Abstract

Robot-assisted surgery is an active interdisciplinary field. Conventional surgical robots are mostly serial architectures, which have the advantages of large workspace, high dexterity and maneuverability. The disadvantages are low stiffness and poor positioning accuracy compared to the parallel structure robots.

This paper presents the development of a parallel surgical robot for precise skull drilling in stereotactic neurosurgical operations. The dimensions of this robot are $35 \times 35 \times 45 \text{cm}^3$, and its weight is about 6kg. This surgical robot has 6 degree-of-freedom. The feed carriage of the bone drilling device mounted the parallel surgical robot provides one additional translational degree of freedom. A master-slave microcontroller-based system is designed for pose control. In applications for neurosurgical operation, the workspace is on the surface of a skull located at one side of the robot. This work analyzed asymmetric workspace on the surface of a sphere representing the skull. A special socket joint design that enlarges the asymmetric workspace of the robot for about 30% is also proposed.

This parallel surgical robot has been integrated with an automatic bone drilling carriage developed in our previous work to achieve completely automatic bone drilling.

Keywords: Robot-assisted surgery; parallel robot; Stewart platform; asymmetric workspace.
1. Introduction

In stereotactic neurosurgical operations, surgeons are most concerned with improving the quality of surgical procedures, including accuracy, security, low morbidity and mortality. Surgeons often use a stereotactic frame fixed on the patients’ head to set the precise location for intracranial lesions. However, use of this cumbersome frame in the operating room limits the instrument’s access and has the detriment of physical discomfort and mental stress for the patient [1, 2]. To overcome the drawbacks of the stereotactic frame, many neurosurgical robot systems have been developed. Glauser, et al. [3] addressed conception and procedure of a robot dedicated to neurosurgical operations, and pointed out that if the tools are robotically operated, the surgeon is free to deal with other tasks during the intervention, thus saving operating time and improving safety. They mentioned that the drill must not penetrate beyond 2 mm inside the skull to prevent injuring the dura. Bone drilling can be done anywhere on a 12 x 11 cm surface defined at the top of the head. Basically, the coordinate system of robot includes 5 degrees of freedom for bone drilling. They also mentioned that surgeons presently work at a precision of about ± 1mm. They defined robot accuracy of ± 0.1mm for the end-of-probe position.

Liu, et al. [2] developed a robot-assisted neurosurgery system that combines the visualization technology with a powerless 6-joint robot arm to realize frameless stereotactic neurosurgery. It provides surgeons with tools to make the preoperative surgery plan and offers a navigator to direct the incisive site and the instrument orientation as well as the bore depth during surgery. The whole system is capable of accuracy less than 3-mm in finding or returning to a preprogrammed target. Following this development, Li et al., [23] developed a medical parallel robot applicable to chest compression in the process of cardiopulmonary resuscitation (CPR). It was a three-prismatic-universal-universal (3-PUU) translational parallel manipulator (TPM).

In recent years, more effort and attention has been given to the development of parallel structure robots. The basic reference for parallel mechanisms is the research by Stewart [4], called “Stewart platform”. Various research issues on Stewart platform have been addressed in literature, including its theory, construction, and investigation [5, 6, 7, 8], inverse and forward kinematic analysis [9, 10], and workspace definition and analysis [5, 6, 11, 12, 13].

In the past decade, a significant amount of research has been done on developing the parallel robot for different medical applications. Tanikawa et al. [14] developed a parallel mechanism on a dexterous micro-manipulation system for use in assembling micro-machines, manipulating biological cells, and performing micro-surgery. Brandt et al., [15] developed a compact robot “CRIGOS” for image-guided orthopedic surgery. Its
modular system was comprised of a compact parallel robot and a software system for planning surgical interventions and for supervision of the robotic device.

