Design of a new haptic device and experiments in minimally invasive surgical robot

Tao Wang, Bo Pan, Yili Fu, Shuguo Wang and Yue Ai
State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, China

ABSTRACT
In this paper, we designed a 8 degrees of freedom (DOFs) haptic device for applications in minimally invasive surgical robot. The device can provide three translational, three rotational and a grasping motion and force feedback capability. It is composed of three parts, including an arm mechanism, a redundant wrist mechanism and a grasping mechanism. The kinematics and gravity compensation algorithms are also detailed in the paper. In addition, the haptic device and a slave surgical robot for minimally invasive surgery (MIS) developed by our lab are integrated as a master-slave surgical robotic system in this paper. In the master-slave robotic system, a new control system is designed to realize real-time master-slave control based on EtherCAT bus technology. Experiments show that the haptic device can effectively compensate gravity at any position in its workspace and successfully realize master-slave operation by the control method, which prove the haptic device designed in this paper can be used as a master manipulator to control the surgical robot.

1. Introduction
In nowadays society, MIS has been widely accepted by patients for its advantages such as: reduced trauma, fast recovery time, less pain and short time hospital care. Nevertheless, due to its own characteristics there are many limitations of the traditional MIS techniques especially for surgeons. The main disadvantages of the traditional MIS include: limited motion DOFs of instrument, fulcrum effect, long training time of surgeon [1–3]. Introducing robotic techniques has brought in great improvements to traditional medical technology [4–5]. The direct results are the appearance of many medical robots to assist surgeons performing MIS. The surgical robots well resolve the problems of traditional MIS and give advantages of enhanced dexterity in operation, 3D image display, intuitive hand eye coordination manipulation, ergonomics and comfort for surgeons [6–7].

The most successful MIS surgical robot da Vinci, produced by Intuitive Surgical Inc., has done hundreds of thousands of cases and brought in great economic and social benefits [8]. Many other prototypes of robotic surgical systems have been successfully developed in research institute and colleges. Raven-II built on the first Raven platform is designed as an open surgical robot platform for research leading to improved performance and new capabilities relative to existing teleoperated surgical robots [9]. The DLR MiroSurge is a versatile system designed to be expandable and useful in multiple surgical applications. The MiroSurge allows for bimanual endoscopic telesurgery with force feedback [10]. The university of Western Ontario designs a haptics-enabled dual-arm (two master two slave) robotic MIS test-bed to investigate and validate the effect of haptics on telesurgical scenarios [11]. These systems have given a lot of research achievements that stimulate the development of robotic surgical technology.

As the medium between surgeon and executive manipulators, the haptic device (also named master manipulator) directly determines the surgeons’ operational feelings and the surgical robot ergonomics. However, most robotic surgical systems use the commercialized general purpose haptic devices to build the systems. The DLR MiroSurge integrates omega.7 haptic device and later new type sigma.7 as the master manipulator to control the slave robot arm, but the cost of sigma.7 is not affordable by most institutes [12]. The Raven-II utilizes Omni as the master controller, however its workspace is relatively small and...
cannot provide torque feedback [9]. The university of Western Ontario designs an 7 DOF force feedback haptic device for a MIS test-bed, nevertheless it has the tradeoff with a lower range of motion in two orientation DOFs [13]. A general purpose 7 DOF haptic device toward robot-assisted surgery also developed by Drexel University, but only a simulation of needle insertion has been developed to test its function [14].

In this paper, a new haptic device, in order to improve these disadvantages, is developed and a master-slave surgical robotic system with the novel haptic device is constructed. The rest of this paper is organized as follows: section 2 describes the development of this haptic device. The next section presents the setup of master-slave surgical robotic system. Experiments and discussion are completed in section 4. Finally conclusions are given in section 5.

2. Development of the haptic device

2.1 Mechanical design of the haptic device

During a robotic MIS, the surgical robot basically replaces the surgeon performing surgery at the patient side compared to traditional ways. The surgical robot is usually designed as two parts according to its function, a surgical instrument which has an enhanced dexterous end effector. And a special mechanism named remote center-of-motion (RCM) mechanism, which assures the surgical instrument moving around a fixed point on the patient’s body [15]. For these functions, the slave surgical manipulator usually has seven DOFs. Hence, the haptic device needs at least seven DOFs to fully control the slave surgical manipulator. That is, the haptic device should provide three translational, three rotational and a grasping motion.

