptic master devices in which various different strengths of forces are simulated.

Many master-slave systems have been proposed such as the Polish cardio-robot RobIn Heart (RIH)
system [4, 5] and the force-reflecting MC2E system [6, 7]. Among these master-slave systems, the
most commercially successful robot master-slave systems are da VinciTM from Intuitive Surgical Inc.
[8] and Zeus from Computer Motion Inc. [9] during last decades. These robot systems have large and
complex mechanism. So, small and simple slave robot has recently been researched [10, 11].

The main objective of this research is to propose a haptic master device using ER fluid and slave
surgery robot. The purpose of haptic master device is not only to generate motion commands for
the slave robot but also to generate the physical constraints of the slave robot to the surgeon. Also, in
order to follow the motion of the haptic master, the new mechanism of slave surgery robot is devised.
Kinematic model of slave surgery robot is analysed. Using the master and robot kinematics, the
interface communication between the proposed haptic master and slave robot is discussed.
Accordingly, the haptic master-slave system which can transfer the repulsive force/torque and desired
position to each other is established by incorporating the slave robot with the master device. In order
to obtain the desired force/torque and position trajectories, a sliding mode controller (SMC) is
designed and implemented. It has been demonstrated that the desired effective torque tracking control
performance is achieved in the time domain.

2. 4DOF ER haptic master
During MIS, the instruments and laparoscope always inserted through fixed small incisions. So, the
required motion of MIS is four (three rotation motions and one translation motion). Accordingly, in
order to operate the slave surgery robot and generate the repulsive force/torque, the 4 DOF haptic
master device is proposed and shown in figure 1. It consists of two actuators: ER spherical joint for 3
DOF rotation motion and ER damper for 1 DOF translation motion. ER spherical joint has been
designed and manufactured in the previous study [12]. Detailed geometric shape and modeling of ER
damper is discussed.

Figure 1. Configuration of 4 DOF haptic master. 

Figure 2. Schematic configuration of ER damper.
In order to realize translational motion, cylindrical ER damper is devised. Figure 2 shows the proposed ER damper consists of columns, piston, inner and outer cylinder. Function of column is to transfer yawing motion of piston to spherical joint. So, if operator rotates the piston, then this motion is transmitted to ER spherical joint via bottom plate. The ER damper is divided into the upper and lower chambers by the piston. These chambers are filled with the ER fluid. When the piston moves, the ER fluid flows from one chamber to the other chamber via the annular duct. The inner cylinder is connected with the positive voltage produced by a high voltage supply unit, playing as the positive (+) electrode. The outer cylinder is connected with the ground playing as the negative (-) electrode. On the other hand, the gas chamber located outside of the annular duct as an accumulator of the ER fluid induced by the motion of the piston. By neglecting the compressibility of the ER fluid, the frictional force and assuming quasi-static behavior of the damper, the damping force can be derived as follows [13]:

\[
F_z = P_1(A_p - A_f) - P_1(A_p - A_s - A_f) = P_dA_s + c_{vis}\dot{x}_p + F_{ER}\text{sgn}(\dot{x}_p),
\]

where \(c_{vis} = \frac{6\mu L}{\pi R t_g} \left( A_p - A_s - A_f \right)^2 \), \(F_{ER} = (A_p - A_s - A_f) \frac{cL}{t_g} \tau_y \), \(\dot{x}_p\), \(A_p\), \(A_s\), \(A_f\) are the piston area, the piston-shaft cross-sectional areas and two column area, respectively. \(P_1\), \(P_2\) and \(P_d\) are pressures in the upper, lower and gas chamber of the damper, respectively. \(P_0\) and \(V_0\) are initial pressure and volume of the accumulator. \(\gamma\) is the coefficient of thermal expansion which is ranging from 1.4 to 1.7 for adiabatic expansion. \(x_p\) is the piston displacement. In this configuration, gas chamber is open. So, \(P_o\) is always constant value, atmospheric pressure. In order to simplify the design procedure, stroke of the translation device is fixed by 40mm which is proper value to surgically operate patients and gap size is also fixed by 1 mm. In order to design compact device, the minimum value of \(r_p\) is 25 mm. With these design values, calculated repulsive force is 98 N which people can sense a change of the force enough.

3. Slave surgery robot

In the previous section, an ER haptic master is proposed. The ER haptic master commands slave surgery robot to operate the surgery. From the slave robot, the repulsive force/torque is measured. This force/torque signal is transferred and generated by ER haptic master. In order to follow the motion of the proposed master, a new mechanism for MIS robot is proposed and analysed.

