Design and analysis of positioning manipulator structure for vascular interventional surgery robot system

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Abstract. The positioning manipulator is an important part of the minimally invasive vascular interventional surgical robot system. In order to make the surgical robot system have high safety, convenience and accuracy, this paper designs a modular lightweight manipulator as a positioning manipulator, which is used to realize the positioning and movement of the propulsion device. First, according to the requirements of the operation, the degree of freedom and configuration method of the manipulator are determined, and the configuration design and parameter selection of the manipulator are completed. Then, according to the structural characteristics of the articulated robot, the D-H parameter method and the inverse transformation method are used to analyze the kinematics of the manipulator and its working space are analyzed. On this basis, the manipulator is analyzed by finite element and verified by static simulation. Finally, the positioning manipulator can realize the function of dragging in its working space by hand to achieve the target pose.

1. Introduction

The positioning manipulator is an auxiliary positioning device in the cardiovascular minimally invasive interventional surgery robot system. The positioning manipulator is used for the fixing, positioning and attitude adjustment of the surgical device. According to the different driving methods, the positioning manipulator can be divided into active and passive positioning manipulators. Active positioning manipulator rely on motors or other power devices to drive joint movement and realize the movement and positioning of the end of the positioning manipulator. The position and trajectory of the end point are executed by a preset program. The passive positioning manipulator does not require any driving device, it needs to be dragged by people to move, its movement trajectory can be changed at will according to environmental requirements, but it is necessary to consider its self-balancing and self-locking issues during design. Passive manipulators are widely used in the medical field, Such as the representative auxiliary positioning device of Da Vinci system and ZEUS robot system [2]. In China, there are the "Li Yuan" stereotactic robot system developed by Beihang University [3] and the positioning manipulator of the "Micro Hand" system developed by Tianjin University [9]. The Navi-Robot, an active and passive positioning manipulator proposed by an Italian scholar, combines the
advantages of an active and passive positioning manipulator, it can be dragged by hand and can also be controlled by a program [4].

The positioning manipulator for minimally invasive interventional surgery needs to have strong environmental adaptability, that is, it can drag and adjust the position of the manipulator at any time. Therefore, this paper proposes a positioning manipulator for realizing the positioning and movement of the end-mounted propulsion device.

2. Structural design of positioning manipulator

2.1. Selection of positioning manipulator structure

The positioning manipulator is designed to realize the positioning and movement of the propulsion device installed at the end. Before determining its specific parameters, it is necessary to select the degree of freedom (DOF), composition form and their configuration method.

In minimally invasive interventional surgery, the operation objects are catheters and guide wires, in order to make the structure of the manipulator compact and the volumetric mass as small as possible, 5 degrees of freedom are sufficient to meet the posture and position requirements of the manipulator.

Affected by the operating room space and the requirements of manipulator flexibility, the 5 joints of the positioning manipulator are all driven by revolute pair, as shown in figure 1.

![Figure 1. Manipulator topology figure.](image)

The essence of the articulated robot is an open-chain linkage system composed of rotating joints and moving joints [5], its joints complete location positioning and posture adjustment. After analysis, it is finally determined that the positioning manipulator adopts a 5R configuration multi-joint robot with 5 degrees of freedom. The first three joints determine the horizontal position of the end, the fourth joint determines the vertical position, and the last joint determines the end posture.

2.2. Modular light weight manipulator

There are two main design methods for the ontology structure of the light weight manipulator. One is to integrate motors, sensors, transmission mechanisms and some circuit control modules inside the robot joints to form a modular joint, and the other is to separate the motors and joints, drive them through a long-distance mechanism to make the joints rotate [7]. The positioning manipulator used in surgery is based on its simple structure and small size, so this paper chooses the first design scheme.

Commonly used robot drive reduction mechanisms include worm gears, gears, harmonic reducers, timing belts, RV cycloid reducers, rope drives and other mechanisms. First of all, for the overall volume, choose worm gears, gears, timing belts and other transmission methods, compared with the direct connection of the motor to the reducer transmission, a larger installation position is required, so neither can be used [7]. In this paper, the joint motor is directly connected to the harmonic reducer, which has a simple structure and a smaller volume.

The joint structure mainly includes a driving device and a transmission device, it can be seen as composed of two parts, namely the input terminal and the output terminal. The location of the drive device is the input terminal, and the location of the harmonic reducer is the output terminal. The joint scheme is shown in figure 2.
According to the specific conditions in the operating room, the final optimal parameters are: the length of the loader arm rotation center distance is 280mm; the length of the mid-arm rotation center distance is 250mm; the length of the vertical arm rotation center distance is 280mm; the length of the rotation center of the vertical arm is 180mm; the length of the swing arm is 180mm; the diameter of the pivoting arm is 120mm. The 3-D models of the manipulator is shown in figure 3.

3. Simulation analysis of positioning manipulator

3.1. Kinematics analysis

There are two main methods to solve the kinematics of the manipulator: D-H parameter method and the product of exponentials formula method based on screw theory [13]. This paper uses the D-H parameter method to study the kinematic equations of the positioning manipulator.

