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Signal Processing and Fabrication of a Biomimetic Tactile Sensor Array with Thermal, Force and Microvibration Modalities
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SuB1: Micro Robotics and Mechatronics for Desk-top Bio-plant

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Automatic cell cutting and nucleus detection
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Cell Coupling System for Somatic Cell Cloning Using Microfluidic Chip
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SuB2: Path Planning

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SuB3: Rehabilitation and Wheelchair

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Strategies for Collision Prevention of a Compact Powered Wheelchair using SOKUKI Sensor and applying Fuzzy Theory
Toshihiko Yasuda, Naoya Suehiro, Katsuyuki Tanaka
Abstract — The minimal invasive surgery reducing an incision is required for a tumor resection in the field of neurosurgery. The minimal invasive surgery has many advantages of operations which are less lost of blood and painless using a thin long pole shape surgical instrument. For all those advantages, it has defects of difficulties of visual insurance and limitations of moving surgical instruments. Therefore, many researchers are developing several manipulators which are capable of minimal invasive surgery using robot technologies to solve these problems recently. However, most developed surgery robots for minimal invasive surgery are limited to the operation of laparoscopic surgery. In this study, we developed a tele-operational master-slave system for the minimal invasive brain surgery. The master manipulator has 4 degree of freedom (DOF) mechanism for the manipulation of slave position and direction. Similarly, the slave end-effector for the minimal invasive brain surgery has a thin long pole shape of 4DOF instrument. The master manipulator and slave end-effector have a similar configuration and 4DOF mechanism which consists of a linear motion and 3 rotational roll-pitch-yaw motions. Therefore, the position command matching between the two systems is very easy. In addition, the master and slave control systems are connected with TCP/IP based internet communication for the tele-operation surgery. Finally, various experimental results are executed to evaluate the performances of the proposed tele-operation master-slave system.

I. INTRODUCTION

WITH various advanced technology such as tele-operation manipulation, fast information transmission, data analysis, and so on, many robot system have been applied to the medical field. Especially, a tele-operation surgical robot as one of medical treatment robot can perform remote surgery with high precision but low risk. Several extensive works on tele-operation robot with master-slave control system have been reported in [1]-[5].

In general such a tele-operation surgical robot can be utilized to the minimal invasive surgery (MIS) [6] [7]. The major advantages of the MIS are smaller incisions, decreased blood loss, less pain, and quicker healing time. However, the MIS needs mature skill of doctor because the DOF of surgical mechanism is highly restricted. To overcome this problem, it has been essential to develop of master-salve typed surgical robot. Once a surgeon just handles a manipulator of master system which might be easy to manipulate, an end-effector of slave system having the demanded DOF follows the command of the master system. By virtue of the master-slave control system for tele-operation robot, it is possible to make a surgeon without high skill operate MIS.

DaVinci system, developed by Intuitive Inc. in the U.S., is a typical surgery robot which enables minimal invasive surgery using a form of master-slave. This system consists of 3 slaves with 7 DOF and 2 masters manipulating slaves [8]-[12]. In addition, RAMS, NeuRobot and NeuroArm systems are representative neuro-surgery robots which enable MIS using a form of master-slave. RAMS was a six-degrees-freedom surgical robot slave made up of a torso-shoulder-elbow body with a three-axis wrist [13]. NeuRobot is a master-slave manipulator system, and it was designed so that a surgeon operates the slave manipulator by controlling three levers on the operation-input device, master manipulator, while watching a 3D monitor [14]. NeuroArm consist of navigation system, force feedback and 8 DOF, but it could not be applied to MIS [15]. If the surgery was operated by only master-slave system, the surgery cannot ensure accuracy and safety.

Fig. 1. Overview of Surgical Robot System
In this paper, we propose a tele-operation surgical robot system available to MIS for brain surgery. Our proposed system is not only master-slave control, but also remote control through TCP/IP based internet environment. The master system to generate control signal for the slave system was designed with 4DOF and force feedback. The slave system consists of mechanism part with 4 DOF and control part for moving an end-effector. The TCP/IP communication is used for data transmission between master and slave systems [16]. In addition, for the accuracy and safety of the operation, we will introduce the image guided surgery system.

The remainder of this paper is constructed as follows. Section II introduces the overview of the proposed tele-operation surgical robot system. Next, the control system for tele-operation is described in Section III. Some experimental results and their analysis are given in Section IV. Finally, Section V presents conclusions and the future works.

