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Kinematic Analysis of the Catheter used in the Robot-assisted Catheter Operating System for Vascular Interventional Surgery

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Abstract—**Vascular Interventional Surgery (VIS) has been widely applied because of its advantages of small trauma and fast recovery in interventional surgery. In the previous work, we designed a master-slave robotic catheter system for VIS. In order to solve the problem that the operating device can not accurately deliver the catheter to the target position, the kinematic analysis of the catheter was carried out. In this paper, we analyzed the kinematics performance of the catheter tip, and obtained the movement rule of the catheter. What's more, we used the movement rule to control the position changes of the catheter to reduce the position error. Finally, we conducted two sets of experiments to push the catheter into the human blood vessel model to measure the distance between the position of the catheter and the position of the target. The experimental results show that use the kinematic modeling to control the movement of the catheter tip can effectively reduce the position error and improve the accuracy of control for the system.**

Index Terms - Kinematic analysis, vascular interventional surgery (VIS), position error, catheter

I. Introduction

With the incidence of cardiovascular and cerebrovascular diseases increased year by year, people pay more and more attention to the treatment of the disease. The medical institutions and research scholars are also committed to VIS technology research and innovation. In recent years, minimally invasive vascular interventional surgery has been widely used for the advantages of less surgical trauma, less pain, shorter recovery time and less cost [1].Compared with the traditional surgery, minimally invasive surgery with modern advanced technology as the support, by laparoscopic and thoracoscopic modern medical devices and associated equipment in the human body performed surgery. Surgery is safer and more reliable, flexible and convenient. Also the master-slave interventional surgery robot system can separate the doctors and patients, the doctor can will be away from harmful radiation, can also reduce the complex operation of expert dependence, let more doctors to master the vascular interventional technology and accelerate the patient's surgical treatment.

In recent years, many experts and scholars at home and abroad have already had some achievements in the research of vascular interventional robot system. South Korea JUN's team developed a robotic catheter navigation system based on the network's master-slave structure. The cardinal extremity of the system and the slave can be achieved through the axial, rotating and bending of three degrees of freedom movement [2]. In Japan Shibaura Institute of Technology, Noor Ayuni Che Zakaria led the team to develop a catheter operating system that can avoid the system failure and artificial operation error [3]. Kagawa University (Guo Lab) developed a master-slave surgical robotic catheter system, and completed the distance between Japan and China's multinational remote teleoperation in 2012 [4]. Beihang University and Navy General Hospital developed a set of force feedback master-slave robot intervention system, which can achieve two degrees of freedom of the pull and rotation of the catheter. They used the fuzzy algorithm to fuse the contact force between the catheter and blood vessels, and feedback to the doctor, so that the doctor's operation experience can play a role in the blood vessel operation [5]. The Southeast University Professor Song Aiguo led the team to design and implement a virtual vascular interventional surgery system based on force/tactile feedback, CAS - Shenzhen Institute of advanced technology research team studied a set of catheter intervention system in line with the traditional physician practices [6].

In this paper, we use a master-slave robot-assisted system designed by our team [7], which mainly consists of two parts: the master operation platform and the slave operation platform. Doctors operate in the main side of the main operator and the information is transmitted to the slave DSP controller by the master DSP controller, from the side of the DSP control the movement of the catheter. The rest of this paper organized as follows. In section 2, the catheter delivery system is introduced. Section 3 introduces the catheter kinematic model and kinematic analysis. Section 4 analyzes the motion space of the catheter. Section 5 proposes the experiments and results. Section 6 is the summary and future work.

II. The Catheter Delivery System

A. Overview of the Robotic Catheter System

In order to eliminate the effect of radiation to the doctor's bodies, the master-slave system is designed to separate the doctor and patient, the doctor operates the system in the

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absence of X-ray radiation environment. The overall interventional system is shown in Fig.1.