According to the requirements of slave surgical manipulator, our haptic device is designed as a 8 DOFs haptic manipulator which can provide three translational, three rotational and a grasping motion. The corresponding function is implemented by three parts, namely, an arm mechanism, a wrist mechanism and a grasper mechanism. First joint of the wrist mechanism is active, which can not only drive the wrist mechanism avoiding singularities but also increase the motion range of the wrist joints. The prototype and details of the haptic device are shown in Figure 1.

The arm mechanism providing three translational motions is composed of the first three joints and corresponding links. It is essentially a serial structure with an auxiliary link. The prototype shows that the joint1 was placed as vertical joint while joint2 and joint3 were placed as horizontal joints. This configuration forms anthropomorphic arm which can achieve the largest workspace. Each joint is driven by a maxon RE30 motor. The transmission system including capstan, steel cable and disk is used to increase motor output torque as well as reduce inertia. The auxiliary link, link3 and disk3 form a parallelogram structure, in which way the actuator is capable of being

![Figure 1. The design and prototype of haptic device.](image)
prepositioned. This way of configuration can reduce the total inertia of whole haptic device. Furthermore, a high resolution absolute encoder is attached to each joint to measure the revolute angle.

The wrist mechanism is mounted on the arm mechanism output and moves along with the arm mechanism. It has a serial kinematics structure with an arrangement of four revolute joints having intersecting axes in a point named center of wrist. The axes are mutually orthogonal in a nominal posture. This way of configuration ensures freely adjusting the rotational motion while not disturbing the translational position. The links of the wrist mechanism are designed as L-shape links. Each link is fixed with a maxon motor DCX16 and bevel gears are used to change the output torque direction. The link4 CAD model shows the details. As previously mentioned, the joint4 is an active joint while the other three are passive joints. The existence of the motor is to compensate gravity and friction as well as force reflection if necessary. An absolute encoder is attached to each joint to measure the rotation angle which is used to calculate the kinematics and dynamics of the haptic device.

The grasper mechanism is designed to realize the grasping movement and feedback force to the thumb and forefinger. The operator can comfortably hold the grasper mechanism body and use the forefinger to control the grasping angle. The motor is used to provide driving force and the capstan transmission system is used to increase output torque. The CAD model clearly shows how it works.

### 2.2 Kinematics and workspace analysis

The haptic device is used as the master manipulator in MIS robotic system. During the MIS, a surgeon holds the haptic device grasper to teleoperate the slave surgical manipulator. The haptic device should transmit the surgeon’s hand motions to the slave side essentially by its position and orientation.

In order to get the grasper’s position and orientation, the kinematics of the haptic device should be obtained. The Denavit-Hartenberg method is used to derive the kinematic equations of this type of manipulator. According to the mechanical structure of the haptic device, the D-H coordinate system is established as shown in Figure 2. Note that the grasper is an independent degree of freedom and it controls the surgical instrument grasping, which is not included in calculating the kinematics. The center of wrist is as the position calculation point while the grasper frame is as the orientation calculation frame.

The D-H parameters of each link is listed in Table 1.

The homogeneous transformation matrix of each link can be written as:

\[
i^{-1}A = \begin{bmatrix}
    cos\theta_i & -sin\theta_i & 0 & a_{i-1} \\
    sin\theta_i cos\alpha_{i-1} & cos\theta_i & -sin\alpha_{i-1} & -d_i sin\alpha_{i-1} \\
    sin\theta_i sin\alpha_{i-1} & cos\theta_i & cos\alpha_{i-1} & d_i cos\alpha_{i-1} \\
    0 & 0 & 0 & 1
\end{bmatrix}
\] (1)

Substituting the D-H parameters into Equation (1) and multiplying the homogeneous transformation matrix sequentially, we obtain the kinematics of the haptic device:

\[
{}^0T = {}^0A_1A_2A_3A_4A_5A_6A_7 \begin{bmatrix}
    n_x & o_x & a_x & p_x \\
    n_y & o_y & a_y & p_y \\
    n_z & o_z & a_z & p_z \\
    0 & 0 & 0 & 1
\end{bmatrix}
\] (2)

