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Development of a parallel surgical robot with automatic bone drilling carriage for stereotactic neurosurgery

Abstract

Robot-assisted surgery is an active interdisciplinary field, which has applications in stereotactic neurosurgical operation, orthopedics surgery, and total knee replacements surgery etc. The conventional surgical robots are almost serial architectures, and the performances are restricted. This paper presents an on-going research in developing a parallel surgical robot for precise skull drilling in stereotactic neurosurgical operations. We are currently developing a small occupancy surgical robot based on parallel mechanisms that has enough stiffness and accuracy. This surgical robot dimensions are $35 \times 35 \times 45 cm^3$, and its weight is 6kg. This surgical robot has six degree-of-freedom. The feed carriage of the bone drilling device, which has one translational degree of freedom, is mounted directly on the parallel surgical robot. The workspace of this parallel surgical robot based on the tip of drill is calculated. In pose control, we have designed a master to slave microcontroller-based fuzzy control system. The possibility of asymmetric workspace design is discussed.

Index Terms — Robot-assisted surgery, Parallel robot, Stewart platform, asymmetric workspace, fuzzy control, microcontroller.

1. Introduction

In stereotactic neurosurgical operation, surgeons are most concerned to improve the quality of surgical procedure, including accuracy, security, low morbidity and mortality. Surgeons use a stereotactic frame fixed on the patients' head to set the precise location. But these cumbersome frames in the operating room limit the instrument's access and have the detriment of the physical discomfort and mental stress to the patient [Hemler, et al., 1992; Liu, et al., 2001]. Glauser, et al. [1991] pointed out that it is time-consuming to obtain the spacial coordinates from CT or MRI scanner suite and plan the position of the various axes and move the patient. Surgeons spent 80% time on preparation, and the remaining 20% only on the operation. Glauser, et al. also considered that if the tools are operated by robot, the surgeon is free to deal with other tasks during the intervention.

Robot-assisted and computer-assisted surgery is an active interdisciplinary field. Chen, et al. [1998] implemented a robotics system for stereotactic neurosurgery. This system consisted of image-guided planning, measurement tools, and a PUMA260 robot execution. Malvisi, et al. [2001] developed a new surgical robot, which emphasizes on reliable safety and fault-tolerance mechanisms, for total knee replacements surgery. Engel et al. [2001] also developed a safe robot system for craniofacial surgery, and the goal is to support the surgeon to drill, saw, and mill the bone using the robot as an intelligent tool.

These surgical robots discussed above were all serial structures. The serial structure robots have advantages of large workspace, high dexterity, and maneuverability, but the disadvantages are low stiffness and poor positioning accuracy. Therefore, in recent years more effort and attention have been given to the parallel structure robot due to its simplicity, large payload capacity, high stiffness and position accuracy. The basic reference for parallel mechanism is the research by Stewart [1965], who used the parallel mechanism as an aircraft simulator motion base, hence the so-called "Stewart platform". Stewart platform is composed of a fixed base, a movable platform, and six variable length actuators connecting with base and platform. Various research issues on Stewart platform, including its theory, constructions and investigation [Fichter, 1986; Merlet, 2000; Yang et al., 1984; Tsai, 1999], inverse and forward kinematics analysis [Nanua et al., 1990; Liu et al., 1990;], and workspace definition and analysis [Fichter, 1986; Gosselin, 1990, 1996; Masory, 1995; Merlet, 2000] have been addressed in literature.

In the past decade, a significant amount of research has been done on developing the parallel robot for different medical applications. Tanikawa et al. [1999] developed a dexterous micro-manipulation system based parallel mechanism for assembling micro-machines, manipulating biological cells, and performing micro-surgery. Shoham et al. [2003] developed the MiniAture Robot for Surgical procedures (MARS), a cylindrical 5

×7 cm^3, 200-g, six-degree-of-freedom parallel manipulator. This robot can be used in a variety of surgical procedures in which precise positioning and orientation of a handheld surgical robot in the vicinity of a rigid bony structure.

