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Joint Type Puncture Robot Research

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***Abstract*—To meet the high requirements of puncture surgery for safety, intuition and maneuverability, this paper proposes a new kind of 6R puncture robot's design. The mechanical structure is described in detail first. A D-H coordinate is created based on the structure, both the normal and inverse kinematics problems are studied. The paper then introduced the scheme of control system and software in general.**

Keywords-Medical robot; Puncture robot; Normal & Inverse Solution of Kinematics

I. INTRODUCTION

CT guiding percutaneous puncture biopsy surgery as a kind of minimally invasive surgery is widely used in the detection and treatment of chest tumor. In actual operation, the surgeon reads the position of tumor via a CT reader, and then visually observe the position and manually puncture. The surgery plan heavily depends on the surgeon's experience and thus with high uncertainty. The case is more obvious when the target is small and the position is deep. In addition, after the CT scanning, the target movement due to cough and other issues will also influence the puncture precision and thus cause repeated positioning and puncture. It will cause the occurrence of pneumothorax, hemoptysis, pleural reaction, air embolism, infection and other postoperative reactions. Taking lung puncture as an example, the occurrence rate of pneumothorax is 10%-40%[5-6] and of hemothrax is 26% - 33%[6-7], which greatly increasing the pain of patients[1].

The development of robot technology provides another solution to all of these faults. Compared with the artificial positioning, the robot localization technology is characterized by high precision, flex operability, shorter operation time, higher success rate, etc. The CT scan data are directly transmitted to the robot system, and converted into a 3D image by the robot system. A surgeon can intuitively make operation plan, and mark out a feeding path. Manipulator accurately guides needle set to the specified location, and swing to specified angle. The technology avoids the blindness due to puncture from the source, improves the success rate and reduce patient's pain.

At present, the puncture robot that having entered the stage of clinical application has four forms, namely rectangular coordinate type, cylindrical coordinate type, joint type and polar coordinate type. Different types have different characteristics. Rectangular coordinate type is characterized by motion decoupling, good intuition, simple control and easiness in achieving precision control, while the motion flexibility is poor and the space is large under

some working space. Cylindrical coordinate type (R2P) is characterized by weak coupling, good motion institution, simple control and good motion flexibility, while the volume is also large. The joint coordinate type features strong motion coupling, poor motion institution, complex control, good motion flexibility and small space in the same working space [2].

II. SYSTEM WORKING PRINCIPAL

The paper introduces a new kind of 6R joint type puncture robot, which features smaller volume, larger working space and better flexibility compared with rectangular coordinate robot and cylindrical coordinate robot.

The patient's image in DICOM format after CT scanning will be transmitted to the robot station. First, the station will map those 2D images to a 3D image and show the result in the station. The surgeon will then customize the operation plan and design the puncture path according to the 3D image. The robot station will solve each joint angle inversely according to the puncture path, in order to control robot mechanical arm electric gripper to hold needle bush and move to the target focus and adjust the puncture position. The surgeon only needs to operate the puncture needle through the hole in the middle of needle bush to complete the puncture surgery. After then the electric gripper is loosen to retract the mechanical arm back. A repeated scan is taken to verify whether the needle tip is in the focus. The scanning and puncturing process is repeat if there are more than one target. After puncturing, a chest CT scan is taken to observe whether there are complications (pneumothorax, bleeding, etc.).

III. MECHANICAL STRUCTURE DESIGN

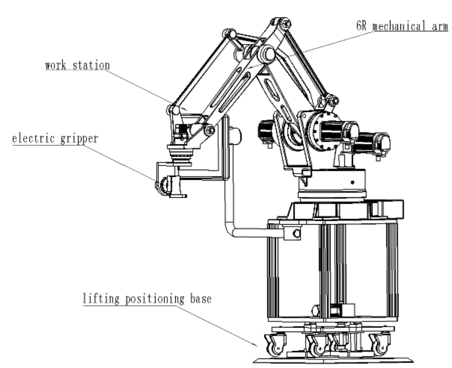

Fig. 1 3D model of puncture robot

The 3D model of puncture robot is shown in Fig. 1. The robot system consists of a lifting positioning base, a 5R mechanical arm, an electric gripper and a work station. The lifting positioning base fixes the robot in a designated position beside CT reader, the electric gripper is responsible for holding needle bush. The core part of work station is a high-performance integrated computer, which is responsible for image processing and position resolution. The mechanical arm drives electric gripper to determine the position and gesture of needle bush.