II. OVERVIEW OF THE PROPOSED SYSTEM

Fig. 1 indicates the overview of the proposed tele-operation robot system for brain surgery. The system has three sub-systems which are master, slave and remote control system. The master system has a manipulator with 4DOF mechanism which is driven by tendon way[17][18]. An end-effector of the slave system was developed as small as possible to enable the end-effector to MIS. Each control system for both master and slave system has a Pentium PC with EPOS position as controller computer. We developed a tele-operation matching which can control the slave system by manipulating the master system instead of direct control of the slave system. Therefore, all position data for each axis at a manipulator of the master system are transmitted to the slave system through the TCP/IP based remote control system. Then, the received data at the slave system must be converted into control command for tele-operation matching. For the matching of the master and the slave system, we designed that both the master system and the slave system have a homogeneous mechanism.

A. Master system

In tele-operation robot, master system is a device taken role in controlling the slave system. We developed the slave system having 4 DOF mechanism structure because we recognized 4 DOF could be enough for minimal invasive brain surgery.

![Fig. 3. SolidEdge Design of Master System](image)

Fig. 2 shows the workspace of minimal invasive brain surgery. Therefore, we designed only 4 DOF slave and master mechanisms such as a translation, roll, yaw, and pitch rotations. In addition, the slave mechanism should cover the whole workspace.

As shown in Fig. 3, the master system is designed with the combination mechanism of parallel and serial type. The master mechanism was actuated by MAXON DC motors with encoders. As shown in Fig. 4, the master system can be manipulated on 4 axes, such as the forward-back moving (translation) at the 1st axis, the left-right rotation (Pitch) at the 2nd axis, the up-down rotation (Yaw) at the 3rd axis and the axial rotation (Roll) at the 4th axis.

The master system is driven by tendon method for all axes except for roll rotational axis. In addition, the motor and the

<table>
<thead>
<tr>
<th>TABLE1 Working range of the Master System</th>
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<tr>
<td>Translation axis</td>
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<tr>
<td>Roll: ±180°</td>
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<tr>
<td>Pitch: ±90°</td>
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<td>Yaw: ±90°</td>
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driving pulley at each axis are connected with tendon wires. By using the tendon wire and the driving pulley, each motor can be controlled precisely with the scale ratio. The scale ratios between the motor axis and the drive pulley are 1:5 for the translation axis and 1:9 for the up-down axis. Table 1 shows the working range of the master system with 4 DOF. Especially, the working range of the translation axis is restricted to 160mm.

Fig. 5 shows the controller part of the master system using EPOS position controller for position control of 4 DC servo motors. All EPOS position controllers are connected with main PC control system for the remote control of the slave system. Firstly, from the encoder of the DC servo motor, the position data of the motor are obtained and then the position data of all axes can be converted into the position data of all axes.

B. Slave system

The developed slave system is controlled by the manipulating of the master system. Similar with the developed master system, the slave system also has an end-effector with 4 DOF mechanism and the diameter of the end-effector is about 8mm. Fig. 6 shows the mechanism of the slave system, which consists of the forward-back directional moving (Translation), the up-down directional snap of tip (Yaw), the right-left directional snap of tip (Pitch), the rotation of the end-effector (Roll). In addition, it was designed for minimal invasive brain surgery.

The actuation of translation axis is conducted by driving a DC servo motor in combination with a ball screw. Moreover, the actuations of rotation for the remained axis are conducted by DC servo motor in combination with tendon mechanism.

Table 1 shows the working range of the master system with 4 DOF.

| Working range of the Master System |
| Translation axis | Translation: 80mm |
| Rotational axes | Roll: ±360°  |
| | Pitch: ±90° |
| | Yaw: ±90° |

The maximum operating range of the slave system is summarized in Table 2. The gear reduction ratio of the motor in translation is 19:1 and those in remaining axes are 192:1. In the translation, because the axis is driven on the ball screw and has low friction value, the smaller gear reduction ratio is selected.

Both the up-down and right-left directional moving on the end-effector of slave system are operated by combination of motor and pulley. A gap between motor and pulley was calibrated by cross joint coupling as shown in Fig. 7.

The forward-back directional moving is generated according to rotation of the ball screw. The lead value of the ball screw is 1, which means 1mm of forward-back directional moving occurs when a ball screw have one rotation. The slave system uses EPOS position controller to control the DC encoder motor. The system is usually linked to a control PC and communicates with the master system through wired or wireless network. A control program of the slave system matches between the positions data at each axis of the master system and those of the slave system.

III. CONTROL SYSTEM FOR TELE-OPERATION

A. Master-slave matching control

We assumed the mechanical structures of both master and slave system are the same. Thus, all position data at each axis of the master system can be directly matched with those of the slave system. First of all, the encoder values of each motor should be transformed into the position data including
translational distance and rotational degrees of each axis. Next, these position will be transmitted to the slave system, and then the control system of slave system matches the position of each axis by its own control logic. Because several intelligent motor control mechanisms are embedded in to the EPOS controller, the control system automatically decides the parameters, for example gain of the PID control algorithm, when a control command comes. Fig. 8 shows the developed master-slave system.