Merlet [2001, 2002] developed a micro robot called MIPS with a parallel mechanical architecture having three degrees of freedom (one translation and two orientations) 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 and to provide to the surgeon an accurate tool that may further offers a partial force-feedback. Brandt et al., [1999] developed a compact robot for image-guided orthopedic surgery, CRIGOS. The modular system comprises a compact parallel robot and a software system for planning of the surgical interventions and for supervision of the robotic device. These investigations developed surgical robot based on parallel structure due to its advantages over serial structures.

The authors developed a modular mechatronic system for automatic bone drilling in orthopedic surgery [2000, 2002]. One of the major objectives of this research was to develop “add-on” devices that are compatible with current DC motor-driven drills that are commercially available. This system has undergone extensive drilling test on real human skulls under various cutting conditions. There were no unexpected failure, and the overshoots of all drilling tests were less than 2mm. This system has three major modules: the control unit, the feed carriage, and the supporting arm as shown in Figure 1. The control unit consists of a control box and a PC. The control box supplies power to the drill, and in the mean time, the electric current consumed by the DC motor of the drill is analyzed. The feed carriage is designed to be a hand tool for the surgeon to hold with both hands to perform drilling operation. The feed carriage can be attached to a supporting arm that has three joints proving five degrees of freedom. The supporting arm is a passive device. The surgeon can manually move the feed carriage to a given angle, and tighten the joints by simply turning a knob. These joints are held solid by hydraulic force. The arm has an electric magnetic base, which intends to eliminate vibration and movement.

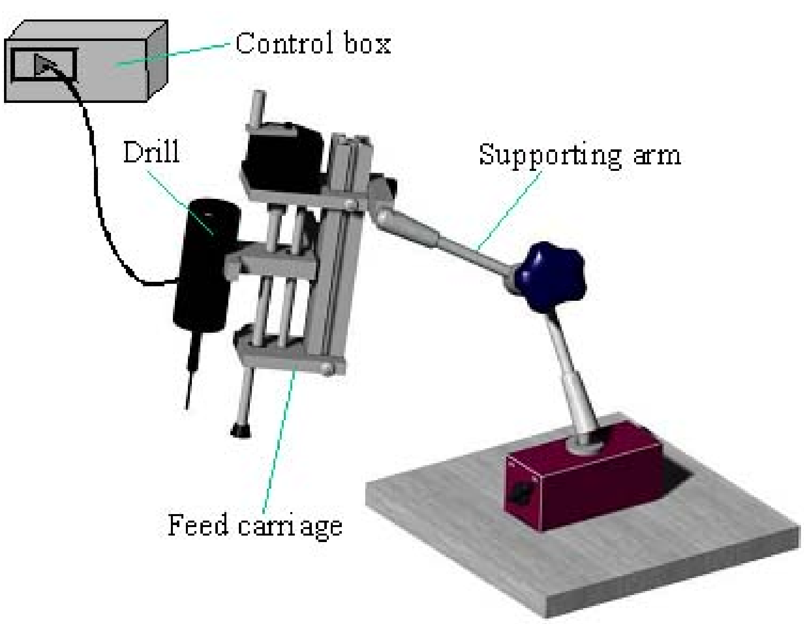


Figure 1. A modular mechatronic system for automatic bone drilling

Following the development of the modular mechatronic system, this paper presents a parallel surgical robot that replaces the passive supporting arm of the automatic bone drilling device. The working prototype is shown in Figure 2. The dimensions of this robot are $35 \times 35 \times 45 cm^3$, 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. This small occupancy surgical robot is based on the parallel mechanisms structure that has six degree-of-freedom to provide enough stiffness and accuracy. The pose controller controls the parallel surgical robot, carrying the feed carriage and the drill, to the pre-defined drilling position with correct orientation automatically. Then surgeon can operates the drill for drilling operation.