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A. Lifting positioning base

The lifting positioning base is the positioning part of robot coordinate system. A fixing plate is pasted on the ground relative to the position of the CT reader. The surgeon drives the robot system to align at the fixing plate. Then gear motor starts rotating and drives the lifting plate up through the ball screw mechanism. At the same time, the positioning plate sinking down related to the lifting plate. The locating pins are then inserted into the pin holes on the fixing plate. The lifting plate continues lifting until it reaches the top of fixing plate, where the trundle can hang in the air, then the positioning action of robot related to CT reader is completed.

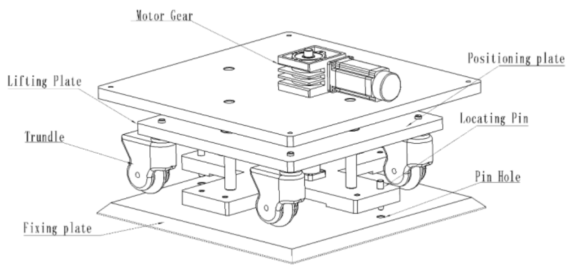

Fig. 2 the Lifting positioning base

B. 6-DOF mechanical arm

The joint robot has two structures, one is direct drive another is parallel connecting rod. The motor of the direct drive robot is directly installed on the rotary joint. The advantage lies in it has simple mechanical structure, while the motor on joint increases the load of higher-level motors and have a bad influence on the effective load. Compared with direct drive rotor, the parallel connecting rod rotor may intensively place the motor besides the base, which is conductive to increasing motor capacity and reducing robot volume. It leaves more space to hang detector on the end of robot and it is more convenient to place the wires .

The paper uses parallel connecting rod robot [8] as shown in Fig. 3. Joint 3 and joint 4 are driven by group 1 and 2 respectively. Shoulder joint 1 rotates around vertical shaft; Shoulder joint 2 and 1 are orthogonal and rotating around horizontal shaft. Elbow joint 3 is parallel to shoulder joint 2; shoulder joint 4 is parallel to shoulder joint 3; wrist joint 5 is orthogonal with shoulder joint 4; wrist joint 5 is orthogonal with wrist joint 5. Joint 1, 2 and 3 are intended to position the arm and joint 4, 5 and 6 determine the orientation.

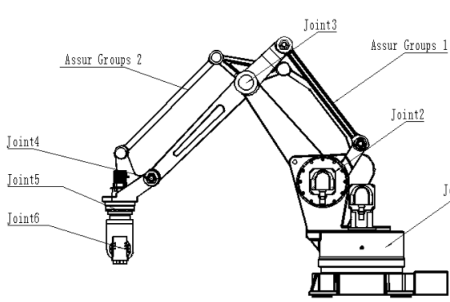

Fig. 3 Mechanical arm part

IV. INVERSE SOLUTION TO ROBOT KINEMATICS

The path planning of robot is the actual application of inverse solution to kinematics, including the inverse solution to position and acceleration [8]. The inverse solution of the joint angle depending on mechanical structure and it is the basis of robot programming.

The coordinate system model of the 6-DOF mechanical arm is show in Fig. 4.

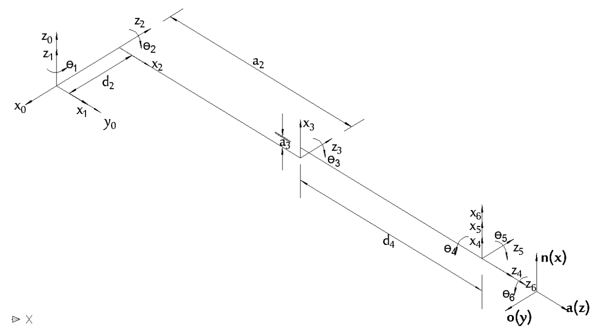

Fig. 4 D-H coordinate system

The meaning of parameters in the figure is shown as follows:

a_{i-1}: distance from z_{i-1} to z_i along with x_{i-1}, representing the length of connecting rod (i-1);

α_{i-1}: angle rotating x_{i-1} from z_{i-1} to z_i;

d_i: distance from x_{i-1} to x_i along with z_i;

Θ_i: angle rotating z_i from x_{i-1} to x_i;

C. Establish D-H coordinate with preposition method

When building D-H coordinate, the transformation matrix of two adjacent coordinate systems is:

$$
{}^{i-1}_{i}T = Rot(x,\alpha_{i-1})Trans(x,a_{i-1})Rot(z,\theta_i)Trans(z,d_i)
$$

$$
= \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -d_i s\alpha_{i-1} \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & d_i c\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

