1. Introduction
Prostate cancer and kidney cancer, as two kinds of urinary system tumors, have extremely high morbidity and mortality, which seriously endanger human health. Percutaneous biopsy and ablation are currently common options for these diseases. Percutaneous needle insertion is a surgical operation in which a microsurgical instrument, such as a puncture needle, penetrate through the skin into the patient's body, reach the lesion target position, and then perform biopsy, ablation, radioactive particle implantation and other surgical operations under the guidance of medical images. It has the advantages of high precision, small trauma, less complications and safe process [1,2]. Unlike endoscope-guided minimally invasive surgery, percutaneous needle insertion surgery, as a kind of minimally invasive surgery, requires external image guidance, such as ultrasound, CT and MRI.

The conventional manual percutaneous needle insertion procedure has many shortcomings: First, due to the lack of information of three-dimensional medical images, the planning of needle insertion surgery relies too much on the experience of the doctor; secondly, the needle insertion and the adjustment of the needle angle are manually operated by the doctor. This is not only dependent on the experience and skills of doctors, but also susceptible to human factors, such as the shaking of doctors' hands and the fatigue of doctors caused by too long operation time.

To overcome these problems, a variety of percutaneous needle insertion robot have been proposed and studied by researchers. Compared with manual needle insertion, robot-assisted percutaneous needle insertion surgery has higher precision and can significantly reduce the labor intensity of doctors. Stoianovici et al. [3] proposed a MINI-RCM & PAKY robot for precise needle insertion under radiological guidance, which consists of a PAKY end effector and a remote center-of-motion (RCM)
actuator module. Taylor et al. [4] designed a steady-hand micromanipulation based on RCM module to extend human micromanipulation capabilities. The URobotics Brady Urological Institute of Johns Hopkins University developed a compact six-degree-of-freedom robot called Acubot [5] for radiological interventions. Based on steady-hand manipulator, many robots for retinal microsurgery, such as EyeRoBot [6], EyeRoBot2 [7] and EyeRoBot2.1 [8], have been proposed by Advanced Medical Instrumentation and Robotics (AMIRo) of Johns Hopkins University. Hong [9] designed and analyzed a real-time ultrasound-guided needle insertion medical robot, which can modify the needle path in real time by using a novel ultrasonic image segmentation technique. H. Bassan et al. [10] present a new 5 degrees-of-freedom (DOF) 3D-ultrasound-guided robotic system capable of performing percutaneous needle insertion for prostate cancer.

At present, most of the percutaneous needle insertion robots adopt three-dimensional positioning sliding table to realize the position and posture decoupling function. However, after combining with the RCM mechanism, the sliding table has many shortcomings; it will reduce the flexibility and compactness of the robot; doctors cannot adjust the position of the robot during the operation, and even the percutaneous needle insertion robotic system will cause the doctor's sight to be blocked and operation inconvenience.

In this paper, a percutaneous needle insertion surgery robotic system is designed to perform the function of percutaneous needle insertion, biopsy, and ablation. The needle insertion robotic system has 6 degrees of freedom and employs a mechanical structure which can decouple the position and posture of the robot. It includes a 4-DOF positioning module and a 2-DOF RCM module. The 4-DOF positioning module can perform the position of the percutaneous needle and the 2-DOF RCM module can perform the orientation of the percutaneous needle, separately.

The rest of the paper is organized as follows: Section 2 describes the mechanical design details of the percutaneous needle insertion robotic system concerning the decoupling of the robot’s position and posture. Section 3 discusses the forward and inverse kinematics modeling of the percutaneous needle insertion robotic system. Section 4 shows the manufacturing and assembly of the overall robotic system. Section 5 concludes the paper.

2. Robotic Design

2.1. Overall Design of Robotic System

Considering the principle of percutaneous needle insertion operation, the robotic system needs to be able to perform a needle insertion operation in three steps, which can improve the accuracy and convenience of the operation. First, doctors need to determine the skin needle insertion site according to the preoperative surgical plan of the robotic system, and then the puncture needle is translated to the desired skin needle insertion point for positioning. Three translational degree-of-freedom of the puncture needle are necessary to reach the desired needle position. In this step, the posture of the needle has not been adjusted yet. Second, the robot system adjusts the orientation of the needle so that the needle axis is aligned with the lesion target. Since it is not necessary to consider the rotation about the needle axis, this step requires two global rotating degree of freedom to orient the puncture needle. During the posture adjustment of the puncture needle, the position of the needle tip cannot be changed. Finally, one translational motion is needed to insert the puncture needle into the skin through the skin needle insertion point.