For simplifying of which, we just list the details of the position items:

\[
\begin{align*}
p_x &= c_i(a_3c_{23} + d_4s_{23} + a_2c_2) \\
p_y &= s_1(a_3c_{23} + d_4s_{23} + a_2c_2) \\
p_z &= a_3s_{23} - d_4c_{23} + a_2s_2
\end{align*}
\] (3)

In these equations, \( s_i, c_i, s_{ij}, c_{ij} \) represent the shorthand notation for \( sin\theta_i \), \( cos\theta_i \), \( sin(\theta_1 + \theta) \) and \( cos(\theta_1 + \theta) \) respectively, in which \( i, j = 1, 2, \ldots, 7 \). The symbols in the following sections have the same meaning.

The haptic device rotates about the first joint from \(-45^\circ\) to \(+45^\circ\). The rotational range for the second joint is from \(-145^\circ\) to \(-30^\circ\), and for the third joint is from \(+30^\circ\) to \(+120^\circ\). The length of second link a2 and third link a3 are 350 mm and 375 mm respectively. The link offset between link 3 and link 4 is 141.5 mm.

Using MATLAB and formula (3) we can draw the translational workspace of haptic device by adopting Monte Carlo Method [16]. The obtained point cloud forms the translational workspace shape of the haptic device and is shown in Figure 3. The red stars stand for random positions that the haptic device can reach. Inside the workspace, a rectangular cube with dimensions of 330 \( \times \) 400 \( \times \) 300 mm is drawn by blue lines. It intuitively gives us the size of the haptic device workspace. The workspace is a larger workspace compared to the commercialized haptic devices. The Omni only provides 160 \( \times \) 120 \( \times \) 70 mm in width, height and depth. The Sigma7 offers a workspace of \( \Phi190 \times 130 \) mm, which is smaller than the workspace of our device. The university of Western Ontario haptic device has a workspace with 480 \( \times \) 450 \( \times \) 250 mm, but its orientation motion range is relatively lower with roll \( \pm 85^\circ \), pitch \( \pm 65^\circ \), yaw \( \pm 85^\circ \). Owning to the design of the active wrist joint, the orientation motion range of our haptic device reaches to roll \( \pm 90^\circ \), pitch \( \pm 90^\circ \), yaw \( \pm 85^\circ \) almost inside its workspace. The active wrist
joint also makes the wrist mechanism more dexterous than other haptic device which usually adopts to three mutually orthogonal joints.

2.3 Gravity compensation with active method

During the surgical procedures, the surgeons operate the haptic device at a relative low velocity, so the dynamic effects of the haptic device can be neglected. However, gravity is an important factor affects the manipulability, because persistent gravity easily makes the surgeon fatigue. Therefore, the effects of gravity should be compensated. Counterbalance masses can be used to compensate gravity but with the shortcoming of increasing the overall masses and the effective inertia of the haptic device. In our design, we use the motor output torque to actively compensate the gravity effects.

To compensate for the weights of the haptic device all over the workspace, the torque each joint generated by gravity should be derived. The gravity applied to each joint of the robot is calculated using potential energy of the links and Lagrange formulation.

![Kinematic model of haptic device](image)

Table 1. D-H parameters for haptic device.

| Joint | $z_{i-1}$ (°) | $a_{i-1}$ (mm) | $o_{i}$ (°) | $d_{i}$ (mm) | Motion range (°) |
|-------|---------------|----------------|-------------|-------------|-----------------|
| 1     | 0             | 0              | 0           | 0           | $-45 \sim 45$   |
| 2     | 90            | 0              | $-90$       | 0           | $-145 \sim -30$ |
| 3     | 0             | $a_{2}$        | 90          | 0           | 30 $\sim 120$   |
| 4     | 90            | $a_{3}$        | 90          | $d_{4}$     | 0 $\sim 180$    |
| 5     | 90            | 0              | 0           | 0           | $-90 \sim 90$   |
| 6     | 90            | 0              | 90          | 0           | 0 $\sim 180$    |
| 7     | 90            | 0              | 0           | 0           | $-90 \sim 90$   |
The potential energy of each link is calculated by equation:
\[ u_i = m_i \dot{g}^T \dot{p}_c, \quad i = 1, 2, \ldots, 7 \] (4)

Where \( \dot{g}^T \) is the 3 \( \times \) 1 gravity vector, \( \dot{p}_c \) is the vector locating the center of mass of the \( i \)th link, and the reference coordinate is chosen as the zero reference potential energy.