Merlet [16, 17] developed a micro robot called MIPS with a parallel mechanical architecture having three degrees of freedom (one for translation and two for orientation) that allows fine positioning of a surgical tool. The purpose of MIPS is to act as an active wrist at the tip of an endoscope, providing to the surgeon an accurate tool that may further offers a partial force-feedback. Shoham et al. [18] developed a parallel manipulator called the MiniAture Robot for Surgical procedures (MARS), which was a 5×7 cm² cylinder, weighting 200g, and with 6 degrees-of-freedom. This robot can be used in a variety of surgical procedures requiring precise positioning and orientation of a handheld surgical robot in the vicinity of a rigid bony structure.

Zimmerman et al. [24, 25] developed the Evolution 1 precision robot (Universal Robot Systems Schwerin, Germany) neurosurgical tool for precise steering of instruments with the cranium. The robot system included seven actuated axes (serial robotic arm), a universal instrument interface, a mobile repositioning system including a control computer rack, and a touch operated graphical user interface. It selected a hexapod robot or Stewart platform as the suitable kinematic structure for the operating robot. The system was used for neuronavigated endoscopic procedures for three patients. They addressed the use of robotic technology for neuroendoscopic procedures is a major advance for controlled movement of the endoscope within the cranium.

The authors previously developed a modular mechatronic system for automatic bone drilling in orthopedic surgery [19, 20]. This system is an “add-on” device that is compatible with commercially available DC motor-driven drills. As shown in Figure 1, this system has three modules: the control unit, the feed carriage, and the supporting arm. The control unit consists of a control box and a PC. The control box supplies power to the drill, and the feed carriage to feed forward in drilling operation. At the same time, a fuzzy controller analyzes the electric current consumed by the DC motor of the drill. When break-through is detected, the power will be cut and stop drilling in order to prevent excessive protrusion of the drill bit, then the feed carriage moves backward to remove the drill from the bone. In extensive drilling tests on real human skulls using different feed rate, there were no unexpected failure, and the overshoots of all tests were well less than 2mm.

The feed carriage is designed to be a hand tool for the surgeon to hold with both hands to perform drilling operations. The feed carriage can also be attached to a supporting arm that has three joints providing five degrees of freedom. The supporting arm is a passive device. The surgeon can manually move the feed carriage to a given position and angle, and tighten the joints by simply turning a knob. These joints are held solid by
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hydraulic force. The arm has an electric magnetic base, used to eliminate vibration and movement.

![Control box](image)

**Figure 1. Modular mechatronic system for automatic bone drilling**

Based on the development of the modular mechatronic system for automatic bone drilling, this paper presents a parallel surgical robot system that uses a Stewart platform to replace the passive supporting arm of the automatic bone drilling device. The laboratory prototype is shown in Figure 2. The dimensions of this robot are 35×35×45cm³, and its weight is about 6kg. The feed carriage of the bone drilling device, which has one translational degree of freedom, is mounted directly on the parallel surgical robot.
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![Parallel surgical robot](image)

**Figure 2. Parallel surgical robot**

Section 2 of this paper describes the geometry of the parallel surgical robot, and Section 3 describes the design of pose controller of the robot. The functions of the pose controller is also verified. Section 4 investigates the asymmetric workspace on the surface of a sphere representing the skull. A special socket joint design which enlarges the asymmetric workspace of the robot for about 30% is also proposed.

