Abstract
With the promoting popularization of vascular interventional surgery (VIS), the demand for the corresponding robot aided system arises spontaneously. In order to train interns, and make them faster qualified for clinical surgery, we develop and produce a master manipulator of vascular interventional surgical robot according to operational requirements in this paper. While accuracy is one of the most important indexes to evaluate a robotic auxiliary system, we have to test it before comprehensive application. The accuracy is mainly influenced by signal’s transmission since the signal in the system has to go through several links which may have distortion due to reasons such as defect of mechanism, slip of wheels, etc. Thus we must carry on an experiment of testing motion signal, including displacement and rotation from doctors transmitted to the master manipulator, and analyze the results to verify master manipulator can accurately capture motion signals of doctor’s hand. Above all, in order to eliminate error accumulation, we would establish error model, through which we can get an error scope at diverse displacement to furnish whole system’s error compensation with this model which is of great important to improve accuracy of device and ensuing activities of project for virtual training system’s design.

Keywords: Vascular interventional robot, Master manipulator, Signal capture, Accuracy experiment, Error model

1. Introduction
Vascular interventional therapy is a new subject which combines imaging diagnosis and clinical treatment. It utilizes needles, catheters and other interventional equipment to make specific devices access to lesions through vascular for the purpose of minimally invasive treatment under the guidance and surveillance of digital imaging equipment such as X-ray, digital subtraction angiography (DSA) machines and so on (Lee and Hong, 2017b). Now it has become one of three mainstays of clinical medicine in coordination with traditional medicine and surgery, involving many clinical disciplines, such as cardiovascular and cerebrovascular intervention, interventional artery, etc. Interventional treatment not only has developed into an important treatment method due to advantages of small trauma, quick recovery and good effect, but also become the first choice for many diseases’ diagnosis and treatment. It will be an important direction of medical science in the future.

However, the current VIS also exposes some shortcomings, which has become more and more serious with the rapid increasing number of patients. For example, due to real-time X-ray imaging is necessary during the operation, doctors have to be exposed to radiation for a long time, and the cumulative radiation exposure is very large which will influence the quality of operation. Doctors must wear lumpish lead suits to resist radiation during surgery, which will make doctors consume greater physical exertion, lead to fatigue, and result in decreased reliability. There are also many other shortcomings.
Considering these problems, different kinds of robot system have been developed (Antoniou et al., 2011) to solve them, such as CorPath designed by Corindus, (Rafael et al., 2006), the Amigo designed by Catheter Robotics Inc. (Frumkin W et al., 2013) and so on. As these vascular interventional robot is designed to consist of a master manipulator and a slave manipulator, it can realize remote control which means doctors can handle master manipulator outside operation room to control slave manipulator inside operation room (Khan et al., 2013b). Thus robots’ assist to doctors during VIS can effectively prevent doctors from exposure to radiation greatly protect doctors due to remote operation (Meng and Zhang, 2013), and improve operation quality. That’s why we need such a medical robot to assist surgery. Therefore, it is of great clinical value and social significance to develop an interventional robotic system for VIS which is easy to operate as well as efficient, safe and low cost (Guo et al., 2012). Due to it can be controlled by human, we call it medical robot, just like we call AGV car as mobile robot.

However, those robot system mentioned above take a method of utilizing rocker (Juan et al., 2011) or handle to input doctors’ hands signal and control slave manipulator, while no matter which would change the doctor's habit of operating, making doctors feel hard to control and have to take a long time to be trained before operation. We had better develop a training system first and improve the structure. Commonly, a vascular interventional surgical robot consists of a master manipulator and a slave manipulator. But in this paper, we aim to design and produce a master manipulator according to operational requirements and combine it with the training system developed by professors of Computer Department which will be used to train interns. Thus only master manipulator will be studied and slave manipulator is not necessary in this paper. Our job is to develop the structure of master manipulator with the aim of not to change doctors’ habit and utilize it to collect hand’s motion signals, then verify its accuracy through a series of tests. Then it can collect accurate data for virtual training system. Above all, we would establish error model according to test data, which can provide a reference for the error compensation of the closed-loop control of the whole training system. Finally, we analyze the reasons for errors and propose some suggestions for reducing the error.