The total potential energy stored in the manipulator is given by
\[ u = \sum_{i=1}^{7} u_i \] (5)

The gravitational vector is derived as:
\[ G(\theta) = \frac{\partial u}{\partial \theta}, \quad i = 1, 2, \ldots, 7 \] (6)

For its tolerable error range and convenience, using the 3D design software CATIA to measure the mechanical properties of each link. The parameters of these links are summarized in Table 2.

### 3. Master-slave surgical robotic system setup

#### 3.1 The slave surgical manipulators

Our lab has developed a new robotic system for MIS. The surgical robotic system is composed of three separate slave manipulators. Two slave manipulators are with surgical instruments and another one is for holding the laparoscopic camera. Each of the three manipulators is fixed on a cart.

The slave manipulators with surgical instrument have the same structure. Each slave manipulator has totally ten DOFs. It can be described as three parts named positioning mechanism, RCM mechanism and surgical instrument as shown in Figure 4. The positioning mechanism includes the first three joints, of which joint1 is a vertical prismatic joint and joint2 and joint3 are vertical revolute joints. All the joints of positioning mechanism are passive, and each has an electromagnetic clutch. A button is fixed on the manipulator and controls the clutches. During the preoperative period, nurses can push the button and move the passive joints until the RCM mechanism reaches an appropriate surgery position. The RCM mechanism is composed of joint4, joint5 and joint6. Joint4 and joint5 are revolute joints while joint6 is a prismatic joint. Their axes intersect a point named remote centre point. The joint6 installs a sliding platform on which the surgical instrument is fixed. The surgical instrument is a cable driven mechanism with a quick change interface, a dexterous wrist like end effector and a long slim hollow rod. The surgical instrument has 4 DOFs which can roll, pitch, yaw and grip. These motions of the instrument joints can significantly extend much more surgeon’s dexterity than the traditional surgical instrument. In addition, the surgical instrument can be easily installed on the sliding platform with quick change interface by pressing the change switch. This allows nurses to change different types of instrument according to operation during MIS. Four maxon DCX16 motors are installed in the platform. The quick change interface cooperating with the instrument’s is connected with the motors’ output shafts which drive the instrument with 4 motion DOFs.

The laparoscope-holding manipulator has six DOFs. It has the same structure for the first three joints as the instrument-holding manipulators. But the RCM mechanism is a parallelogram structure which provides 3 DOFs. One link of the parallelogram is designed as sliding platform which the laparoscope can move along with, and the other two DOFs are also revolute joints.

The D-H coordinate system, forward kinematics and inverse kinematics are detailed in [17]. So this paper will not discuss this issue.

### Table 2. The links parameters.

| \( i \) | \( m_i \) (kg) | \( x_{cmi} \) (mm) | \( y_{cmi} \) (mm) | \( z_{cmi} \) (mm) |
|---|---|---|---|---|
| 1 | 2.429 | 12.4 | 53.6 | -60.267 |
| 2 | 1.806 | 39.192 | -81.023 | -1.613 |
| 3 | 0.658 | 242.632 | -1.02 | 0 |
| 4 | 0.307 | 0 | 106.02 | 61.579 |
| 5 | 0.275 | 0 | 82.356 | -44.099 |
| 6 | 0.230 | 0 | 37.758 | -36.707 |
| 7 | 0.185 | 4.5 | 12.8 | 9.62 |

![Figure 3. Reachable workspace of the haptic device.](image)
3.2 The slave surgical manipulators

Including the new haptic device and the slave manipulators, a master-slave surgical system has been set up as shown in Figure 5. The haptic device acts as the master system and the slave surgical manipulator as the slave robotic system. The laparoscope manipulator holds a laparoscope camera focusing on the workspace of the end effector of the instrument. A 3D screen is used to observe the movements of the instrument.