To achieve the step-by-step surgical procedure mentioned above, the robotic system should be able to kinematically decouples rotating and translational motions of the needle. The robotic system consists of a 4-DOF positioning robotic arm, a 2-DOF RCM wrist and a needle insertion driver. The puncture needle is fixed into the insertion driver and then mounted on the 2-DOF RCM wrist so that the tip of the needle is located at the RCM point. The 4-DOF positioning robotic arm can realize the exact position of the puncture needle. The 2-DOF RCM wrist can accurately adjust the posture of the needle. The combination of these two modules can ensure the kinematic decoupling of the position and posture of the puncture needle. Figure 1 shows the three-dimensional model of percutaneous
needle insertion robotic system.

Figure 1. The three-dimensional model of percutaneous needle insertion robotic system

2.2. 4-DOF Positioning Robotic Arm

For locating the puncture needle position, it is redundant to use 4-DOF positioning robotic arm, but the redundant robotic arm can ensure that the needle can reach the desired needle insertion point at different postures. This feature enhances the flexibility of the operation. The robotic arm can bypass some obstacles to reach the target point, and can change the position of the arm according to the doctor's needs, so as to avoid the obstruction of the doctor's sight and the inconvenience of operation.

The multi-joint robotic arm must be decoupled. There are two typical decoupling schemes, one is using connecting links for decoupling and the other is using cable-driven links structure for decoupling [11]. The decoupling design using cable-driven links is simple, but it will increase the size of the structure and make it bulky. The connecting links decoupling schemes is complex, but its structure is compact and light. For medical robots, compactness and lightweight are more important, so the decoupling schemes using connecting links is adopted in this design.

The rotation angles of the active rods AD and AB are $\alpha$ and $\beta$, then the rotation angles of the connecting rod DE and EJ at the rotating joints D and E are

$$DE = \beta - \alpha$$
$$EJ = -\beta$$  \hspace{1cm} (1)
Based on the above dual-parallelogram decoupled linkage mechanism, the 4-DOF global positioning robotic arm is developed, as shown in Figure 3. This robotic arm not only realize global positioning for puncture needle, but also does not affect the orientation of the subsequent RCM mechanism and the puncture needle.

**Figure 3.** 4-DOF global positioning robotic arm

### 2.3. 2-DOF Remote Center-of-Motion Wrist

In percutaneous needle insertion procedures, the tip of the puncture needle is first translated to the skin needle insertion point by 4-DOF global positioning robotic arm, and then it needs to be oriented to point to the lesion target with the position of the needle tip unchanged. Since it is not necessary to consider the rotation of the puncture needle about its own axis, the posture adjustment of the puncture needle requires only two degrees of freedom.

The schematic of the remote center-of-motion linkage mechanism is shown in Fig. 4. This mechanism uses a dual-parallelogram linkage to achieve a fixed virtual center of rotation, which is the point O in Figure 4. If the virtual connecting rods BO and HO are connected respectively, two parallelogram linkages "ACHO" and "AEGO" can be obtained. When rod AE is the driving connecting rod, the parallelogram linkage ABCD can ensure that the joint H rotates around the virtual point O and the parallelogram linkage ABEF can ensure that the joint G rotates around the virtual point O. Thus, the connecting rod GH can rotate around the virtual point O. This realizes the function of remote motion center.

**Figure 4.** Schematic of the RCM Linkage Mechanism

The 2-DOF dual parallelogram RCM wrist designed in this paper is shown in Figure 5. The distal virtual point serves as the desired skin needle insertion point. It can ensure that the position of the puncture needle tip is not changed when the surgical needle is rotated about the distal virtual center point. Thus, the surgical puncture needle can be freely rotated and moved in the patient's body through a small wound.
3. Kinematics Analysis of Robotic System

The robotic system consists of a mechanism with position and posture decoupling, and it also includes an RCM mechanism. So, the kinematics of such robotic system is quite different from the conventional serial robot. Now, we use the classical D-H method to derive the kinematics model of the robotic system, and then analyze the multi-solution problem of inverse kinematics according to the practical application background.