Doctors in the main terminal control master manipulator, the position information of the catheter movement acquired by master manipulator of linear displacement sensor, and the catheter rotation information are collected by optical encoder, DSP acquire and process the information and sent to the main terminal of the PC. The host computer sends the information to the slave computer through the network communication protocol, from the side of the computer to send commands to the same side of the DSP to control the axial and radial movement of the catheter so that it can follow the master manipulator. At the same time, slave manipulator will transmit all the force information that is subjected to the catheter to the main operator. The force feedback information generated by the master manipulator will be displayed on the monitor interface [14]. Doctors can use the visual feedback from the side of the camera and monitor the information in the system to control the operation [8]. In this way, it not only can improve the safety and accuracy of the operation, which is responsible for the patient, but also for the doctor's health. In addition, more doctors can use this system to train, improve surgical proficiency and success rate.

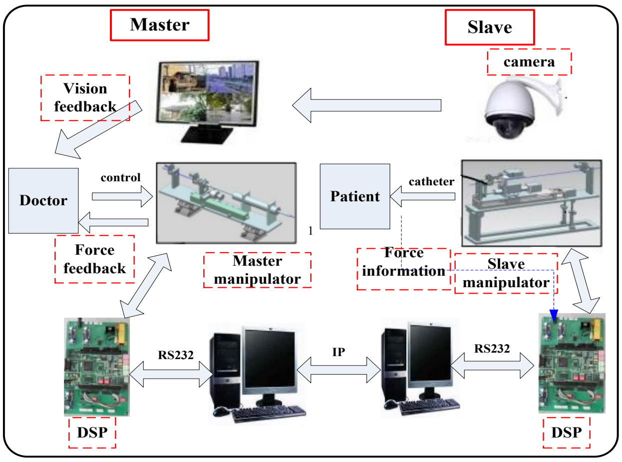


Fig.1 The whole concept map of the vascular intervention system

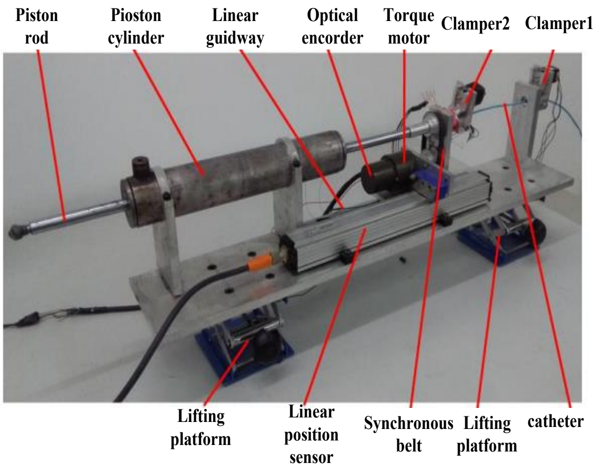


Fig.2 The master manipulator platform

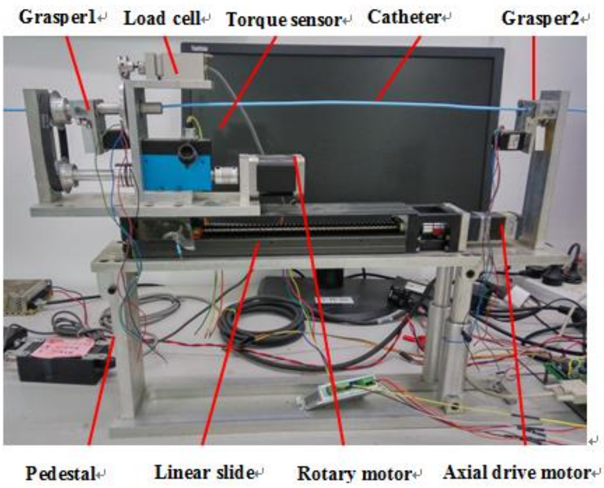


Fig.3 The slave manipulation platform

B. The Master Manipulator

The master manipulator includes motion information collect unit and force feedback unit [13] [16]. The diagram of our designed master manipulator is shown in Fig.2. Surgeons can directly operate the real catheter on the master manipulator, and can directly use their own operation skills accumulated in surgical. The catheter pass through the hollow damper piston rod, the magneto rheological fluid damper can be changed by the catheter in the course of various obstacles l push by changing the size of the damper coil current to achieve the force feedback, the feedback force is directly applied to the hands of the doctor, the doctor can feel more real . The main operating base is installed on two lifting platform, operators can adjust the height of the manipulator according to the operator’s own needs. Here we installed two clamps, which is responsible for switch catheter clamping in the process of forward and backward. During the catheter movement, the linear displacement sensor measurements of magnetic block and damper will move together, real-time acquisition of catheter axial movement information. Optical encoder and DC motors coaxially mounted together, they are synchronized with the movement of the piston rod, optical encoder measured rotation angle is the angle of rotation of the catheter surgery.

