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A Preliminary Study on Joint to Joint Control Master Device for Single Port Laparoscopic Surgery Robot

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Abstract – Unlike da Vinci surgical system, in a single port laparoscopic surgery (SPLS) robot, all joints of the slave robot are located inside abdomen. Therefore, all joints of the slave robot should be controlled separately for surgical safety. In this study, a master device was developed for PLAS which is one of the slave robots for SPLS. Because all joints of the slave robot are inserted in the human body during the surgery, we need to develop a master device which can control each joint of the robot separately. We focused on developing the master device in a perspective of the following factors. First, DOF and structure of a target slave robot must be analyzed. Then, according to ergonomics, joint matching among the master, slave, and human arm should be considered. Through this matching, each joint motion of the slave robot can be decoupled. In addition, we proposed mapping factors, which can minimize the trajectory error of the tips between the master and the slave. We confirmed that each joint of the slave robot can be manipulated separately and that both tips have similar trajectory.

Keywords – Master device, Single port laparoscopic surgery robot, joint to joint control, Mapping factor

1. Introduction

Single Port Laparoscopic surgery (SPLS) is an operation which makes one incision around the navel as an entry point of surgical tools. Due to making only one incision around the navel, SPLS offers for patients less post-operative scar, less post-operative pain, and faster recovery compared with traditional open surgeries and even multi-port laparoscopic ones. However, as the surgical instruments are intersected through the navel, the operation is counter-intuitive for surgeons [1]. Therefore, SPLS prompts surgeons not only to have experienced delicate operating skills, but also to spend a great deal of operating time.

In order to address this problem, a number of master-slave systems for SPLS have been developed. A typical example is da Vinci surgical system [2]. To manipulate the slave robot, da Vinci adopts tip control master device which control the only tip of the slave robot by calculating the change in the rotation and translation of the tip. This type of master is commonly used for general-purpose applications, as well as surgical applications.

Another type is a joint to joint control master device, which manipulates not only the tip, but also the intermediate joints of the slave robot separately using joint-to-joint mapping. With tip control, the motion of each joint cannot be monitored precisely. However, in general slave robots for SPLS, most joints of the robot are located in the body; therefore, all joints, including the tip, should be operated within safe limits. If we use tip-control, some unmonitored intermediate joint motion may result in damage to tissue; therefore, joint to joint control is preferable. Joint to joint control is performed for each joint space, in contrast to the tip-control in Cartesian space. An example all-joint control method is the master–slave Mutual Telexistence system [3], where the operator can easily manipulate a specific joint of the slave robot via joint-linking motions of the master and the slave. As far as we know, however, there is no master device which can control all joints of a six-DOF surgical robot separately.

Here we describe the development of a new master device for six-DOF SPLS robots, which supports joint to joint control. The master was designed for the PLAS robot [4], which is one of the slave robot for SPLS.

We designed the master device considering slave robot and human arm to decouple each joint motion of the slave robot. In addition, we found optimal mapping factors between the master and slave robots based on kinematics analysis. The master and slave have differing joint structures; therefore, a simple 1:1 joint mapping leads to a big trajectory error. An inverse Jacobian method cannot be applied because of coupling motions of the joints; instead we found appropriate mapping factors that minimize the trajectory error. We performed simulations to investigate the correctness of the mapping factors.

2. Methods

2.1 Design of a Master device

In order to manipulate the PLAS which has 6 DOF by using joint to joint controlling method, four rotational joints, two yaw axes, one pitch axis, one roll axis, and two prismatic joints are required in the master device. For controlling each joint of the slave robot separately, all joints of the master device must be decoupled. In order to decouple four rotational joints, we designed that joint 2 is manipulated by the elbow, and joint 3, 4, and 6 are rotated by the wrist. In case of two prismatic joints, joint 1 and 5 are moved by translation of the forearm and fingers respectively as shown in figure 1. Figure 2 shows CAD model of the designed master device.

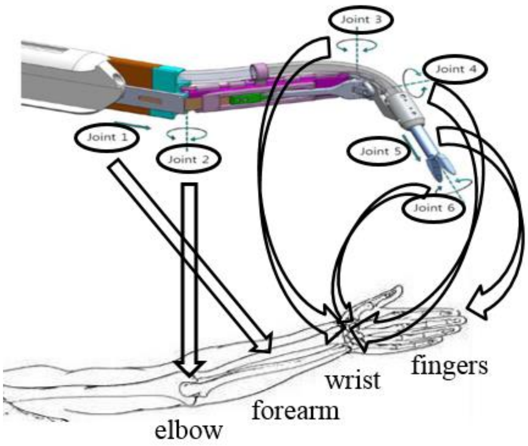

Fig. 1. Joint matching between the slave robot and human arm.