2. Design of master manipulator

2.1 Signal transduction in robot system

The common interventional robot consists of master manipulator and slave manipulator. The slave manipulator is located in the operating room where is full of X-rays, while master manipulator is outside operation room. The signal transduction of interventional robotic system is shown in Fig. 1. Doctor operates master manipulator outside the operation room which means inputting their hands’ signal to the system. Then master manipulator will collect the action signals of the doctor's hands and send signals to the operating room. Afterwards, the slave manipulator hand drives wire and catheter to the focus inside the human body so as to achieve the purpose of remote treatment. After analyze the signal transduction process, we draw a conclusion that the accuracy of the system mainly depends on the accuracy of signal acquisition at the master manipulator if we want to develop a training system. Therefore, the error measurement experiment must be carried out for the subsystem, namely, the signal acquisition accuracy of the master manipulator.

Fig. 1 Signal transduction of robot system and virtual training system for vascular interventional surgery
Figure 1 demonstrates signal transduction in the system. We also add transduction in the slave manipulator to make it easier to understand. Our job will focus on master manipulator which is circled with red dotted line in Fig. 1. Though master manipulator is used to collect signals and not to handle catheter directly, it controls the slave master manipulator. That’s why we still call it master manipulator.

### 2.2 Mechanism design of master manipulator and method for collecting motion signal of hands

As the common therapy of VIS is that doctors place medical equipment or medicine on the catheter and directly deliver the medical equipment or medicine to the lesion by catheter, the catheter is required to be capable of traveling around the vessel and rotating itself in order to realize a smooth entry into vascular branches under doctor's operation. When we decompose motions described above, we can finally draw a conclusion that the catheter must have two degrees of freedom—axial degree of freedom and rotational degree of freedom. In order to enable catheter to meet such motion characteristics, catheter and wire for VIS are generally performed through two methods, push or pull and rotation. Based on the analysis above, the structure of the interventional structure is designed as which is shown in Fig. 2.

![Module 1](image1.png) ![Module 2](image2.png)

**Fig. 2 Structure of master manipulator**

In order to collect two motion signals from the doctor's hand respectively, the structure is equipped with two capture modules 1 and 2. Module 1 is designed for the doctor's "push and pull" movement, which captures the axial motion signal, and its internal structure is shown in Fig. 2(a), which consists of a shell frame 1, a handle 2, a guide tube 3, a press block 4, two friction wheels 5 and 8, an encoder 6, two shafts 9 and 11, four springs 10. The catheter 7 passes through two friction wheels, and when doctor pulls or pushes catheter 7, the catheter 7 will drive two friction wheels 5 and 8 to rotate. At the same time, the encoder 6 aligned with master wheel 8 will record the wheel’s speed and revolution, to accomplish acquisition of hands motion signals through which we can gain axial displacement of the catheter after calculating. In order to avoid distortion of the motion signal of catheter during transmission, a compression device is necessary, concluding a press block 4 and a handle 2 and four springs 10. The pressure between the two friction wheels can be adjusted by compression device so as to avoid catheter slipping or being crushed during the process of advancing and retreat.

Module 2 is designed to capture the rotating motion signal of the doctor's hands. The structure is shown in Fig. 2(b). It is composed of a rotary encoder 12, an operating tube 13. As the catheter is made of flexible multiplex metal, when doctors rotate catheter, it is unable to drive parts. Thus we design an operating tube 13, with which encoder aligns could capture rotating motion signal (Guo et al., 2014).

Master manipulator’s mechanism structure and two signal acquisition modules’ layout could not only meet the operation requirements, but also maintain doctor’s habit which has been formed in conventional VIS, helping the doctors
and interns get accustomed to it quickly and improving accuracy to the great extent simultaneously.

3. Signal capture accuracy experiment and analysis

In order to verify the accuracy of the motion signal captured by master manipulator and provide a theoretical basis for the clinical application of the interventional robotic system, a series of tests are essential, and the experimental data ought to be analyzed scientifically so as to verify the reliability of the mechanism (Yonemoto et al., 2011), and establish error model for closed-loop control and propose improving scheme according to the results.