C. The Slave Manipulator

The slave manipulator contains catheter motor drive unit and force information detection unit. Catheter movement includes the axial and radial motion. Two fixtures are installed on the operating device to clamp the catheter, which is used to prevent the catheter from sliding, and can imitate the action of the doctor in the operation. When the catheter moves forward, the clamper 2 is released, and the clamper 1 clamps the catheter to make forward and do rotate movements. We need to move the catheter back when traveling to unable to move forward. Then release fixture 1, fixture 2 clamping catheter do backward movement [9] [10]. The whole process of the catheter forward and backward is caused by the axial drive motor by controlling the linear slider to complete, radial motion is realized by stepping motor.

Force information detection unit includes a load cell and torque sensor. Load cell is used to detect the axial resistance in the process of catheter is inserted into human body blood vessel, torque sensor is measuring the resistance when catheter do radial movement, catheter subjected to various forces of information will be passed to the host, implement force feedback [12]. The real structure of the slave manipulation platform shows in Fig.3.

III. Kinematic Model and Kinematic Analysis of the Catheter

The doctor operates on the proximal side of the catheter and the distal catheter followed the same movement. The transmission of the remote catheter is realized through the operation platform, and the structure of the system is shown in Fig.4. As you can see from the Fig.4, the structure is mainly composed of two parts, one part is the slave operating system, the other part is the glass tube model used in the experiment. This procedure is to push the catheter into a model of a glass tube with multiple branches, and simulate the process of transporting the catheter into the blood vessel.

Here we see catheter as a grid connecting rod, the distal end of the catheter may be deformed so we assume that it is the curvature of the curved part of the arc constant and no torque is produced in the bending process [11]. The bending kinematic model of the distal catheter tip is shown in Fig.5.