D. Solve robot joint angle with Paul inverse transformation method

To determine the position matrix ${}^0_6T$, some intermediate results should be calculated first:

$$
{}^4_6T = {}^4_5T\,{}^5_6T = \begin{bmatrix} c_5c_6 & -c_5s_6 & -s_5 & 0 \\ s_6 & c_6 & 0 & 0 \\ s_5c_6 & -s_5s_6 & c_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}
$$

$$ {}^{3}_{6}T={}^{3}_{4}T{}^{4}_{6}T=\begin{bmatrix} c_4c_5c_6-s_4s_6 & -c_4c_5s_6-s_4c_6 & -c_4s_5 & a_3 \\ s_5c_6 & -s_5s_6 & c_5 & d_4 \\ -s_4c_5c_6-c_4s_6 & s_4c_5s_6-c_4c_6 & s_4s_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

Multiply ${}^{1}_{2}\mathrm{T}$ by ${}^{2}_{3}\mathrm{T}$ according to the characteristics of joint robot, we can get:

$$ {}^{1}_{3}T={}^{1}_{2}T{}^{2}_{3}T=\begin{bmatrix} c_{23} & -s_{23} & 0 & a_2c_2 \\ 0 & 0 & 1 & d_2 \\ -s_{23} & -c_{23} & 0 & -a_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

And then we can get ${}^{1}_{6}\mathrm{T}$:

$$ {}^{1}_{6}T={}^{1}_{3}T{}^{3}_{6}T=\begin{bmatrix} {}^{1}n_x & {}^{1}o_x & {}^{1}a_x & {}^{1}p_x \\ {}^{1}n_y & {}^{1}o_y & {}^{1}a_y & {}^{1}p_y \\ {}^{1}n_z & {}^{1}o_z & {}^{1}a_z & {}^{1}p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5) $$

Where

$$ {}^{1}n_x = c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5c_6 $$

$$ {}^{1}n_y = -s_4c_5c_6 - c_4s_6 $$

$$ {}^{1}n_z = -s_{23}(c_4c_5c_6 - s_4s_6) - c_{23}s_5c_6 $$

$$ {}^{1}o_x = -c_{23}(c_4c_5s_6 + s_4c_6) + s_{23}s_5s_6 $$

$$ {}^{1}o_y = s_4c_5s_6 - c_4c_6 $$

$$ {}^{1}o_z = s_{23}(c_4c_5s_6 + s_4c_6) + c_{23}s_5s_6 $$

$$ {}^{1}a_x = -c_{23}c_4c_5 - s_{23}c_5 $$

$$ {}^{1}a_y = s_4s_5 $$

$$ {}^{1}a_z = s_{23}c_4c_5 - c_{23}c_5 $$

$$ {}^{1}p_x = a_3c_{23} + a_2c_2 - d_4s_{23} $$

$$ {}^{1}p_y = d_2 $$

$$ {}^{1}p_z = -a_3s_{23} - a_2s_2 - d_4c_{23} $$

Kinematic equation of robot may be written as:

$$ {}^{0}_{6}T=\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}={}^{0}_{1}T(\theta_1){}^{1}_{2}T(\theta_2){}^{2}_{3}T(\theta_3){}^{3}_{4}T(\theta_4){}^{4}_{5}T(\theta_5){}^{5}_{6}T(\theta_6) \quad (6) $$

Firstly solve θ_1, inverse transformation ${}^{0}_{1}\mathrm{T}^{-1}$ left multiplies kinematic equation(2). According to ${}^{0}_{1}\mathrm{T}$,

$$ {}^{0}_{1}T^{-1}=\begin{bmatrix} c_1 & s_1 & 0 & 0 \\ -s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7) $$

So:

$$ \begin{bmatrix} c_1 & s_1 & 0 & 0 \\ -s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}={}^{1}_{6}T \quad (8) $$