During MIS, the instrument is inserted through fixed small incision of patient. So, it is important to realize the pivot rotation motion, a mechanism of slave robot featuring fixed bar and gimbal structure is proposed as shown in figure 3. Ball joint of the fixed bar is assumed as small incision of patient and gimbal structure can smoothly rotate the instrument around the ball joint. Slave robot is composed of five active joints. Four revolution joints determine a position of end position of slave robot arm. In order to maintain horizontality of gimbal structure, other revolution joint rotates gimbal structure. It is helpful to stable the system. The other revolution joint rotates instrument following the yawing motion of master. The fixed bar can hold the instrument to realize pivot rotation motion. \(l_1\) is the length from bottom to first arm, \(l_2\) is the length of first arm, \(l_3\) is the length of second arm. \(l_4\) is the length of instrument. \(l_5\) is the length from robot to fixed pivot point on X-axis. \(\theta_1\) is angle of robot on Z-axis. \(\theta_2, \theta_3\) are angle of robot arm, respectively. Using forward and inverse kinematics of robot, the rotation angle of each slave surgery robot arm is derived as follows:

\[
\theta_1 = \arctan\left(\frac{y}{x}\right), \theta_2 = \arctan\left(\frac{c}{\sqrt{a^2 + b^2 - c^2}}\right) - \arctan\left(\frac{a}{b}\right), \theta_3 = \arctan\left(\frac{x \cdot \cos(\theta_3) + y \cdot \sin(\theta_3) - L_s \cdot \cos(\theta_s)}{L_s + L_z \cdot \sin(\theta_s) - z}\right) - \theta_2,
\]

\[
\theta_4 = \frac{\pi}{2} - \theta_2 - \theta_3, \quad \text{where} \quad a = -2L_z(x \cdot \cos(\theta_s) + y \cdot \sin(\theta_s)), b = 2L_z(L_s - z), \quad c = L_s^2 \left( x \cdot \cos(\theta_s) + y \cdot \sin(\theta_s) \right)^2
\]
From the MIS robot, the repulsive force/torque such as viscosity and stiffness of the touched tissue or organ is measured and transferred to the haptic master. Then, the haptic master generates a repulsive force/torque using ER fluid.

4. Tele-operation control
ER fluids are known to exhibit hysteretic behaviors. Mechanical friction also exists at the spherical joint. This requires robust control schemes such as a sliding mode controller (SMC). So, SMC for haptic master has been designed in the previous study [14].

\[
\begin{align*}
    \dot{u} &= \frac{1}{\omega_n^2} \left( c \dot{\theta}_i + \ddot{\theta}_i \omega_n^2 + 2 \zeta \omega_n \dot{\theta}_i + \omega_n^2 T_i + k_{sat}(S) \right), \quad k > |d| \\
    u &= \frac{1}{\omega_n^2} \left( c \dot{\theta}_i + \ddot{\theta}_i \omega_n^2 + 2 \zeta \omega_n \dot{\theta}_i + \omega_n^2 F + k_{sat}(S), \quad |k| > |d| \right)
\end{align*}
\]

Figure 4 shows the photograph of the manufactured haptic master combined with the ER spherical joint and the ER damper. In order to measure positional information to be transferred to the slave system, two spherical link with encoders (Omron) are adopted to the joint. When operator moves the gripper of the master system, position information such as rotational angle is obtained from encoders (Omron), whose resolution is 3600 pulse/rotation, and transferred to the slave system. Figure 5 shows the photograph of the manufactured slave robot. Slave robot is operated and deforms the object upon the position information. Each servomotor of slave robot is controlled by built-in microprocessor. PID controller is programmed in microprocessor. At the same time, the force/torque, which is to be reflected to the user, is measured by force sensor as shown in figure 6. The generated force/torque of haptic master is measured by a 6 axes force sensor (ATI, Nano17) at the mid point of the gripper. The SMC given by Eq. (13) and (15) is then activated to reflect the desired force/torque from slave robot. For palpation test, poached egg is used.
**Figure 4.** Manufactured 4 DOF ER haptic master.

**Figure 5.** Manufactured slave robot.

**Figure 6.** Experimental apparatus of master and slave robot system.

**Figure 7.** Position tracking control results.

**Figure 8.** Torque tracking control results.
The operation link was freely moved by a voluntary person in back-and-forth manner and its position information of master was transferred to the slave robot. Figure 7 presents position tracking results of the slave robot about Y axis. At the same time, the measured torque signal is transferred to the master. Figure 8 presents torque tracking control responses of rotation motion about Y axis. From the result, it is clearly seen that the desired torque trajectories from slave robot are well achieved without exhibiting significant tracking errors. From these results, the proposed slave system was successfully operated and communicated with the master without time delay problem.

5. Conclusion
In this study, a haptic master device using ER spherical joint and ER damper for MIS robot was proposed and integrated with the slave robot. The ER damper was designed based on the Bingham model. In order to realize motion of the 4 DOF ER haptic master, a new mechanism of slave surgery robot was proposed. Kinematic analysis of the slave robot was studied. For implementation of MIS robot system, the interface communication between master and slave robot has been analysed. Accordingly, the haptic master-slave system has been established by incorporating the slave robot with the master device in which the repulsive force/torque and desired position are transferred to each other. In order to obtain the desired torque trajectories, a sliding mode controller (SMC) was designed and empirically implemented. It has been demonstrated that the desired effective torque tracking and position control performances are well achieved. It is finally remarked that the haptic master and slave robot developed in this work will be incorporated with the wireless communication for MIS application in the near future.

Acknowledgments
This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2010-0015090). This financial support is gratefully acknowledged.

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