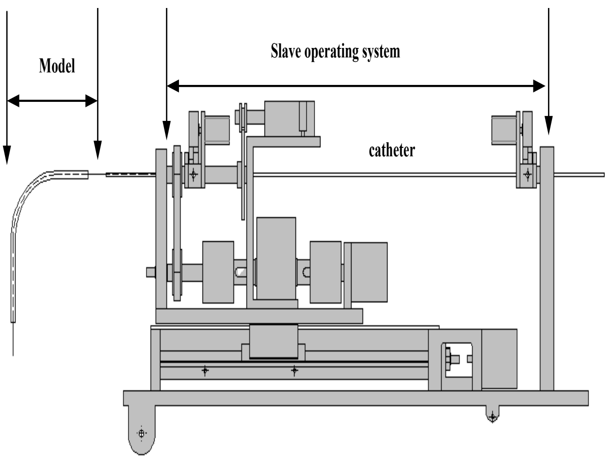


Fig. 4 Schematic of catheters drive

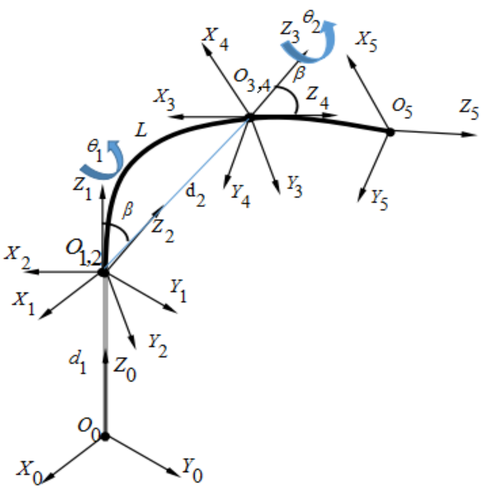


Fig.5 Kinematic model of catheter

In Fig.5 we use the variables d, β, θ, to represent the catheter forward, bending and rotating three degrees of freedom, respectively. L represent curved arcs arc of the catheter that is a constant. d3 is the length of the catheter at the top which is a constant too. d3 represent the displacement of the forward/backward of the catheters.d2 indicates the changing of the displacement after the catheter is curved. The {o0} coordinates is regard as base coordinate of the distal end of the catheter. {o5} coordinates as the catheter tip point coordinates.

According to the D-H parameters, the transformation matrix between each coordinate system is obtained by using (1), and the position relationship between the base system and the end coordinate system is finally determined.

$$T_5^0 = T_1^0 T_2^1 T_3^2 T_4^3 T_5^4 \tag{1}$$

According to (1) to obtain homogeneous transform matrix between the two coordinate of $\{o_0\}$ and $\{o_5\}$, the calculation results are shown in (2).s and c stand for sin and cos, respectively. By the (2) to get the coordinate of the catheter tip coordinate in the base coordinate, as shown in (3).

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \begin{bmatrix} d_3 s\beta s\theta_1 \\ -d_3\left(c\beta s\beta + c\beta s\beta c\theta_1\right) - Ls(\beta)^2/\beta \\ d_1 + d_3\left(c(\beta)^2 - s(\beta)^2 c\theta_1\right) + Lc\beta s\beta/\beta \end{bmatrix} \tag{3}$$

According to the transfer relation of the kinematics model of catheter by catheter proximal and distal end can obtain Jacobi matrix, then the Jacobi matrix for inverse solution and get the relationship between the position coordinates and three variables, and then by adjusting the input variables to reduce the position error. The relationship between the position of the catheter tip and the variables is shown in (4). The 3-order Jacobi matrix is shown in (5).

$$\begin{bmatrix} \delta d_1 & \delta\theta & \delta\beta \end{bmatrix}^T = J^{-1}\begin{bmatrix} \Delta x & \Delta y & \Delta z \end{bmatrix}^T \tag{4}$$

$$J = \begin{bmatrix} 0 & \mathrm{d}_3 s\beta c\theta_1 & d_3 c\beta s\theta_1 \\ 0 & \mathrm{d}_3 s(2\beta) s\theta_1/2 & -d_3 \mathrm{c}(2\beta)(1 + c\theta_1) - L\left(\beta s(2\beta) - s^2(\beta)\right)/\beta^2 \\ 1 & d_3 s\theta_1 s^2(\beta) & -d_3 s(2\beta)(1 + c\theta_1) + L\left(\beta c(2\beta) - s(2\beta)/2\right)/\beta^2 \end{bmatrix} \tag{5}$$

IV. Analysis of The Motion Space of the Catheter

Using MATLAB software programming analyze spatial movement of the catheter, you can draw three-dimensional motion space of the catheter tip. The total length of the catheter used is 60mm, the catheter can be pushed a distance of 0-20mm, and catheter can be bent in the range of the angle β, the rotation angle θ of the catheter range. It can be drawn from the catheter tip movement space three-dimensional map shown in Fig.6.