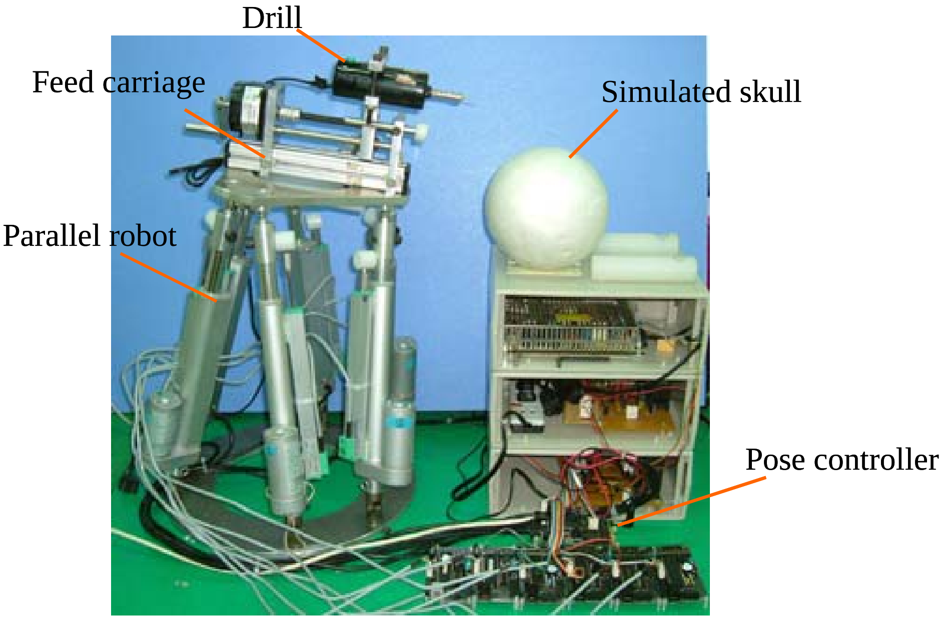


Figure 2. Parallel surgical robot

This paper is organized as follows. Section 2 presents the kinematics model of the parallel surgical robot. The asymmetric workspace of this parallel surgical robot is analyzed in Section 3. Section 4 introduces the pose controller for parallel surgical robot. At last, Section 5 concludes this research.

2. The kinematics model of the parallel surgical robot

The parallel surgical robot developed in this research is shown schematically in Figure 3. It is a six-degree-of-freedom UPS (universal-prismatic-spherical) mechanism, and there is an additional translational degree of freedom at the automatic bone drilling carriage mounting on the parallel surgical robot. The fixed base coordinate system $\{B\}$ is placed at the base center O_b with 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 tip of drill over the feed carriage. The links lengths are denoted as L_1 to L_6. The geometric configurations of movable platform are similar to that of fixed base as shown in Figure 4. The position of six links is arranged symmetrically on the fixed base, on a radius R_b circle. The X-axis of $\{B\}$ is on the line which bisects the angle $B_1O_bB_6$. The α_b angle is the half of the angle $B_1O_bB_6$.