B. TCP/IP based remote control system

We also developed a remote control system based on TCP/IP connection which can be applied to tele-operation surgery by operating slave system in remote according to the manipulation of the master system. Usually, the data transmission should be fast and reliable to achieve a safe and successful tele-operation surgery in remote. Therefore, we selected the TCP/IP based communication to build remote control system owing to the reliability and robustness of the TCP/IP connection. Fig. 9 indicates a general process of the TCP/IP connection.

We configured a computer mounting the master system as a server and a computer mounting the slave system as a client. Our developed master-slave systems are communicated with each other with the speed of 56Mbps in the wireless internet environment.

C. Kinematics of Master-slave

It is necessary to solve the kinematics of both master and slave system for the purpose of determining the position of end point from values of encoder. The inverse kinematics of the slave system can be used to calculate the angle of the end point.

\[
T_1^0 = \begin{bmatrix} R(3x3) & T(1x3) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
\]

For the forward kinematics of master system, the first link-driven variable is \(d_1\), and each axis rotation values of links are \(\theta_2, \theta_3\) and \(\theta_4\). Table 3 shows the D-H parameters of the kinematics. By calculating the forward kinematics with the D-H parameters, we have the transformation matrix of master system in (1).

\[
R_2^0 = \begin{bmatrix} s\theta_2 c\theta_3 & -c\theta_2 s\theta_3 & c\theta_3 \\ s\theta_2 c\theta_3 & c\theta_2 s\theta_3 & -s\theta_3 \\ -s\theta_2 & s\theta_2 & 0 \end{bmatrix}
\]

\[
P_0^4 = \begin{bmatrix} L_4 c\theta_3 - L_2 \\ -L_4 s\theta_2 s\theta_3 + L_2 c\theta_3 \\ -L_4 c\theta_2 s\theta_3 + L_2 c\theta_3 + (L_1 + d_1) \end{bmatrix}
\]

For the inverse kinematics of slave system, the first link-driven variable is \(d_1\), each link length variable are \(L_1\), \(L_2\), \(L_3\) and \(L_4\) each axis rotation values of each axis are \(\theta_2, \theta_3\) and \(\theta_4\). Table 4 shows the D-H parameters of the kinematics. By calculating the kinematics with the D-H parameters, we have distance and angle of each axis in (2), (3), (4) and (5).

\[
d_1 = \sqrt{x^2 + (y + l_1)^2} + L_2 \tag{2}
\]

\[
\theta_2 = \tan^{-1}\left(\frac{y + l_1}{x}\right) \tag{3}
\]

\[
\theta_3 = \sin^{-1}\left(\frac{\sqrt{x^2 + (y + l_1)^2}}{l_3 + l_1}\right) \tag{4}
\]

\[
\theta_4 = \tan^{-1}\left(\frac{r_2}{r_3}\right) \tag{5}
\]
IV. EXPERIMENT AND ANALYSIS

We verified the performance of the developed system by experiments. For the experiment, we configured the scale ratio of forward-back translational motion is 5:1 and that of the remainder motions such as yaw, pitch, and roll is 1:1.

Fig. 10 shows the results as the master system request the slave system to generate a certain degree of motion. Fig. 10 (a) indicates the end-effector of slave system moves 1cm of translational direction when the manipulator of master system moves 1cm for the forward direction.

Fig. 11 shows the performance of control for 4 axis of slave system. We checked that there were no differences between the demand value and the actual value of control command for all axis of slave system. In other word, the control mechanism of the slave system is very well, as the actual value quickly follows the demand with high accuracy.
This paper proposes a tele-operation master-slave system for minimal invasive brain surgery. Our proposed system consisted of a manipulator of master with 4DOF, an end-effector of slave system with 4DOF, and a remote control system based on TCP/IP connection. By analyzing the workspace of minimal invasive brain surgery, we recognized 4DOF mechanism, which are translation, pitch, yaw, and roll, could be enough to do the brain surgery. We also demonstrated master-slave matching control with the proposed system by performing experiments.

In the future, we are going to extend our developed system to an image-guided brain surgery system. To achieve the image guiding, we consider the optical tracker based end-point tracking and conduct a study on coordinate matching between world coordinate system and image coordinate system. Also, we will develop a safety system for brain surgical procedures by using sensitive force-feedback system.

Fig. 12. Experiment of Surgical Robot System

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