In this paper, the positioning manipulator can be regarded as a series of links connected by joints. Among them, the variable of the rotary joint is the angle of rotation $\theta$, and the variable of the moving joint is its displacement $d$. Through two translations and two rotations transformation, the relative pose matrix of adjacent coordinate systems is obtained.

3.1.1. Forward kinematics. Refer to the D-H method to establish a linkage coordinate system, as shown in figure 4.
Figure 4. Link coordinate system.

Calculate the transformation matrix of each link, and from this, the homogeneous transformation matrix from the end of the manipulator to the base point is obtained, as in equation (1).

\[
^{0}_{5}T = ^{0}_{1}T(\theta_1)^{1}_{2}T(\theta_2)^{2}_{3}T(\theta_3)^{3}_{4}T(\theta_4)^{4}_{5}T(\theta_5)
\]  

(1)

Since the first three joints of the manipulator are all rotating in the horizontal plane, their axes are parallel, thus equation (2) can be obtained, the latter two joints can be obtained in the same way as equation (3).

\[
^{0}_{5}T = ^{0}_{3}T(\theta_1)^{1}_{2}T(\theta_2)^{2}_{3}T(\theta_3) = \begin{bmatrix}
    c_3c_{12} - s_3s_{12} & -c_3s_{12} - s_3c_{12} & 0 & a_3c_{12} + a_2c_1 \\
    c_3c_{12} + s_3s_{12} & c_3s_{12} - s_3c_{12} & 0 & a_3s_{12} + a_2s_1 \\
    0 & 0 & 1 & d_2 - d_3 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

(2)

\[
^{3}_{5}T = ^{3}_{2}T(\theta_4)^{4}_{5}T(\theta_5) = \begin{bmatrix}
    c_4c_5 - s_4s_5 & c_4s_5 + s_4c_5 & 0 & a_4c_4 \\
    0 & 0 & -1 & -d_5 \\
    c_4s_5 + s_4c_5 & c_4c_5 - s_4s_5 & 0 & a_4s_4 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

(3)

Multiplying equation (2) and equation (3) can obtain the transformation matrix \(^{0}_{5}T\) from the end of the manipulator \(\{5\}\) to the base point \(\{0\}\), this transformation matrix is the basis of kinematic analysis.

3.1.2. Inverse kinematics. The methods of inverse kinematics mainly include inverse transformation method, geometric method and Pieper method. This paper uses the inverse transformation method to solve the inverse kinematics. Transform the kinematic equation obtained in the previous section into equation (4).

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

(4)

Multiply formula (4) with the inverse transformation matrix to the left to get equation (5).
Let the elements (1,3), (2,1) and (3,2) on both sides of equation (5) be equal respectively, we can further obtain $\theta_1$. In the same way, let the elements of (2,4), (1,3), (3,4), (3, 2) in equation (5) be equal respectively, we can get $\theta_2$, $\theta_3$, $\theta_4$, $\theta_5$. It can be seen that there are 11 solutions for the inverse solution of the manipulator, but due to mechanical constraints, it is impossible to realize all joint paths.

3.2. Working space analysis.

There are many ways to solve the workspace, the most commonly used are graphical and analytical methods.

![Workspace of positioning manipulator.](image)

In this paper, the software MATLAB is used to simulate the manipulator workspace. Within the variation range of each joint variable $\theta = 1, 2, 3, 4$, rotate from the first joint to the last joint in a certain step length, thereby obtaining the working space, the simulation result is shown in figure 5.

It can be seen from figure 5 that the working space of the manipulator is continuous without obvious holes, and the size of the working space reaches the indicators of the required working space.

4. Statics analysis

Considering the dead weight of the positioning manipulator and the weight of the end load, bending deformation is inevitable. The amount of manipulator deformation is closely related to its structural rigidity. In order to reduce weight, steel is used as the key load-bearing component for the manipulator material, and duralumin alloy is used for the remaining components.

This paper uses ANSYS software for finite element analysis and static simulation. First, the 3D model is imported into WorkBench and the geometry module is established, then the material is set and the bottom of the head joint is fixed. Through testing, it is found that the deformation of the robot arm is the most serious when it is fully deployed. Finally, the static load is applied to the end of the robot arm and the solution is solved by meshing. The analysis results are shown in figure 6 and figure 7.

It can be seen from the figure 6 and figure 7 that under the limit force of the manipulator, the total deformation is maximum 0.2mm, and the stress 14.45Mpa. It can be seen that the positioning manipulator designed in this paper meets the needs of strength and rigidity safety.
5. Conclusion

The positioning manipulator is an important part of the robot system for minimally invasive vascular interventional surgery, based on configuration analysis, this paper designs a positioning manipulator with five degrees of freedom. This positioning manipulator is directly driven by a motor, and a torque sensor is installed at the end. The torque sensor receives the force signal when the human hand applies force, and the drive motor provides power.

According to the D-H method, the kinematics positive and negative solutions of the positioning manipulator are solved, MATLAB is used to verify the working space of the positioning manipulator, and use ANSYS for static analysis to verify the safety and correctness of this design.

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