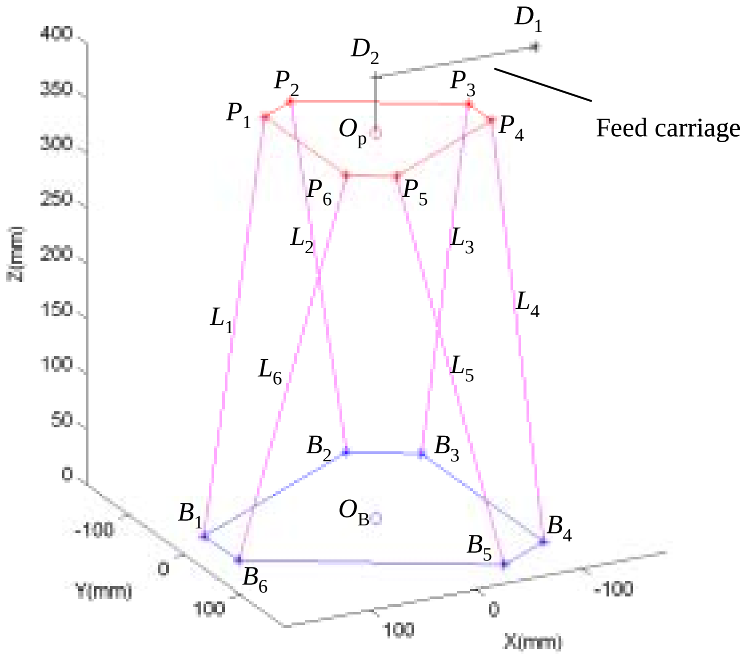
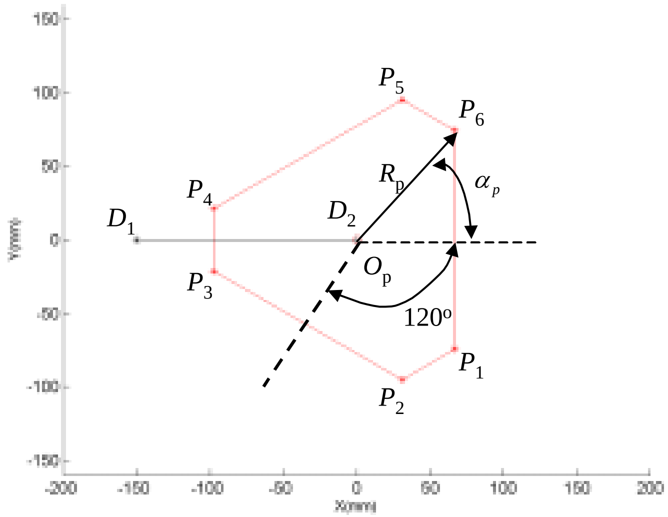
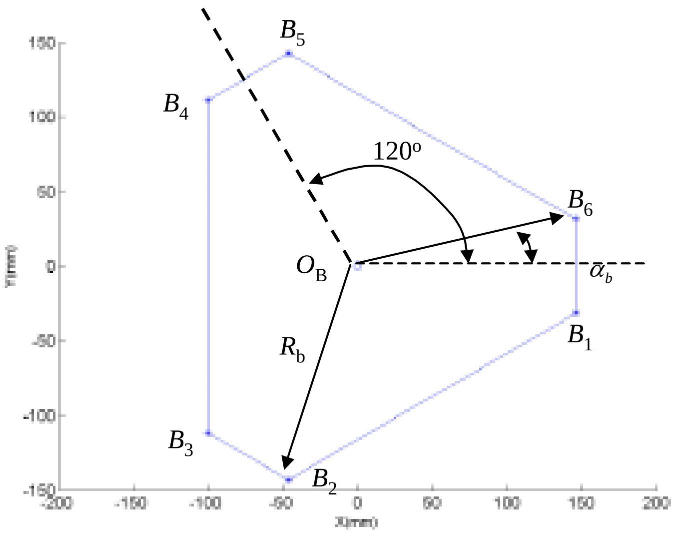


Figure 3. Schematic diagram of parallel surgical robot



Movable platform geometries



Fixed base geometries

Figure 4. Geometric configuration of movable platform and fixed base

In parallel robot problems, generally forward kinematics involves the solution of a set of highly nonlinear simultaneous equations, and is rather complicated [Nanua et al., 1990; Liu et al., 1993]. In this study, inverse kinematics [Tsai, 1999; Merlet, 2000] is used to analyze the workspace of this parallel surgical robot and design its pose controller.