As the catheter is in a different bending angle, the space is also different. We can set the bending angle beta are π/3 and π/12, observing the change of the range of motion of the catheter.

$$
{}^{0}T_5 = \begin{bmatrix} c\theta_1 c\theta_2 - c\beta s\theta_1 s\theta_2 & -c\theta_1 s\theta_2 - c\beta c\theta_2 c\theta_1 & s\beta s\theta_1 & d_3 s\beta s\theta_1 \\ c\theta_1 s\theta_2 c^2(\beta) + c\theta_2 s\theta_1 c\beta - s\theta_2 s^2(\beta) & c\theta_1 c\theta_2 c^2(\beta) - s\theta_1 s\theta_2 c\beta - c\theta_2 s^2(\beta) & -c\beta s\beta - c\beta s\beta c\theta_1 & -d_3(c\beta s\beta + c\beta s\beta c\theta_1) - Ls^2(\beta)/\beta \\ c\beta s\beta s\theta_1 + s\beta c\theta_2 s\theta_1 + c\beta s\beta c\theta_1 s\theta_2 & c\beta s\beta c\theta_2 - s\beta s\theta_1 s\theta_2 + c\beta s\beta c\theta_1 c\theta_2 & c^2(\beta) - s^2(\beta)c\theta_1 & d_1 + d_3(c^2(\beta) - s^2(\beta)c\theta_1) + Lc\beta s\beta/\beta \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)
$$

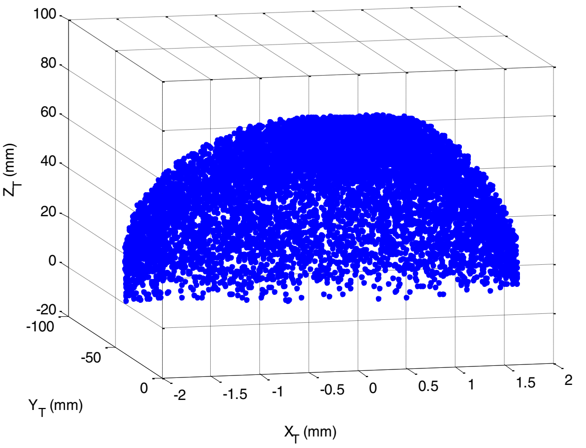


Fig.6 Motion space of catheter terminal

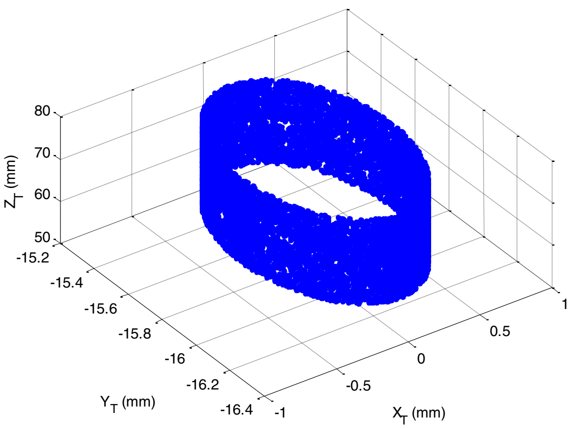


Fig.7 The catheter motion space, when $\beta=\pi/12$

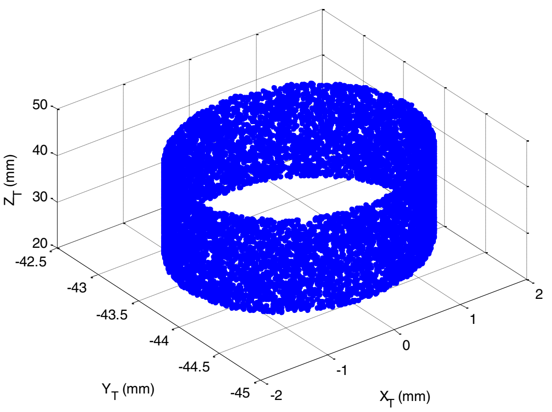


Fig.8 The catheter motion space, when $\beta=\pi/3$

From Fig.7 and Fig.8 we can see that when the catheter bending angle is certain, the catheter is pushed and rotated, the movement space is roughly cylindrical, when the bending angle increases, the motion space of the catheter is also increased accordingly. However, due to the limitation of catheter material and the shape of the blood vessel, the catheter bending angle cannot be more than $\pi/2$.