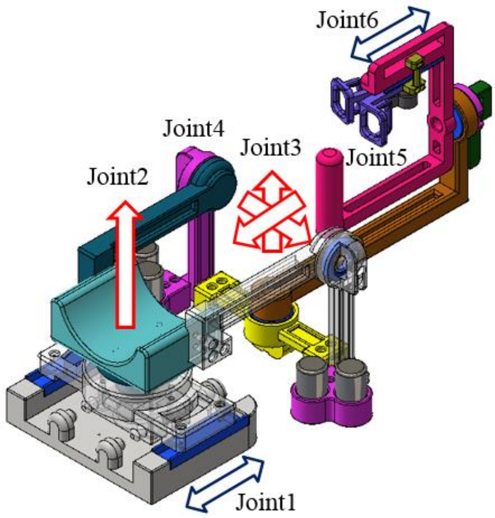

Fig. 2. CAD model of the proposed master device.

Counterbalancing also should be considered to reduce fatigue of operators. Since the weight of the links after joint 4 is about 240g, the joint 4 is tilted approximately 60 degrees. Owing to the weight, it is difficult to rotate the joint 4. Given that the wrist is rotated on average from 0 to 50 degrees in abduction / adduction, operators have to withstand the weight. In order to reduce this burden, joint 4 should be tilted about 25 degrees as steady state. Using the positioning stage, ml=ML, we apply it to the joint 4, $\mathbf{m}(\mathbf{rsin\theta}+\mathbf{lcos\theta})=M(\mathbf{Lcos\theta}-\mathbf{rsin\theta})$, when theta is 25 degrees. Then we get the weight of counterbalancing as 460 g.

2.2 Mapping Factor

In a master slave system which has different structure between master device and slave robot, inverse Jacobian is generally adopted as a control method to get the same trajectory of tips between master and slave. However, the method cannot be adopted to the joint to joint control system due to coupling problem. Although, simple 1:1

Table 1 Comparisons of the control methods.

Control method	Tip control	Joint to joint control
Inverse Jacobian	O	X
1:1 Mapping method	X	O
Proposed method	△	O

Table 2 Mapping factors between master and slave.

Joint i	Mapping factor
1	On / Off
2	$\frac{(C_{23}(d_6C_4)+a'_2C_2)}{(C_{23}(a_3+d_5C_4)+a_2C_2)}$
3	$\frac{(d_6C_4)}{(a_3+d_5C_4)}$
4	$\frac{(d_6)}{(d_5)}$
5	1
6	1

joint mapping allow to decouple all joint motions, it leads big trajectory error of the tips. To realize joint to joint control with small trajectory error of the tips, all joints control method was proposed (see Table 1). We assumed $\boldsymbol{\theta}'_{Si}=K_1*\boldsymbol{\theta}'_{Mi}$; that is, each joint of the slave robot was assumed to be actuated in response to motion of the corresponding joint of the master device. Using following equations, a diagonal matrix **K** was constructed.

$$\mathrm{v_S}=\mathrm{v_M}, \tag{1}$$

$$\mathrm{J_S}\Theta'_\mathrm{S}=\mathrm{J_M}\Theta'_\mathrm{M}, \tag{2}$$

$$\mathrm{J_S}\mathrm{K}*\Theta'_\mathrm{M}=\mathrm{J_M}\Theta'_\mathrm{M}, \tag{3}$$

$$\mathrm{J_S}\begin{bmatrix}K_2 & 0 & 0\\ 0 & K_3 & 0\\ 0 & 0 & K_4\end{bmatrix}=\mathrm{J_M}. \tag{4}$$