Make the elements in (2,4) on both ends of matrix equation equal, we can get $\boldsymbol{\theta_1}$:

$$ -\boldsymbol{s_1p_x + c_1p_y = d_2} \quad (9) $$

make (1,4) and (3,4) on both ends of matrix equation equal, , we can get $\boldsymbol{\theta_2}$ $\boldsymbol{\theta_3}$:

$$ \begin{cases} c_1p_x + s_1p_y = a_3c_{23} - d_4s_{23} + a_2c_2 \\ -p_z = a_3s_{23} + d_4c_{23} + a_2s_2 \end{cases} \quad (10) $$

make (1,3) and (3,3) on both ends of matrix equation equal, we can get:

$$ \begin{cases} c_1a_x + s_1a_y = -c_{23}c_4c_5 - s_{23}c_5 \\ a_z = s_{23}c_4c_5 - c_{23}c_5 \end{cases} \quad (11) $$

and θ_4 θ_5 can be solved.

make (2,1) on both ends of matrix equation equal, we can get:

$$ -\boldsymbol{s_1n_x + c_1n_y = -c_5c_6s_4 - c_4s_6} \quad (12) $$

and thus $\boldsymbol{\theta_6}$ can be solved.

Up to now, the robot coordinator has been decoupled completely.

According to the target position coordinator under robot base system obtained from image processing system, the surgeon may then plan the operation route in workstation software and form the motion track of the mechanical arm. Each joint angle is solved inversely according to the track and the intermediate position between the starting point and ending point will be generated by the computer automatically.

V. CONTROL SYSTEM DESIGN AND SOFTWARE PROGRAMMING

A. Motion control hardware plan design

To facilitate robot software development, the hardware system should have strong openness. Hereby, our robot chooses high-performance computer (PC) and an open CNC motion controller (PMAC) to construct an open platform. The system takes PC as upper computer and PMAC programming multi-shaft motion controller as lower server (the core part of motion control). The upper computer completes the calculation of joint angle and the lower server achieves the concrete movements.

B. Motion control software plan design

The upper computer uses 3D image software developed with Visual Studio C++2012 and VTK, to achieve the 3D image reconstruction and planning operation in the image.

VTK is a kind of free software which developed by the famous Kitware Company. The software has been successively applied in multiple puncture robots as the image processing software.

Robot workstation first reads DICOM document obtained by scanning. The DICOM image are then reconstructs into a 3D image of focus via Ray-Casting method [2, 9, 10]. The operation planning is then accomplished in the 3D image and form the needle path. The system will map the needle path in 3D image to the robot space according to spatial mapping relationship and inversely solve the motion parameters.

VI. DEPICT THE SHAPE OF THE ROBOT'S WORK SPACE WITH 3D MODELING SOFTWARE

To meet the needs of puncture, the parameters of movement scope for each joint angle of the connecting rod are shown in table 1.

TABLE1. PARAMETERS OF MOVEMENT SCOPE FOR EACH JOINT ANGLE

i	**a_{i-1} α_{i-1}** **d_i θ_i**	**Joint Variable Scope**	**Link Parameters**
1	0 0° **0** θ_1(90°)	-160°~160°	a_2=431.8
2	**0** -90° d_2 θ_2(0°)	-225°~45°	a_3=20.32
3	**0** -90° d_2 θ_2(0°)	-45°~225°	d_2=149.09 d_4=433.07
4	a_3 -90° d_4 θ_4(0°)	-110°~170°	
5	**0** 90° **0** θ_5(0°)	-100°~100°	
6	**0** -90° **0** θ_6(0°)	-226°~226°	

The working space of the robot is shown in figure 5. From the graph we know that the robot workspace is a semicircle similar region with the radius of about 760 mm. The work scope of surgery is the limited rectangle area above patients.

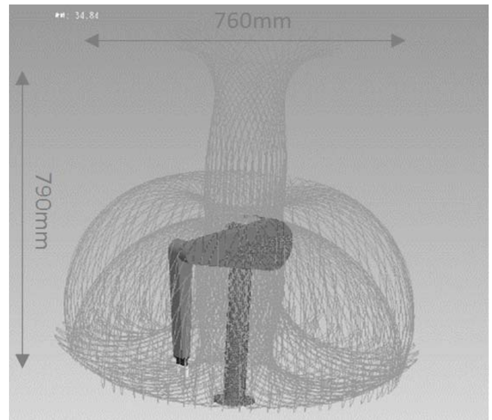

Figure 5 robot's Work space of

VII. CONCLUSIONS

The paper presents a new kind of Six Degrees of Freedom joint type puncture robot design. D-H method is used to build the mathematical model of the system according to the mechanical parameters of 3D model. To get the inverse solution to kinematics of the joint angles, we choose the Paul method.

The new design can effectively reduce the volume of the robot in the same working space and positioning precision in actual application will be greatly increased, and get good flexibility in gesture positioning procedure.

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