To achieve the experiment objective, we have to gain two sets of data. One of them means doctor’s hands signal and another one means signals which will be used to make animation in training system or drive catheter in slave manipulator. Only these two sets of data have little difference can we draw a conclusion that the master manipulator can transmit signals precisely.

3.1 Experiment Scheme

The catheter is the core equipment of VIS, and also the core equipment of the test. Common types of catheter include VER (vertebral artery catheter), RH (hepatic artery catheter), coronary catheter (JRF, JL4). Their diameters vary from 4F to 6F (1F=0.33mm) (Chen et al., 2004). According to the feedback from the hospital, who cooperates with us, the hospital's clinical VIS tend to use RH (hepatic artery catheter) which makes us use RH to conduct experiment as well.

The platform of this experiment is master manipulator of the interventional robot and measuring device. The whole measuring system is shown in Fig. 3.

Module 1 captures the axial motion signal, namely, displacement, using a photoelectric rotary encoder of TOONE, whose model is ZSP3004EC while module 2 captures the rotary motion signal, namely rotation angle, using Maxon rotary
encoder, and its model is 110516. The output modes of the two encoders are three-phase square wave output, both of which are 500 line encoders, namely 500ppr, and pulse period is 0.72 degrees. Considering the accuracy index, we can get pulse period of 0.18 degree through quadruple frequency. These two sensors, with very high accuracy, are widely used in a variety of industrial occasions and the effects of their own errors on the experiment can be neglected.

The measuring device is composed of assembles 1 and 2 which is shown in dashed part of Fig. 3, wherein the assemble 1 is composed of an operation tube 13, an indicator 16 and a frame 15. We've made a scaleplate on the frame, as shown in the green section of the picture. When we rotate the operating tube, the operating tube will drive the indicator to rotate, so we can get the angle of the operating tube according to the pointer and the scaleplate. The structure and measurement principle of assemble 1 is somewhat like a clock. Assemble 2 is composed of catheter 7 and some frames where we make a scaleplate, as shown in the blue section of the picture. When catheter is driven to move forward and backward, we can get displacement through reading the value of scaleplate.

After we get displacement and rotation from encoders and measurement device respectively, we can compare them to judge whether the master manipulator is able to collect signals from doctors precisely.

3.2 Capture accuracy experiment of position

In clinical surgery, the doctor needs to accurately control the catheter's movement in the blood vessel. When blood vessels travel and enter the branches, there must be little collision with the blood vessels. Therefore, it is necessary to verify the capture accuracy of displacement and rotation.

The absolute error of slave manipulator to capture displacement is defined as the difference between catheter's displacement operated by doctors and catheter’s displacement captured by master manipulator. The formula is:

\[ \varepsilon_a = l_a - l_b \] (1)

Among them, \( \varepsilon_a \) is the absolute error, \( l_a \) is the displacement of the catheter operated by doctors, and \( l_b \) is the displacement measured by master manipulator.

Considering the movement of catheter is quite similar as lathe, we use lathe’s computing method about position accuracy and repeatability to calculate the catheter’s. According to the international standard ISO 230-2 1997 (Ibaraki and Ota, 2014), the mathematical model of evaluating the position accuracy and repeatability is:

\[ A = \max \left[ x_i + 2s_i \right] - \min \left[ x_i + 2s_i \right] \] (2)

\[ R = \max \left[ 4s_i \right] \] (3)

\( A \) indicates position accuracy and \( R \) indicates repeatability. \( x_i \) is the average position deviation of the i-th measurement points while \( s_i \) is standard uncertainty of the i-th measurement points. Their formulas are:

\[ x_i = \frac{1}{n} \sum_{j=1}^{n} x_{ij} = \frac{1}{n} \sum_{j=1}^{n} (P_{ij} - P_i) \] (4)

\[ s_i = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (x_{ij} - x_i)^2} = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (P_{ij} - P_i - x_i)^2} \] (5)

In the formulas, \( j \) is cycle index; \( P_i \) is theoretical location of the i-th measurement points which is the displacement operated by doctors in this paper; \( P_{ij} \) is actual position of the i-th measurement points in the j-th test.