2. **Geometry of the parallel surgical robot**

The geometry of this parallel surgical robot, illustrated in Figure 3, is composed of a fixed base, a movable platform, and 6 variable length actuators connecting the fixed base and the movable platform. This is a 6 degrees-of-freedom universal-prismatic-spherical mechanism, and there is an additional translational degree of freedom at the automatic bone drilling carriage mounting on the end-effector of parallel surgical robot. The fixed base coordinate system \( \{B\} \) is placed at the base center \( O_b \) with the Z-axis perpendicular to the base plane. The movable platform coordinate system \( \{P\} \) is located at the center \( O_p \) of the moving platform. \( P_1 \) to \( P_6 \) (ball joints) and \( B_1 \) to \( B_6 \) (universal joints) are the joint pairs attached to the movable platform and the fixed base. \( D_1D_2 \) represents the feed carriage. \( D_1 \) is the drill tip of the feed carriage. The link lengths are denoted as \( L_1 \) to \( L_6 \).
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Figure 4 shows the geometry of the movable platform and the fixed base. The SSM (Symmetric Simplified Manipulator) geometry [21] is used for the joints layout. The positions of the joints are arranged symmetrically on the fixed base, on a radius $R_b$ circle. The X-axis of $\{B\}$ bisects the angle $B_1O_bB_6$. Table 1 lists the actual dimensions. The minimum and maximum value of the link length of the linear actuators used in the robot are denoted by $l_{\text{min}}$ and $l_{\text{max}}$. The rotational angle of a ball joint $\lambda$ is defined as the angle between the Z-axis of the movable platform attached to its socket and the vector along the link connected to the joints. The maximum angle of ball joints $\lambda_{\text{max}}$ used in this work is 25°. The maximum feed depth $f$ of the feed carriage is 60mm.
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![Diagram of movable platform and fixed base](image)

(a) movable platform

(b) fixed base

Figure 4. Geometry of the movable platform and the fixed base

Table 1. Dimensions of the parallel surgical robot

<table>
<thead>
<tr>
<th>$R_b$</th>
<th>$R_p$</th>
<th>$\alpha_b$</th>
<th>$\alpha_p$</th>
<th>$l_{min}$</th>
<th>$l_{max}$</th>
<th>$\lambda_{max}$</th>
<th>$D_1D_2$</th>
<th>$D_2O_p$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150mm</td>
<td>100mm</td>
<td>12°</td>
<td>48°</td>
<td>333.97mm</td>
<td>483.97mm</td>
<td>25°</td>
<td>150mm</td>
<td>100mm</td>
<td>60mm</td>
</tr>
</tbody>
</table>

3. Design of pose controller

In neurosurgery, the surgeon defines a given pose ($x$, $y$, $z$, $\psi$, $\theta$, $\phi$) for the drill, in which ($x$, $y$, $z$) is the 3D position of tip of drill, and ($\psi$, $\theta$, $\phi$) represents yaw, pitch, roll
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angles that determine the drilling direction. A set of valid drill pose for the feed carriage can be obtained after checking the link length and joint angle constraints [22]. Using inverse kinematics analysis, the pose of movable platform can be expressed by a 3×3 orientation matrix \( \mathbf{R} \) and a translation vector \( \mathbf{q} \) which define \( \{P\} \) with respect to \( \{B\} \). Vectors \( \mathbf{l}_i \) connecting \( \mathbf{b}_i \) (coordinate of the \( i \)-th universal joint) to \( \mathbf{p}_i \) (coordinate of the \( i \)-th ball joints) expressed in \( \{B\} \), are given by:

\[
\mathbf{l}_i = \mathbf{R}\mathbf{p}_i + \mathbf{q} - \mathbf{b}_i
\]  

Finally, the link lengths of linear actuators are given by:

\[
L_i = \|\mathbf{R}\mathbf{p}_i + \mathbf{q} - \mathbf{b}_i\| 
\]  

Figure 5 shows the structure of the pose controller of the parallel surgical robot. The PC-based, high-level controller processes the inverse kinematics analysis to obtain the desired lengths of the linear actuators. The low-level controller consisting of 7 microcontrollers carries out the fuzzy control algorithm to extend or retract the 6 linear actuators to the desired lengths. In this master-slave structure, the master microcontroller is used to process commands of actuator lengths from the host computer and communicate with each slave microcontroller in turn. Inter-integrated circuit (I2C) is used as the communication interface between the microcontrollers. The 8-bit microcontroller PIC is used in this research, with CPU, memory, oscillator, watchdog, and I/O incorporated within the same chip.
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Figure 5. Structure of the pose controller

Each linear actuator is controlled by a motor driver that receives control signals from a slave microcontroller. A displacement transducer with a resolution of 0.05% (linearity) is attached to each link. A fuzzy control algorithm is implemented in the microcontroller. In many tests with the laboratory prototype, the maximum positioning error for each linear actuator is less than 0.3mm.