V. EXPERIMENTS AND RESULTS

The experimental platform is set up as shown in Fig.9. The vascular model is a systemic vascular model. The specific operation method has been introduced in the first second parts. Here we do two sets of experiments to compare, and in each group we do ten times of experiment, the first set of experiments are directly push catheter to the target position according to the monitoring interface. The other group is looking at the monitoring interface while also using the method of catheter kinematics to control the catheter to reach the target position. In each set of experiments, the distance of the catheter move to the actual position should be recorded, and the error and the average error between the actual position and the target position are calculated. In order to make the analysis of the experiment a little bit simple, when we are doing the insertion of the catheter, every time is make the catheter into the same certain model, think its bending angle is the same. Experimental results are shown in Fig.10.

In the second set of experiments, we should use the catheter kinematic modeling to control the movement of the catheter. Δz is known. From the above experiments, we can get the value of Δx and Δy. We can use (5) calculate the change value of θ, β, d when each time move catheter. Due to the inverse Jacobi matrix is associated with the value of the variable θ and β, the value of θ before every mobile catheter would take the last movement at the end of the value. From the previous experimental data we can conclude that the inverse Jacobi matrix, it can get the distance of the catheter reach the target position need to move and rotate. Experimental results are shown in Fig.11.

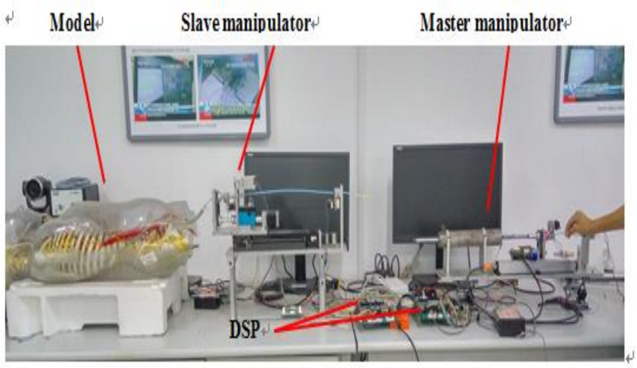
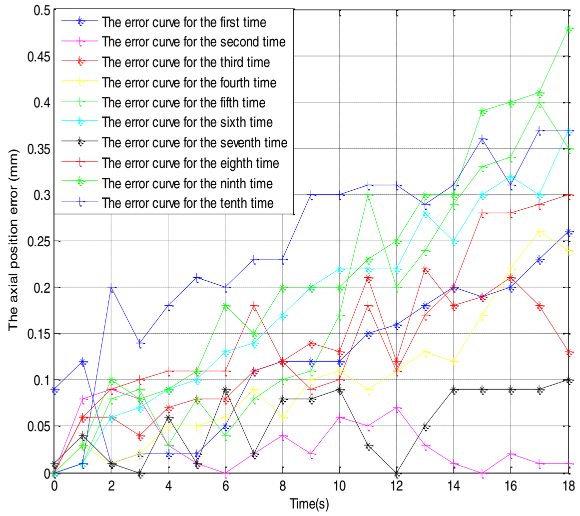
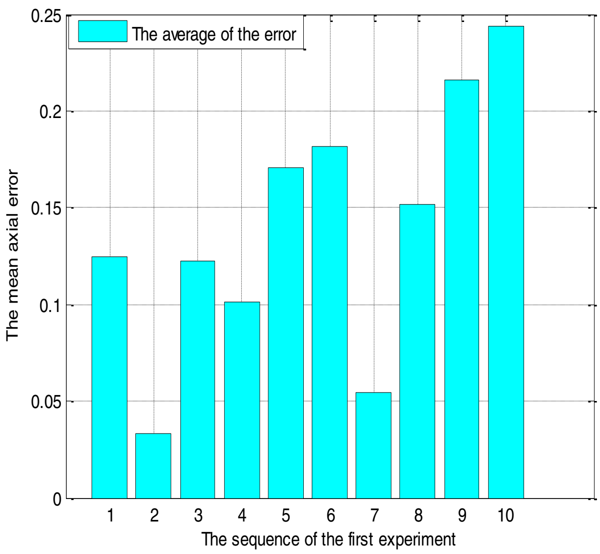