3.1. Forward Kinematics Analysis

First, we set up the D-H coordinate system of the percutaneous needle insertion robotic system, as shown in Figure 6. There is a virtual coordinate system O3' on the robot arm because of decoupled mechanism. In addition, considering the requirement of needle insertion angle for percutaneous surgery, a fixed 100-degree angle is set between joint 4 and joint 5 of the percutaneous robotic system.

The base coordinate system O0 is placed on the mounting base of the percutaneous robotic system. The directions of the coordinate systems O1-O3 are arranged in parallel in space. Moreover, the Z direction of coordinate system O1 is consistent with the Z direction of base coordinate system O0. The posture of the joint 4 is only rotated by a certain angle with respect to the Z axis of the base coordinate system O0. The coordinate system O4 is set at the intersection of the axis of joint 4 and joint 5. The coordinate system O5 and O6 are set at the virtual point of RCM mechanism.

Second, the parameters of the robotic system links are listed in Table 1.
Table 1. Parameters of the robotic system links

| link | \(a_i\) | \(\alpha_i\) | \(d_i\) | \(\theta_i\) |
|------|--------|---------|-------|---------|
| 1    | 0      | 90°     | \(d_1\) | \(\phi_1+0°\) |
| 2    | \(a_2\) | 0       | 0     | \(\phi_2+90°\) |
| 3    | \(a_3\) | 0       | 0     | \(\phi_3-90°\) |
| 3'   | \(a_4\) | -90°    | 0     | \(\phi_3'-0°\) |
| 4    | 0      | -100°   | \(d_2\) | \(\phi_4-90°\) |
| 5    | 0      | 90°     | \(d_3\) | \(\phi_5+90°\) |
| 6    | 0      | 90°     | 0     | \(\phi_6+90°\) |

Finally, the forward kinematics analysis based on the classical D-H method is derived as follows. To make the matrix simple, we use \(c_\theta\) and \(s_\theta\) instead of \(\cos \theta\) and \(\sin \theta\). The homogeneous transformation matrix between adjacent coordinate systems of the robotic system can be expressed as follows:

\[
A_1^0 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(2)

\[
A_2^1 = \begin{bmatrix}
c_{\theta_1} & 0 & s_{\theta_1} & 0 \\
-s_{\theta_1} & 1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(3)

\[
A_2^3 = \begin{bmatrix}
c_{\theta_2} & 0 & s_{\theta_2} & 0 \\
-s_{\theta_2} & 0 & a_{\theta_2} c_{\theta_2} & 0 \\
0 & 0 & c_{\theta_2} c_{\theta_2} & s_{\theta_2} \\
0 & 0 & s_{\theta_2} c_{\theta_2} & s_{\theta_2}
\end{bmatrix}
\]

(4)

\[
A_4^3 = \begin{bmatrix}
c_{\theta_4} & 0 & s_{\theta_4} c_{\theta_4} & -s_{\theta_4} s_{\theta_4} & 0 \\
-s_{\theta_4} c_{\theta_4} & c_{\theta_4} c_{\theta_4} & -c_{\theta_4} s_{\theta_4} & c_{\theta_4} s_{\theta_4} & 0 \\
0 & -1 & 0 & 0 & 1
\end{bmatrix}
\]

(5)

\[
A_5^4 = \begin{bmatrix}
c_{\theta_5} & 0 & s_{\theta_5} & 0 \\
-s_{\theta_5} & 1 & 0 & d_5 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(6)

\[
A_6^5 = \begin{bmatrix}
c_{\theta_6} & 0 & s_{\theta_6} & 0 \\
-s_{\theta_6} & 0 & -c_{\theta_6} & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(7)