The calculation mentioned above is about displacement test. Indeed, rotation test is the same principle as it.

3.2.1 Displacement signal capture accuracy measurement experiment

According to the hospital’s feedback, in the actual operation process, the catheter, under the doctor's operation, in large artery can move fast forward and backward and the distance is about 30~120mm, since the large artery is quite thick, and has less vascular branches. Under X-ray's supervision, doctors can operate more smoothly along the catheter. When
catheter arrives in target organs such as heart, liver, bladder and so on, it needs to be rotated as well as pushed or pulled to enter the branch of the blood vessel and the advancing distance is 1mm~30mm at this time. Therefore, the displacement measured each time should be within the range mentioned above during displacement measurement experiment. In order to restore the surgical scene more visually, we divide experiment into two stages: the stage of fast forward in the arteries, during which each target displacement is 30~120mm; the stage of looking for entry of vascular branch, during which each target displacement is 1mm~30mm. Therefore, we choose several specific displacement for experiment in each stage, each displacement test is performed ten times. During the experiment, we would pull or push catheter 7, the catheter 7 will drive two friction wheels 5 and 8 to rotate. At the same time, the encoder 6 aligned with master wheel 8 will record how many pulses have been generated. After we get the number of pulses, we can calculate the displacement of catheter. The calculation process is as follows.

\[ D = n_p \cdot \theta_p \cdot r_m \]  

In the formulas, \( D \) is displacement; \( n_p \) is the number of pulses; \( \theta_p \) is the measuring increment of encoders; \( r_m \) is the radius of master wheel.

In this way, the absolute position accuracy and repeatability can be studied simultaneously. The values of the selected displacement and experiment results are shown in the table1. These displacements are our target. Actually we cannot and control catheter to move at certain displacement precisely and this is not necessary for a contrastive experiment as well. We only need to ensure what we input is close to the manipulator’s output.

<table>
<thead>
<tr>
<th>No.</th>
<th>Displacement [mm]</th>
<th>Error range [mm]</th>
<th>Position Accuracy</th>
<th>Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-0.38~0.10</td>
<td>0.059</td>
<td>0.059</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-0.10~0.09</td>
<td>0.074</td>
<td>0.059</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>-0.22~0.37</td>
<td>0.237</td>
<td>0.160</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>-0.09~0.35</td>
<td>0.239</td>
<td>0.144</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>0.05~0.44</td>
<td>0.245</td>
<td>0.131</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>0.22~0.53</td>
<td>0.406</td>
<td>0.190</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>-0.38~0.80</td>
<td>0.495</td>
<td>0.360</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>-0.16~0.86</td>
<td>0.577</td>
<td>0.294</td>
</tr>
<tr>
<td>9</td>
<td>70</td>
<td>0.37~1.04</td>
<td>0.776</td>
<td>0.181</td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>0.79~1.53</td>
<td>1.256</td>
<td>0.198</td>
</tr>
<tr>
<td>11</td>
<td>120</td>
<td>1.27~1.74</td>
<td>1.577</td>
<td>0.167</td>
</tr>
</tbody>
</table>

Line charts of absolute error of two phases are shown in Fig. 4.

![Fig. 4 Absolute error of displacement in first phase and second phase](image1)

Figure 4(a) is the absolute error of displacement in the first phase, while Fig. 4(b) is the second phase. It illustrates that at any stage, absolute error of catheter’s displacement captured by encoders changes with the value of displacement.
Generally, the greater the displacement, the greater the error. The error corresponding to each displacement fluctuates within a certain range which means, under such mechanism, each displacement, even those which are not tested, has corresponding error range. This is an important inspiration for establishing error models. As to the repeatability, it is not only influenced by accuracy of mechanism, but also influenced by users or experimenters because repeatability explores consistency of data. As catheter is controlled by experimenters, if experimenters cannot promise to perform same displacement each test, it will lead to a large repeatability. That’s why repeatability becomes large with the increase of displacement generally, but there are still two exceptions—30mm and 50mm. Surprisingly, according to our experience in the experiment, these two displacements are the hardest displacement to perform.