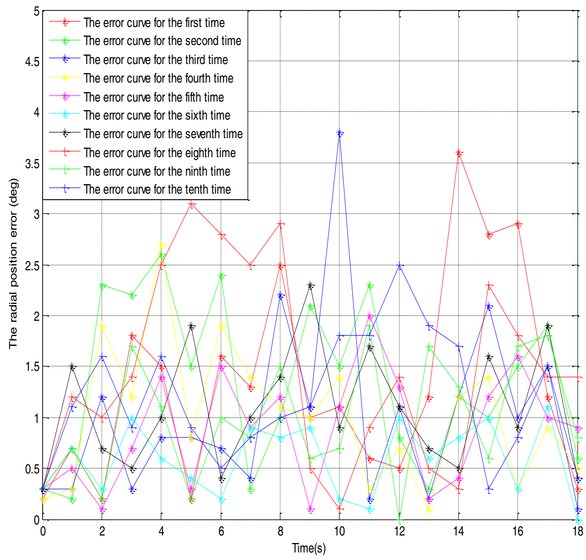
Fig.9 The experimental platform



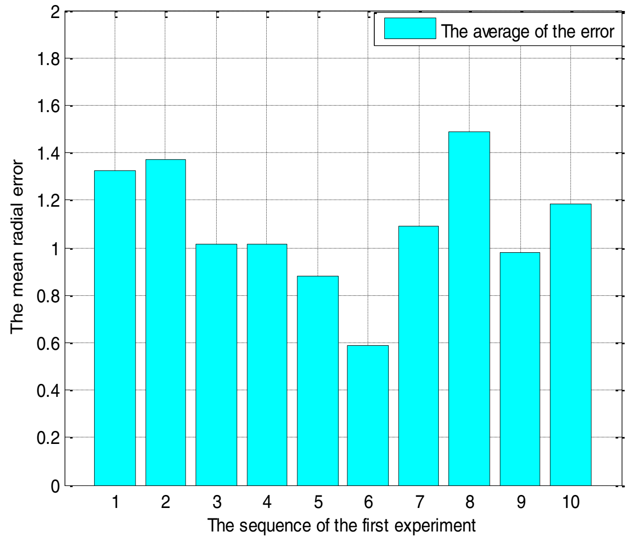
(a) The axial error between target position and real position