Then the forward kinematics equation of the needle insertion arm can be obtained as follows.
\[ T_6^b = A_6^0 A_5^0 A_4^0 A_3^0 A_2^0 A_1^0 \]
\[ = \begin{bmatrix} n_x & s_x & a_x & p_x \\ n_y & s_y & a_y & p_y \\ n_z & s_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} R & P \\ 0 & 1 \end{bmatrix} \]  
(9)

where

\[ n_x = c_{14}s_{a_6}c_6 + s_{14}s_5s_6 - c_{14}a_{a_6}c_5s_6 \]
\[ n_y = s_{14}s_{a_6}c_6 - c_{14}s_5s_6 - s_{14}a_{a_6}c_5s_6 \]
\[ n_z = a_{a_6}c_6 + s_{a_6}c_6 \]
\[ s_x = s_{14}c_3 + c_{14}s_{a_6}s_5 \]
\[ s_y = s_{14}c_{a_6}s_5 - c_{14}c_5 \]
\[ s_z = -s_{a_6}s_5 \]
\[ a_x = c_{14}s_{a_6}s_6 - s_{14}c_5s_6 + c_{14}a_{a_6}c_5c_6 \]
\[ a_y = s_{14}s_{a_6}s_6 + c_{14}s_5c_6 + s_{14}a_{a_6}c_5c_6 \]
\[ a_z = c_{a_6}c_6 - s_{a_6}c_6 \]
\[ p_x = c_1(a_3 + a_5c_4 - a_2s_2) + c_{14}s_{a_6}d_5 \]
\[ p_y = s_1(a_3 + a_5c_4 - a_2s_2) + s_{14}s_{a_6}d_5 \]
\[ p_z = a_2c_2 + a_3s_3 + d_4 - d_4 \]  
(10)

There are seven joint variables in the forward kinematics, as in (9), but one of them is the virtual joint variable because of the mechanism decoupling. Therefore, the entire robot arm has 6 degrees of freedom, the first four degrees of freedom are redundant positioning degrees of freedom of the needle, and the last two are rotating degrees of freedom for the needle’s posture. Next, to make the equations simple, six generalized variables \( q_1 \) to \( q_6 \) are defined, which correspond to the driving of six motors of the robotic system respectively. According to the (1), the joint variables in (9) can be rewrote by generalized variables as follows

\[ \theta_1 = \varphi_1 = q_1 \]
\[ \theta_2 = \varphi_2 + 90^\circ = q_2 + 90^\circ \]
\[ \theta_3 = \varphi_3 - 90^\circ = q_3 - 90^\circ \]
\[ \theta_4 = \varphi_4 = -q_4 \]
\[ \theta_5 = \varphi_5 + 90^\circ = q_5 + 90^\circ \]
\[ \theta_6 = \varphi_6 = q_6 + 90^\circ \]  
(11)

From the (9) and (11), the posture rotation matrix \( R \) contains only \( q_1 \), \( q_4 \), \( q_5 \), \( q_6 \), and the position translation matrix \( P \) contains only \( q_1 \), \( q_2 \), \( q_3 \), \( q_4 \). This clearly confirms that the percutaneous needle insertion robotic system has the characteristics of position and posture decoupling.

3.2. Forward Kinematics Analysis
Next, the closed-form solution method is used to solve the inverse kinematics of the robotic system.

Considering the element \( s_z \) in (9) and (10), we have

\[ s_z = -s / s_{a_6} \]
\[ c_z = \pm \sqrt{1 - s_z^2} \]  
(12)
Then, the generalized variable $q_5$ can be obtained as

$$q_5 = \arctan 2(s_x, c_y)$$

(13)

Considering the $s_x$ and $s_y$ in (10), the simultaneous formulas can be obtained as

$$\begin{align*}
\begin{cases}
s_4 c_5 + c_4 c_5 s_5 = s_x \\
s_4 c_5 s_5 - c_4 c_5 = s_y 
\end{cases}
\end{align*}$$

(14)

Solving the (14), the sum of the generalized variable $q_1$ and $q_4$ is given as

$$q_1 + q_4 = \arctan 2(s_{14}, c_{14}) = \arctan 2(bc + ad, ac - bd)$$

(15)

where

$$a = c_4 s_5, \quad b = c_5, \quad c = s_4, \quad d = s_y$$

(16)