A simple experiment was designed to verify the functions of the pose controller and the accuracy of the laboratory prototype of the parallel surgical robot. In the experiment, the tip of the drill is moved to 9 different target points, 3 points in each axis, as listed in Table 2. A 3D digitizer, which is a 4-joint passive serial mechanism, was used to obtain the actual coordinates achieved by the tip of the drill. The position accuracy of the 3D digitizer itself is 0.23mm. Table 2 shows the errors of displacement for the drill tip in each axis. The position errors of the target points in \( x \) and \( y \) coordinates are significantly larger than that in \( z \) coordinates. In our observation, the backlash of the joints in our laboratory prototype causes greater errors in \( x \) and \( y \)-axes.
Table 2. Errors of displacement for the drill tip in each axis

<table>
<thead>
<tr>
<th>Index</th>
<th>Target points</th>
<th>Absolute errors (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>1</td>
<td>[0, 0, 20]</td>
<td>1.17</td>
</tr>
<tr>
<td>2</td>
<td>[0, 0, 40]</td>
<td>-0.95</td>
</tr>
<tr>
<td>3</td>
<td>[0, 0, 60]</td>
<td>-1.58</td>
</tr>
<tr>
<td>4</td>
<td>[20, 0, 0]</td>
<td>1.61</td>
</tr>
<tr>
<td>5</td>
<td>[40, 0, 0]</td>
<td>0.26</td>
</tr>
<tr>
<td>6</td>
<td>[60, 0, 0]</td>
<td>0.74</td>
</tr>
<tr>
<td>7</td>
<td>[0, 20, 0]</td>
<td>1.66</td>
</tr>
<tr>
<td>8</td>
<td>[0, 40, 0]</td>
<td>-1.28</td>
</tr>
<tr>
<td>9</td>
<td>[0, 60, 0]</td>
<td>0.10</td>
</tr>
<tr>
<td>Max. error</td>
<td></td>
<td>1.66</td>
</tr>
</tbody>
</table>

The accuracy of orientation of the movable platform is also examined. Positions of 3 specified points on the movable platform are used to calculate the yaw and pitch angle of the movable platform. Table 3 shows the error in orientation in 16 different target poses.
Table 3. Errors in orientation for the movable platform