In nurosurgery, the surgeon defines a given pose (x, y, z, ψ, θ, ϕ) for the drill, in which (x, y, z) is the 3D position of tip of drill, and (ψ, θ, ϕ) is (*yaw*, *pitch*, *roll*) that determines the drilling direction of drill. We can obtain a set of valid pose of drill on feed carriage after checking the link length and joint angle constraints [Masory et al., 1995]. In this study, we check the length of six actuators as the link lengths have minimal and maximal values denoted by l_{min} and l_{max}. The rotational angle of a ball joint λ is defined as the angle between the Z-axis of movable platform attached to its socket and the vector along the link connected to the joints. The maximal angle of ball joints λ_{max} used in this work is 25^o. The maximum feed depth f of the feed carriage is 60mm. The initial geometric properties of the parallel surgical robot are summarized in Table 1.

Table 1. The initial geometric properties of the parallel surgical robot

R_b	R_p	α_b	α_p	l_{min}	l_{max}	λ_{max}	D_1D_2	D_2O_p	f
150mm	100mm	12^o	48^o	333.97mm	483.97mm	25^o	150mm	100mm	60mm

3. Pose controller system design

There are two parts in the pose controller system in this parallel surgical robot. As shown in Figure 5, the PC based, high-level controller processes the analysis of inverse kinematics, and the low-level controller consisting of 7 microcontrollers carries out the control algorithm for the 6 linear actuators. A master microcontroller is used to process commands of actuators length from the host computer and communicates with each slave microcontroller in turn. I2C is a two wire communicate interface between the microcontrollers. The master microcontroller may send or request data to/from any slave microcontroller. The 8-bit microcontroller PIC [Microchip Technology Inc.] is used in this research. It has CPU, memory, oscillator, watchdog, and I/O incorporated within the same chip.