### 3.2.2 Axial velocity information capture accuracy measurement

In addition to two important parameters of displacement and rotation of the catheter, there are also speed index during the operation. However, as the whole process will be carried out under X-ray irradiation, and when necessary, even DSA will be used, the axial speed of the catheter will not be very high. Moreover, under the condition of ensured displacement accuracy, the impact of speed on the operation will not be great as well. Thus we only need to experimentally verify the capture accuracy of the axial velocity at master manipulator.

Previously, we have carried out displacement capture accuracy experiments, and the selected displacements were all possible distances of catheter conducted by doctors. Therefore, the speed capture accuracy experiments were performed on the basis of these selected displacements. When the displacement is fixed, several speed measurements are carried out to analyze the doctor's hand speed and the speed that the encoder catches. We pull catheter in the measurement device, meanwhile use a camera to take a photo per 0.1ms. After getting a series of photos in which we can find that each photo record a position of catheter, we can pick up two photos whose positions’ difference equals the displacement has been fixed before. Then we calculate the number of photos exist between these two photos, plus 0.1ms and can get the time when catheter moves at certain displacement. Finally, we can get velocity through dividing displacement by time. The measuring process is shown in Fig. 5 which takes 90mm as an example.

![Fig. 5 The measuring process of velocity](image)

The principle of computing is same as displacement and the absolute error of velocity are shown in Fig. 6:

![Fig. 6 Absolute error of velocity](image)

The label of fold line at the top right corner in Fig. 6 like “Velocity_10” means velocity at the displacement of 10mm.
As the catheter is conducted by experimenter rather than motor, the velocity corresponding to each displacement fluctuates greatly. This is normal since jitter occurs when the catheter is operated manually and to reach certain displacement, experimenter cannot always arrive at terminal point at the same speed. But none of this had any effect on the experiment which actually focus on the difference of velocity between doctor and encoder. The experimental results show that the error of velocity capture increases with the increase of displacement. The greater the displacement, the more signal is lost. The relevant parameters for evaluating accuracy will be list in table 2 below.

### 3.2.3 Rotation signal capture accuracy measurement

When the catheter moves to the branch of the vessel, as the tip of the catheter is curved at the front, it can be rotated around itself to find the branch inlet. Therefore, the circumferential rotation of the catheter becomes a very important index of motion, and the project also puts forward some requirements for the accuracy of the rotation angle of the master manipulator.

In order to carry out the experiment, we select several angles of rotation which may be applied by doctors during operation, according to the doctor's habits, and for the reliability of subsequent analysis, we add some measuring angles. As there are too many measuring angles and each angle would be tested 10 times which will result in a messy graphics, we draw a sketch map of measuring angles as Fig. 7(a) shows to make Fig. 7(b) easy to understand and save space for the paper as well instead of listing every angles which can be discovered in Fig 7(a) in the table, like table 1 for displacement.

We test each angle several times, and obtain the absolute error of each experiment through same method of displacement. Then we set up coordinate system with three parameters: test times, test angles and absolute errors to depict absolute error of rotation which is shown in Fig. 7(b).

![Fig. 7 Sketch map and absolute error of rotation](image)

Figure 7(b) demonstrates that test points concentrate on degrees of 0 to 90 since when the catheter comes to the branch inlet of the vessel, it would be a little difficult to entry. Thus doctors will rotate catheter frequently and slightly of which degree is within the range of 0 to 90, resulting in plenty of test points. The absolute error of rotation has the same rule as the displacement’s.

### 3.3 Result and comparison

As have finished capture accuracy experiment of position which includes displacement, velocity and rotation angle, it ought to analyze and judge the rationality of mechanism structure through experimental result shown in table 2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Criterion of positioning accuracy</th>
<th>Criterion of repeatability</th>
<th>Maximum positioning accuracy of experiment</th>
<th>Maximum repeatability of experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>≤3</td>
<td>≤2</td>
<td>1.5769</td>
<td>0.3602</td>
</tr>
<tr>
<td>Velocity</td>
<td>≤1</td>
<td>≤1</td>
<td>0.7763</td>
<td>0.4456</td>
</tr>
<tr>
<td>Angle of rotation</td>
<td>≤3</td>
<td>≤2</td>
<td>1.4730</td>
<td>1.4493</td>
</tr>
</tbody>
</table>
The calculation methods and equations for positioning accuracy and repeatability of velocity and angle of rotation is same as displacement which has been introduced before. There too many data during computational process, we merely list the maximum value of them to compare with the criterion according to project. Although table 2 illustrates that positioning accuracy of displacement and rotation as well as repeatability of rotation exceed 1, all parameters meet the demands since these errors depend on catheter’s trip adopted by us which is quite large. If I list original experimental data here, we will find that their relative errors are quite small.