Considering the $n_z$ and $a_z$ in (10), the simultaneous formulas can be obtained as

$$\begin{align*}
\begin{cases}
c_4 c_6 s_6^2 + s_4 c_5 s_6 = n_z \\
c_4 c_5 s_6 - s_4 c_6 = a_z
\end{cases}
\end{align*}$$

(17)

Solving the (17), the generalized variable $q_6$ can be expressed as

$$q_6 = \arctan 2(s_x, c_y) = \arctan 2(fg + he, eg - hf)$$

(18)

where

$$e = c_4 s_5, \quad f = s_4 c_5, \quad g = n_z, \quad h = a_z$$

(19)

Considering the $p_x$ and $p_y$ in (10), the simultaneous formulas can be obtained as

$$\begin{align*}
\begin{cases}
c_4 (a_y + a c_5 - a_2 s_2) + c_4 s_4 d_4 = p_x \\
s_4 (a_y + a c_5 - a_2 s_2) + s_4 s_4 d_4 = p_y
\end{cases}
\end{align*}$$

(20)

Solving the (20), the generalized variables $q_1$ and $q_4$ can be expressed as

$$q_1 = \arctan 2(p_x - c_4 s_4 s_4 d_4) / (p_x - c_4 s_4 s_4 d_4)$$

(21)

Considering the $p_x$, $p_y$ and $p_z$ in (10), the simultaneous formulas can be obtained as

$$\begin{align*}
\begin{cases}
a y + a c_5 - a_2 s_2 = A \\
a y + a c_5 - a_2 s_2 = B
\end{cases}
\end{align*}$$

(22)

where

$$A = (p_x - c_4 s_4 s_4 d_4) / c_1 - a_y$$

or

$$A = (p_y - s_4 s_4 d_4) / s_1 - a_y$$

(23)

$$B = p_y - d_4 + d_4 - c_4 d_4$$

(24)

The value of $A$ is determined by the one where $c_1$ or $s_1$ is not close to zero. Solving the (23) and (24), the generalized variables $q_2$ and $q_3$ can be expressed as

$$\begin{align*}
q_2 &= \arctan 2(s_z, c_z) = \arctan 2(BC - AD, AC + BD) \\
q_3 &= \arctan 2(s_z, c_z) = \arctan 2(BE - AF, AE + BF)
\end{align*}$$

(25)

where
4. Manufacturing and Assembly of Percutaneous Robotic System

First, the manufacturing of the robotic system is performed according to the three-dimensional model in Figure 1. The first five rotating joints of the robot adopt an integrated joint module (model: RCM, from Kollmorgen Corp., Shanghai, China), which integrates a frame-less motor, a custom harmonic reducer, a high-precision absolute dual encoder, a low-voltage DC motor driver and a temperature sensor. Since the sixth rotating joint of the robot cannot adopt the integrated joint module due to structural reasons, a brushless motor module is adopted and an absolute encoder is used to measure the joint rotative angle accurately. Next, in order to achieve the precise force control of the robotic system, a specially customized single-axis SRI torque sensor is integrated at each rotating joint of robotic system. Finally, the overall machining and assembly of the robotic system is shown in Figure 7.

![Figure 7. Overall machining and assembly of the robotic system](image)

5. Conclusions

In this paper, a percutaneous needle insertion robotic system is developed with functions of biopsy and ablation. Such robotic system can overcome the shortcomings of the conventional manual percutaneous needle insertion procedure and make the percutaneous needle insertion surgery safer and more precise. The needle insertion robotic system has 6 degrees of freedom and employs a mechanical structure which can ensure the kinematic decoupling of the position and orientation of the robotic system. It integrates a 4-DOF positioning module, which can perform the position of the percutaneous needle, and a 2-DOF RCM module, which can accurately adjust the orientation the percutaneous needle. The combination of these two modules can ensure the kinematic decoupling of the position and orientation of the robotic system. The kinematics model of the robotic system based on classical D-H method is established, and the forward kinematics and inverse kinematics of the robotic system are analyzed. The multiple solutions to the inverse kinematic model can be chosen according to the actual situation. Finally, the manufacturing and assembly of the overall robotic system is performed and the robot can achieve percutaneous biopsy and ablation for tumor in urinary system.

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