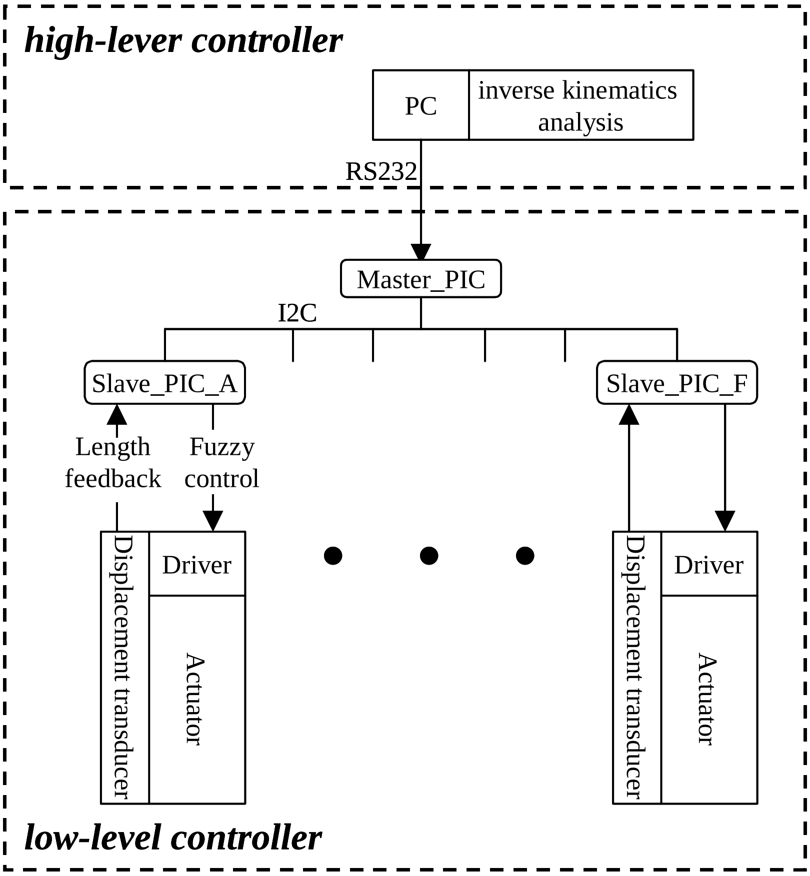


Figure 5. The pose controller system

Each linear actuator is controlled by a motor driver that receives control signal from slave microcontroller. The motor driver is a full bridge driver for DC motor control. The 4 function modes provided by this motor driver includes of forward motion, reverse motion, stop and braking, are controlled by two logic signals (High or Low). A displacement transducer with a resolution of 0.05% (linearity) is attached to each link. The control algorithm applied in this study is fuzzy logic control algorithm. The fuzzy controlling algorithms are programmed in C programming language and implemented in microcontroller system.

4. The analysis of asymmetric workspace

It is well known that the major drawback of parallel robots is their restricted workspace in comparison with serial robots. The workspace analysis and description of parallel robots have been widely studied over the past decade. Many researchers [Fichter, 1986; Gosselin, 1990, 1996; Masory, 1995; Merlet, 2000] presented effective algorithms for determination of the various workspaces and these workspaces have symmetric characteristics. However, few studies have been done on asymmetric workspace analysis of parallel robots. One of the major objectives of this work is to investigate 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. The workspace was shifted by the feed carriage. This asymmetric workspace determines the proper position of the skull. The tip of drill can approximately reach within the range of –30mm~-280mm in the *X*-axis, ±140mm in the *Y*-axis, and 420mm~580mm in the *Z*-axis.

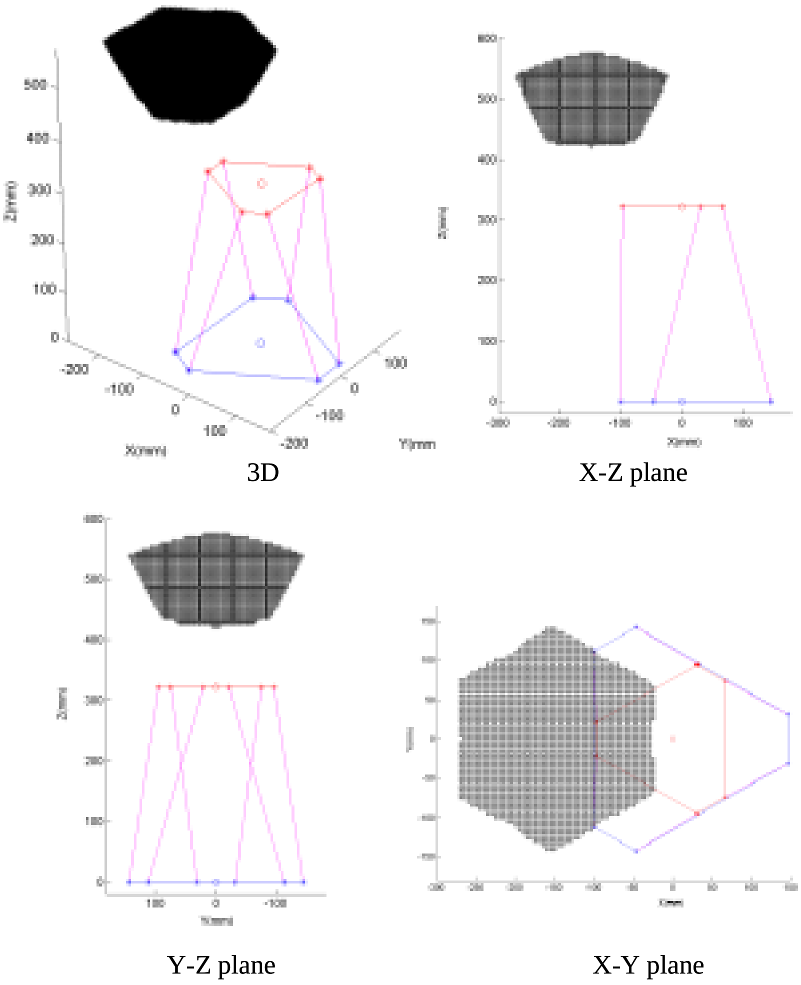


Figure 6. Workspace of the tip of drill relative to parallel surgical robot

A simulated skull represented by a sphere is created as shown in Figure 7. The radius of the simulated skull is 75mm. *S* denotes the desired drilling point. β 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╳180 mesh is put on the sphere, and we checked 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 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).