(b) The mean square error of the axial position

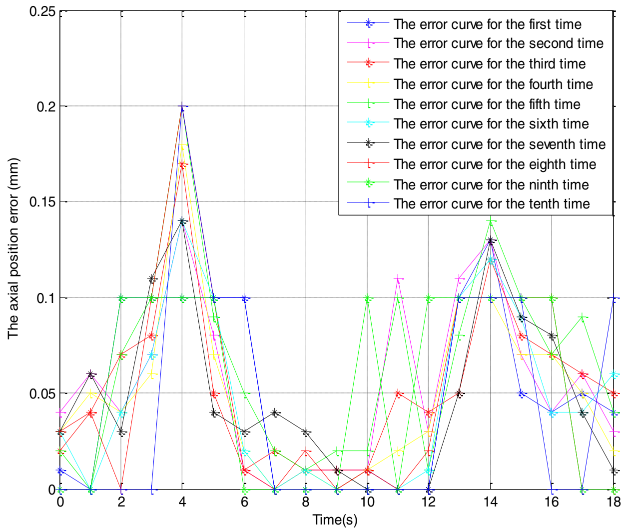


(c) The radial error between target position and real position

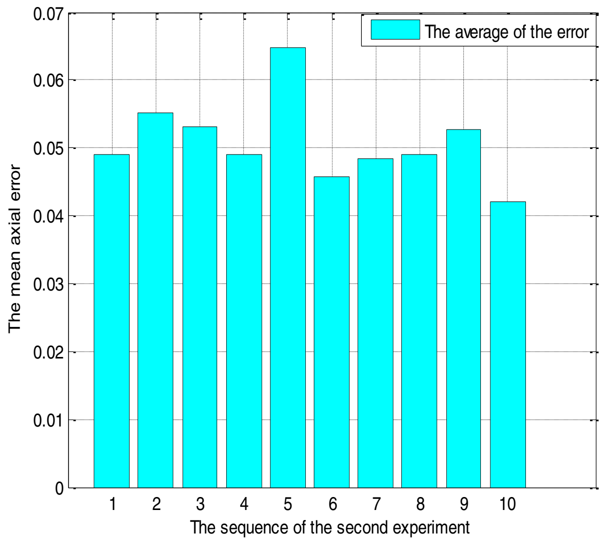


(d) The mean square error of the radial position

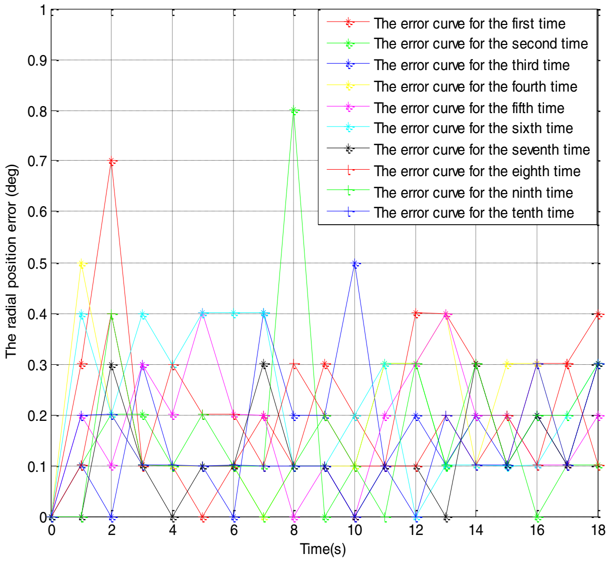
Fig.10 The experimental error without using kinematics analysis



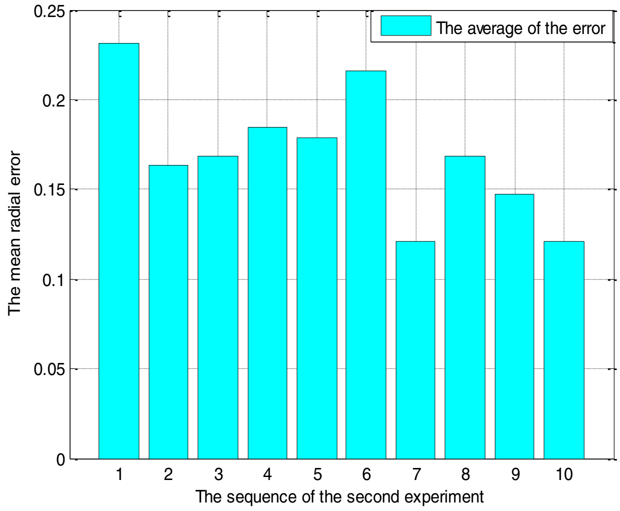
(a) The axial error between target position and actual position



(b) The mean square error of axial position



(c) The radial error between target position and actual position



(d)The mean square error of radial position

Fig.11 The experimental error by using kinematics analysis

Through the experimental curves, we can see that the axial position error between actual position and target position is reduced from 0.5mm to less than 0.25mm, the radial position error by 4 degrees reduced to less than 1 degree. Using catheter kinematics analysis control the movement of the catheter really can greatly reduce the position error. But due to the change of the catheter is related to the state of the last movement, it is needed to calculate in real time, which will prolong the time of the experiment.

VI. Conclusions and Future Work

In this paper, the catheter kinematic model was established and the motion space of the catheter was studied. By the kinematic model, the relationship between the model and catheter tip position was obtained. The actual position of the catheter and the target position were compared by using the catheter movement rule control the changing state of the catheter in the vascular model. The result indicated that the modeling approach was suitable for controlling catheter position and reducing the position error. In the future, we plan to do the research on the localization of catheter based on kinematic model "in vivo".

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