<table>
<thead>
<tr>
<th>Points</th>
<th>Target poses (x, y, z, Yaw, Pitch)</th>
<th>(Yaw and Pitch)</th>
<th>Yaw(°)</th>
<th>Pitch(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(+40, +40, +50, +5°, 0°)</td>
<td>(5.13°, 0.43°)</td>
<td>0.13°</td>
<td>0.43°</td>
</tr>
<tr>
<td></td>
<td>(+40, +40, +50, -5°, 0°)</td>
<td>(-5.02°, 0.30°)</td>
<td>0.02°</td>
<td>0.30°</td>
</tr>
<tr>
<td></td>
<td>(+40, +40, +50, 0°, +5°)</td>
<td>(0.40°, 4.90°)</td>
<td>0.40°</td>
<td>-0.10°</td>
</tr>
<tr>
<td></td>
<td>(+40, +40, +50, 0°, -5°)</td>
<td>(0.07°, -5.48°)</td>
<td>0.07°</td>
<td>0.48°</td>
</tr>
<tr>
<td>2</td>
<td>(-40, +40, +50, +5°, 0°)</td>
<td>(4.87°, 0.31°)</td>
<td>-0.13°</td>
<td>0.31°</td>
</tr>
<tr>
<td></td>
<td>(-40, +40, +50, -5°, 0°)</td>
<td>(-5.31°, 0.19°)</td>
<td>0.31°</td>
<td>0.19°</td>
</tr>
<tr>
<td></td>
<td>(-40, +40, +50, 0°, +5°)</td>
<td>(0.29°, 4.79°)</td>
<td>0.29°</td>
<td>-0.21°</td>
</tr>
<tr>
<td></td>
<td>(-40, +40, +50, 0°, -5°)</td>
<td>(0.06°, -5.13°)</td>
<td>0.06°</td>
<td>0.13°</td>
</tr>
<tr>
<td>3</td>
<td>(-40, -40, +50, +5°, 0°)</td>
<td>(4.40°, 0.15°)</td>
<td>-0.60°</td>
<td>0.15°</td>
</tr>
<tr>
<td></td>
<td>(-40, -40, +50, -5°, 0°)</td>
<td>(-5.14°, 0.15°)</td>
<td>0.14°</td>
<td>0.15°</td>
</tr>
<tr>
<td></td>
<td>(-40, -40, +50, 0°, +5°)</td>
<td>(0.29°, 4.67°)</td>
<td>0.29°</td>
<td>-0.33°</td>
</tr>
<tr>
<td></td>
<td>(-40, -40, +50, 0°, -5°)</td>
<td>(0.44°, -5.16°)</td>
<td>0.44°</td>
<td>0.16°</td>
</tr>
<tr>
<td>4</td>
<td>(40, -40, +50, +5°, 0°)</td>
<td>(4.75°, 0.34°)</td>
<td>-0.25°</td>
<td>0.34°</td>
</tr>
<tr>
<td></td>
<td>(40, -40, +50, -5°, 0°)</td>
<td>(-5.13°, 0.64°)</td>
<td>0.13°</td>
<td>0.64°</td>
</tr>
<tr>
<td></td>
<td>(40, -40, +50, 0°, +5°)</td>
<td>(0.46°, 4.57°)</td>
<td>0.46°</td>
<td>-0.43°</td>
</tr>
<tr>
<td></td>
<td>(40, -40, +50, 0°, -5°)</td>
<td>(0.27°, -5.59°)</td>
<td>0.27°</td>
<td>0.59°</td>
</tr>
</tbody>
</table>

These experiments verify that the pose controller can achieve the desired pose correctly, though the laboratory prototype of the parallel surgical robot obviously needs better engineering work to reduce the backlash of the joints, so that the accuracy in both position and orientation can be further improved.

4. Analysis of asymmetric workspace

It is well known that the major drawback of parallel robots is their more restricted workspace than serial robots. The workspace analyses of parallel robots have been widely studied over the past decade. Many researchers [5, 6, 11, 12, 13] have presented effective algorithms to determine the various workspaces, which are symmetric in nature. In our application of skull bone drilling, the desired workspace is on one side of the parallel surgical robot. In particular, the desired workspace is on the surface of the skull. Therefore we hope to investigate how to enlarge the asymmetric workspace on the surface of a sphere representing the skull.

The relative positions of the skull and the robot obviously have significant influence on the workspace. The constant orientation workspace is analyzed based on the interval analysis approach to find the possible locations the tip of the drill can reach while the
moveable platform maintains a fixed orientation, $\psi = \theta = \phi = 0^\circ$, as shown in Figure 6. This asymmetric workspace provides the range of proper position of the skull. The tip of drill can approximately reach within the range of $-30\text{mm}~-280\text{mm}$ in the $x$-axis, $\pm 140\text{mm}$ in the $y$-axis, and $420\text{mm}~-580\text{mm}$ in the $z$-axis.