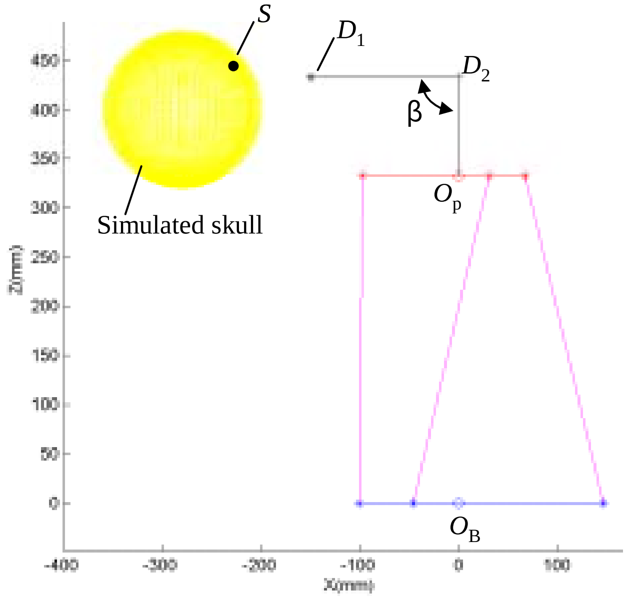
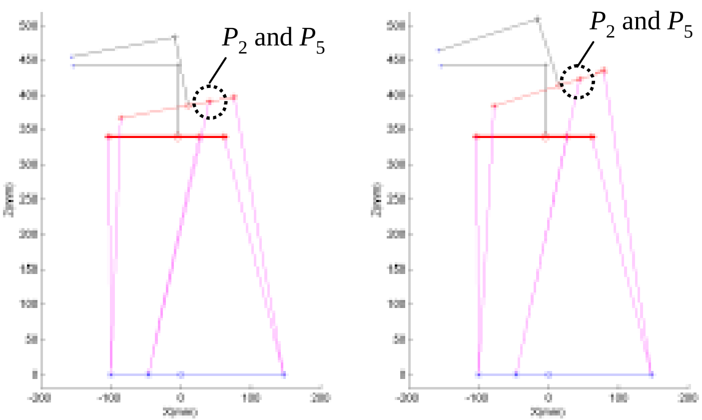


Figure 7. Simulated skull localization

In practical applications, the ball joint's motion is restricted by the physical construction of the joint, especially by the maximum ball joint angle λ_{max}. λ_{max} of the ball joints used in this work is 25^o, but initial angles of all ball joints are approximately 15^o while all 6 links are retracted. There is only 10^o 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 P_2 and P_5 ball joints restrict the tip of the drill to reach a wider workspace (the simulated skull) located on the negative X-axis.



P_2 and P_5 ball joints angle have been constrained

P_2 and P_5 ball joints angle have been compensated

Figure 8. The simulation result of different limitation of ball joints angle

To further increase the workspace, Figure 9 shows a special design 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^o~25^o to 15^o~40^o. Figure 9 is shown the simulation result that the offsetting socket for P_2 and P_5 ball joints can increase the asymmetric workspace.