Commercial driver can provide motors with torque control, velocity control and position control as well as encoder interface and a lot of I/O ports. It is beneficial for easily constructing low level joint control. Consequently, we select Elmo drivers as the drive units of all the joints in both master and slave robotic system. The Elmo driver is a compact, integrated digital servo driver which supports the EtherCAT communication. EtherCAT is a real-time distributed industrial field bus. It is predominant for high efficiency, high speed data transmission and flexible expandability. All the Elmo drivers of the robotic system as slave stations can be added into the EtherCAT bus network provided by an EtherCAT master station, then the control signals are transmitted in real-time through the EtherCAT bus [18].

As for the main computer, a Bechhoff 6630 industrial computer running the Beckhoff’s TwinCAT3 software is adopted. The TwinCAT3 real-time motion control software is utilized as the main control platform which integrates programming environment and motion control functions. All the algorithms, including encoders’ data collection, I/O signals processing, haptic device control algorithm, master-slave intuitive control algorithm, are programmed in TwinCAT3. The TwinCAT3 can be also set up as an EtherCAT master station which can easily connect with drivers by EtherCAT communication. This facilitates the arrangement of motor wires, encoder wires. An EtherCAT Router is also used for its flexible with tree and star topology connection of haptic devices and slave manipulators.

3.3 Master-slave control architecture and control algorithm

The master-slave control architecture can be described as high level control and low level control architectures which is shown in Figure 6. The high level control mainly realizes the algorithms while the low level control realizes the joints’ control. Between them, the EtherCAT bus is used to transmit commands and feedback information. The low level control configuration occurs in tuning motor period. It includes configuring the motor and encoder parameters and tuning PID parameters of the motors. When tuning is done, the low level just receives commands from high level control.

The high level control includes several control algorithms, such as gravity compensation strategy, active joint control strategy, intuitive control strategy and adjustment control strategy.

Both gravity compensation strategy and active joint control strategy are for the haptic device and...
implemented in the master controller process. Gravity compensation is to counteract the gravity of links. The controller reads the joints angles from the Elmo divers and calculates the output torques which each joint of the haptic device should be applied to by using the formulation derived in section 2. Then the controller commands the Elmo drivers to output the corresponding torques. During the movement of the master haptic device, the singularity position will occur when the axes of joint 5 and joint 7 coincide. Actively driving the joint 4 can prevent this situation happening. Active joint control strategy is aimed at driving the active joint to avoid singularity position of the wrist by keeping the active joint synchronously move with joint 6.

Intuitive control is one of the most different features that robot-assisted MIS from traditional way. It makes the surgeon feel teleoperating the surgical instrument just like using his own hand. This way can reduce surgeons' training time and increase the surgical procedure accuracy. To achieve intuitive motion
control, the end-effector motion of the haptic device should be described in the 3D monitor coordinate system, and the motion of the surgical instrument end effector should be described in the endoscope coordinate system. The relationship can be described as

$$D_{MT} \cdot M_H T = E_{ST} \cdot S_T T$$

(7)

Wherein, $D_{MT}$ is the transformation matrix from master base coordinate system to 3D displayer coordinate system, $M_H T$ represents the hand position and orientation to the master base coordinate system, $E_{ST}$ is the transformation matrix from slave base coordinate system to endoscope coordinate system, $S_T T$ denotes instrument end effector position and orientation to slave base coordinate system.

Intuitive control makes sure the motion of the end effector maps with the motion of the surgeon’s hand. In one control period, the controller first read the varied joints angles of the haptic device, then it calculates the kinematics of the haptic device. The incremental values of the motion can be obtained by comparing with the previous period. After that, the incremental values are multiplied by a scaling factor, which can set the proportional relationship between master and slave manipulators. Add the scaled incremental values to the slave manipulator and calculate the inverse kinematics of the slave manipulator. By comparing the calculated joint angles with the values in the previous motion period of the slave manipulator, the incremental angles of this period is obtained as motion commands. Finally, the motion commands are sent to the joint motors after smoothing the motion trajectory.