The Jacobian of the simplified slave robot, $\boldsymbol{J_S}$ is given by

$$\begin{bmatrix}(-S_{23}(a_3+d_5C_4)-a_2S_2) & (-S_{23}(a_3+d_5C_4)) & (-d_5S_4C_{23})\\ (C_{23}(a_3+d_5C_4)+a_2C_2) & (C_{23}(a_3+d_5C_4)) & (-d_5S_4S_{23})\\ 0 & 0 & (d_5C_4)\end{bmatrix}$$

and Jacobian of the simplified master device $\boldsymbol{J_M}$ is defined by

$$\begin{bmatrix}(-S_{23}(d_6C_4)-a'_2S_2) & (-S_{23}(d_6C_4)) & (-d_6S_4C_{23})\\ (C_{23}(d_6C_4)+a'_2C_2) & (C_{23}(d_6C_4)) & (-d_6S_4S_{23})\\ 0 & 0 & (d_6C_4)\end{bmatrix}.$$

Using the third row vector of equation (4), the term K_4 may be obtained; i.e.,

$$(d_5 C_4)K_4 = (d_6 C_4), \qquad K_4 = \frac{d_6}{d_5}. \tag{5}$$

K_3 may then be calculated from the second row vector of equation (4); i.e.,

$$\left(C_{23}(a_3 + d_5 C_4)\right)K_3 = \left(C_{23}(d_6 C_4)\right),$$

$$K_3 = \frac{(d_6 C_4)}{(a_3 + d_5 C_4)}. \tag{6}$$

K_2 can be calculated using the second row vector of equation (4); i.e.,

$$\left(C_{23}(a_3 + d_5 C_4) + a_2 C_2\right)K_2 = \left(C_{23}(d_6 C_4) + a'_2 C_2\right),$$

$$K_2 = \frac{\left(C_{23}(d_6 C_4) + a'_2 C_2\right)}{\left(C_{23}(a_3 + d_5 C_4) + a_2 C_2\right)}. \tag{7}$$

The first, second and third rows vector of equation (4) are related to v_x, v_y, and v_z, respectively. The mapping factors are listed in Table 2.

3. Experiments and Results

Using the proposed master device, controlling PLAS has been performed as shown in figure 3. When the elbow was rotated, the joint 2 of the robot was rotated. Also, when the wrist was rotated in order of yaw, pitch, roll, the joint 3, 4 and 6 were rotated in sequence. Finally, when forearm and fingers were translated, the joint 1 and 5 of the slave robot were moved forward and backward. Form these result, it was confirmed that each joint of the slave robot can be controlled separately by decoupling all joints of the master device.

For measuring the trajectories of the tips between the master device and slave robot, we made simulation by using VTK graphic library (Kitware Inc., Clifton Park, NY). When the each joint angle of the master device was calculated from encoder values of the master device, the corresponding joint angle of the slave robot is calculated by multiplying the mapping factors to each joint angle of the master device. Finally, we can obtain the trajectories of both tips. In order to compare the trajectories of the tips between master and slave, the master device was arbitrarily manipulated approximately 203 mm. Although slave robot moved about 195 mm and they have 8 mm error, the shape and distance of the trajectories are almost same.

4. Conclusion

In this paper, a new six-DOF master device has been developed to control each joint of SPLS robot separately.

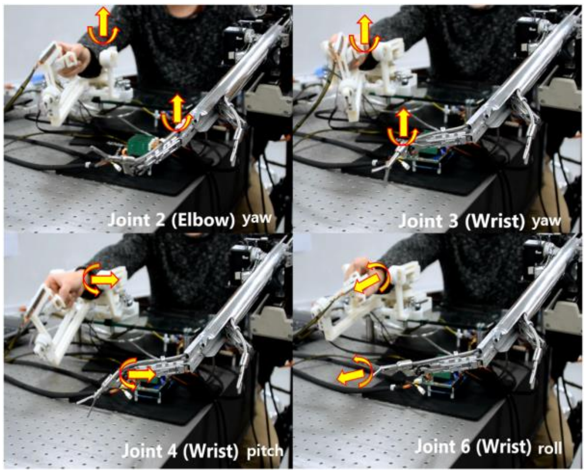

Fig. 3. Decoupling motions of the master and slave.

Unlike the da Vinci surgical system which controls only the tip of slave robot, we could control all joints that are located inside abdomen during the surgery.

We developed an ergonomic master device to decouple all joints of the slave robot. When we designed the master device, we considered joint of the slave robot as well as that of the human arm. In addition, mapping factors were determined based on kinematic analysis, and used to realize joint to joint control with minimal error at the tips between the master device and the slave robot.

Acknowledgement

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