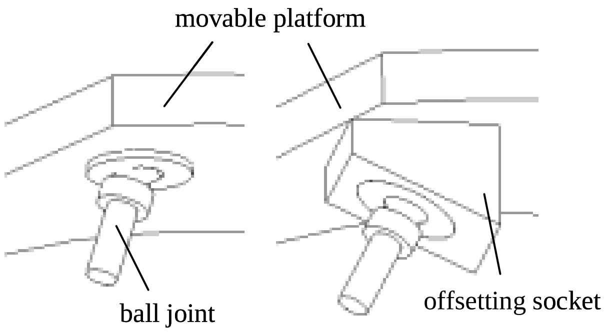


Figure 9. The different of assembly of ball joints

Figure 10 shows the effect of using this offsetting socket for P_2 and P_5 ball. The workspace contains 393 grid points when the center of the simulated skull is at (-300, 0, 440), and the number of reachable points increases to 452 using the offsetting socket for P_2 and P_5 ball joints. When we change the relative positions of the skull and the robot, the maximum number of reachable grid points is 512, when the center of simulated skull is at (-240, 0, 450). The area of these 512 grid points is approximately 70╳35mm^2.

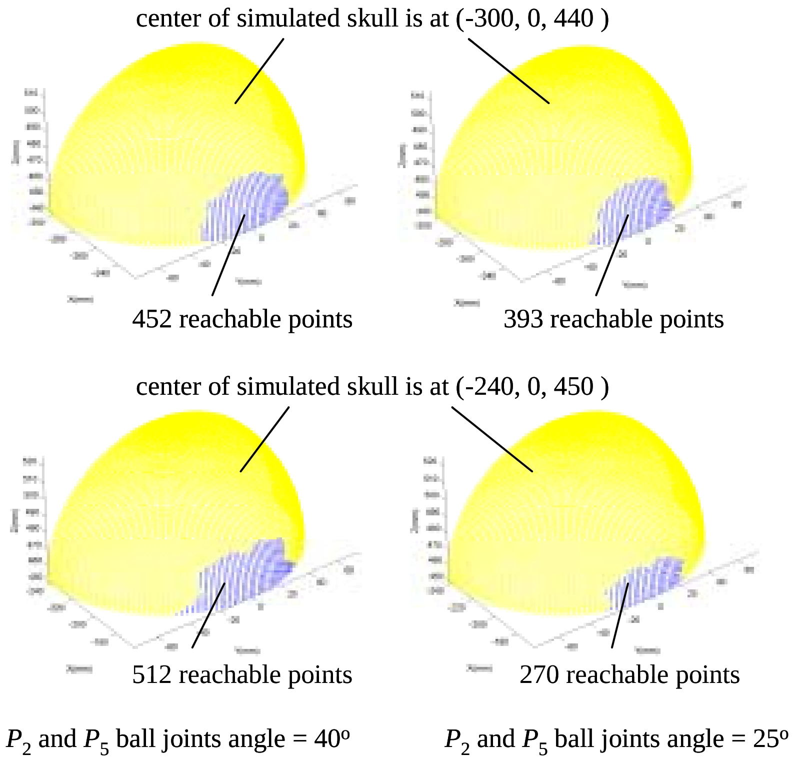


Figure 10. The comparison with different assembly ball joint angle for P_2 and P_5

5. Conclusion

This paper presents an on-going development of a parallel surgical robot for precise skull drilling in neurosurgical operation. We chose parallel structure robot for this work due to its advantages in size, weight, low cost, and safety. The inverse kinematics, motion simulation, and geometric design parameters of this surgical robot were carefully studied. The pose controller based on fuzzy algorithms has been developed.

The major drawback of parallel robots is their restricted workspace in comparison with serial robots. In the neurosurgical operation application, the workspace is on the surface of a skull located at one side of the robot. We analyzed this asymmetric work space and found out the optimal relative positions of the skull and the robot to achieve the maximum workspace on the skull. We also propose a special offsetting socket design, which will significantly enlarge the workspace.

In the future work, more design parameters will be studied, for example the angle β in Figure 7, in order to further expand the workspace.

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