The adjustment control strategy should be implemented which is used to do some adjustment during surgical procedures. In the surgical process, the haptic device may move to or near its boundary, or two haptic devices may collide with each other, or the haptic device needs to be adjusted to its comfortable operation zone. The main controller cuts off the connection between the haptic device and the slave manipulator. After adjusting the haptic device to the desired position, the controller connects the master and slave manipulators again.

4. Experiments and discussion

One of the experiments is gravity compensation experiment. The effect of the experiment is shown in Figure 7. By moving the haptic device to arbitrary position and orientation inside its workspace, it can be seen that the haptic device can stay balance at any point with the compensation function of gravity. Meanwhile, the active joint control strategy for the haptic device is also effective. It successfully avoids the singularity of the wrist mechanism. This experiment verifies the effectiveness of the compensation control strategy and the active joint control strategy for the haptic device. It greatly increases the maneuverability and helps to save the user’s labor.

Another experiment is master-slave operation experiment. In this experiment, a surgical training module is used as an experimental object, which is placed inside the surgical instrument workspace of one slave robot. The laparoscope robot is adjusted to view the working area. The operator looks at the 3D

Figure 7. Gravity compensation experiment.
screen to do the experiment under the master-slave control strategy realized in the previous section. With the 3D visual feedback, the operator manipulates the haptic device to control the instrument at the slave side to get close to the black ring, grip it, and pick it up from a column, and then put it through another column. The ring is put through 4 different columns in order. Some processes of the experiment are shown in Figure 8. During the experiment, the trajectories of the master and the end point of the instrument are recorded as well. The two trajectories are drawn in one coordinate system which is shown in Figure 9. The blue line is the instrument end point’s trajectory while the red one is the master’s trajectory. The scaling factor is set to 3:1. It can be seen from Figure 9 that the instrument can follow the master haptic device to move with the same motion trend, which proves the haptic device proposed in this paper is able to be applied in the minimally invasive surgical robotic system as a master manipulator.

**Discussion**

Haptic device plays an important role in master salve robotic surgical systems. The haptic device designed in this paper meets the needs of controlling slave surgical robots, which requires three translational, three rotational and a grasping motion. The gravity compensation experiment reveals that the haptic device is able to reduce surgeon’s fatigue. The distribute control architecture adopted in this paper is advantageous for its robustness, flexible expandable, and easy maintaining. The master-slave operation experiment and the trajectories of master-slave motion have proved the effectiveness and feasibility of the haptic device as a master manipulator in the surgical robotic system. The master-slave control period can be modified for the master-slave control algorithm has been programmed as TwinCAT motion control tasks. Currently, the control period has been set to be 2 ms. According to the data collected from the motor encoder, the average delays of the master-slave control is about 8.4 ms, basically less than 10 ms. Although the scaling factor in the training module experiment is 3:1 due to the laparoscope amplification effect.
The scaling factor can be set to 5:1 which used to do fine operation and 1:1 which used to quickly adjust the position of the instrument. The RMSE for the master-slave tracking error is 3.3122 mm in the X direction, 3.0053 mm in the Y direction, and 2.7161 mm in the Z direction. Compared with the data in the literature, the tracking error of the master-slave system is bigger. But under the visual feedback, operators can adjust the haptic device to decrease the error.

5. Conclusion
In this study, a new 8 DOFs haptic device is presented. The haptic device has the characteristic of large workspace compared with commercialized haptic device and other devices which have been used in MIS surgical robots. Its active wrist joint also provides larger orientation motion ranges and dexterity than these haptic devices. After that, the haptic device and a slave surgical manipulator constitute a master-slave surgical robotic system. The gravity compensation of the haptic device successfully eliminates the gravity effects when the user manipulates the haptic device working inside its workspace, and greatly increases the maneuverability and helps to save the user’s labor. Using a training surgical module, the operator can manipulate the haptic device to control the instrument to reach, grip, pick the ring from one column to another which simulates the MIS operation action. The master-slave operation experiment verifies the control strategies in which the haptic device can be used as a master manipulator in the surgical robotic system. Future works include manufacturing a right handed haptic device to compose a bimanual tele-operation surgical system and realize complex MIS procedures such as suture, knot tying, designing some safety preventions in control software and other auxiliary interfaces such as foot pedals, control panel and so on, and trying animal experiments in real surgical environment.

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