![Diagram of workspace](http://designer.mech.yzu.edu.tw/)

**Figure 6. Workspace of the tip of drill relative to parallel surgical robot**

Then a simulated skull represented by a sphere with radius of $75\text{mm}$ is used, as shown in Figure 7. $S$ denotes the desired drilling point. $\beta$ is the angle between the feed direction $D_1D_2$ and the $z$-axis of movable platform. It is very important that the tip of the drill $D_1$ reaches $S$, and the feed direction $D_1D_2$ coincides with the normal vector at $S$. A $180\times 180$ mesh is put on the sphere. The step size of the mesh projected on the sphere simulating the
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skull is about 2.18mm². Kinematics analysis described in the previous section is used to check the number of grid points on the sphere that can be reached by the tip of the drill with the feed direction $D_1D_2$ coincides with its normal vector. The location of the center of the simulated skull influences the number of reachable points. The maximum number of reachable points is 393 when the center of simulated skull is at (-300, 0, 440).

![Simulated skull localization](image)

**Figure 7. Simulated skull localization**

In practical applications, the ball joint’s motion is restricted by the physical construction of the joint, especially by the maximum ball joint angle $\lambda_{\text{max}}$. $\lambda_{\text{max}}$ of the ball joints used in this work is 25°, but initial angles of all ball joints are approximately 15° while all 6 links are fully retracted. There is only 10° in the positive direction of rotation, which greatly restricts the workspace. This is especially true for links $P_2$ and $P_5$ as shown in Figure 8, because the $P_2$ and $P_5$ ball joints restrict the tip of the drill from reaching a wider workspace (the simulated skull) located on the negative $x$-axis.
To further increase the workspace on the sphere, Figure 9 shows a special-designed offsetting socket, in which the ball joints can be installed along a specific direction. Using the offsetting socket for $P_2$ and $P_5$ ball joints compensates the ball joint angle from $0^\circ$–$25^\circ$ to $15^\circ$–$40^\circ$. Figure 10 shows the effect of using this offsetting socket for the $P_2$ and $P_5$ ball joints. When the center of the simulated skull is at (-300, 0, 440), the number of reachable points increases from 393 to 452 using the offsetting socket for $P_2$ and $P_5$ ball joints. The maximum number of reachable grid points is 512, when the center of simulated skull is at (-240, 0, 450). This offsetting socket design enlarges the asymmetric workspace by approximately 30%. The area of these 512 grid points on the sphere is approximately $70 \times 35 \text{mm}^2$.

Figure 8. Simulation results of different limitations of ball joint angles

Figure 9. The different of assembly of ball joints
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5. Discussion and Conclusion

This paper presents the development of a parallel surgical robot for precise skull drilling in stereotactic neurosurgical operations. We chose a parallel structure robot for this work due to its advantages in size, weight, low cost, and safety. A master-slave microcontroller-based system is designed for pose control. The major drawback of parallel robots is their more restricted workspace than serial robots. In applications for neurosurgical operation, the workspace is on the surface of a skull located at one side of the robot. This asymmetric workspace on the surface of a sphere representing the skull is analyzed and a special socket joint design which enlarges the asymmetric workspace of the robot for about 30% is also proposed.

This parallel surgical robot has been integrated with the automatic bone drilling carriage developed in our previous work to achieve completely automatic bone drilling. The linear actuators of the parallel robot extend to move the tip of the drill to the desired pose. The feed carriage of the drill begins to feed forward to start drilling operation. The
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Drill should always be normal to the surface of the skull for sensing the electric current consumed by the DC motor of the drill. The electric current has a direct relation with the cutting torque on the drilled. When break-through is detected, the drill stops, and the feed carriage moves backward to remove the drill from the bone. Finally, the linear actuators of the parallel robot retract fully and the robot returns to its original position, awaiting commands for the next drilling.

Important aspect of this work is to integrate parallel surgical robot with an automatic bone drilling carriage developed in our previous work to achieve completely automatic bone drilling. The functions of the pose controller and the accuracy of the laboratory prototype of the parallel surgical robot were verified. This laboratory prototype of the parallel surgical robot obviously needs better engineering work to reduce the backlash of the joints, so that the accuracy in both position and orientation can meet the required precision.

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References

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