4. Establishment of error model

Although the selected displacement in the experiment basically covers the possible displacement of the catheter during the operation, it is a discrete measurement and does not include all cases. Generally, structure’s mechanism characteristics, mismachining tolerance, material etc, will cause the motion error of a device. The relation between them can be expressed by function in Eq. (7).

\[
\text{Error} = f(c, \bar{T}, m, t, \ldots )
\]  

Where \( c \) is mechanism characteristics, \( \bar{T} \) presents mismachining tolerance, \( m \) and \( t \) indicates material and moving stroke respectively. Ellipsis means that there are many other factors which will influence error. We know all those factors mentioned above will influence the accuracy of device, but we can’t get to know the extent they would influence which means these factors can’t quantitatively analyze error. The problem is something like a black box. Even if we don’t know the inner structure of the black box, we only notice how it responds to the information stimulus, and notice its input and output’s relationship that the input is the motion information of hands while the output are displacement and degree in the paper, and we can study it. Thus we can find out basic laws from experimental exploration to facilitate theoretical modeling to some extent according to the data we have get (Chen et al., 2015a).

To achieve this, we sort the point cloud in Fig. 4 and Fig. 7(b) in ascending order, then fit the discrete data (Minka et al., 2005) through Matlab so that we can get formulas through 1stOpt (Cheng et al., 2016) and the point clouds are also transformed into three dimensional surface plots which we call them error models.

4.1 Error model of displacement

As is shown in Fig. 8 and Fig. 9, these two models allow the absolute error covering all the displacements in two phases. No matter how much the displacement of the catheter is, it is capable to obtain the scope of the displacement’s error of the catheter captured by master manipulator from doctors under certain displacement. These two models can furnish whole robot system a reference for precise control and accuracy of capturing axial displacement of catheter.

![Fig. 8 Error model of first phase](image)

The established error model is shown in the following formula:
The x indicates test times and y indicates displacement, and both of them are the core of error model. The specific value of the coefficient $P_i$ will be listed in table 3.

\[
E(x, y) = \frac{p_1 + p_2 \ln x + p_3 \ln^2 x + p_4 \ln y + p_5 \ln^2 y + p_6 \ln^3 y}{1 + p_7 \ln x + p_8 \ln^2 x + p_9 \ln y + p_{10} \ln^2 y + p_{11} \ln^3 y}
\]  

(8)

Fig. 9 Error model of second phase

The formula of this surface is:

\[
E(x, y) = \frac{p_1 + p_2 \cdot \ln x + p_3 \cdot \ln^2 x + p_4 \cdot y + p_5 \cdot y^2}{1 + p_6 \cdot \ln x + p_7 \cdot \ln^2 x + p_8 \cdot \ln^3 x + p_9 \cdot y + p_{10} \cdot y^2}
\]  

(9)

When we want to acquire error scope at certain displacement which means we have got the value of y, then the Eq. (8) as well as Eq. (9) and Eq. (10), will change into a unary function about x. We can calculate the function’s maximum and minimum. The absolute error of this displacement is range from minimum to maximum.

4.2 Error model of angle of rotation

Similarly, the error model of rotation is established as well which is shown in Fig. 10.

\[
\text{Fig. 10 Error model of rotation}
\]

The formula of this surface is and the coefficients of each formula are shown in table 3:
\[ E(x, y) = \frac{p_1 + p_2 \cdot x + p_3 \cdot x^2 + p_4 \cdot y + p_5 \cdot y^2 + p_6 \cdot y^3}{1 + p_7 \cdot x + p_8 \cdot x^2 + p_9 \cdot y + p_{10} \cdot y^2} \] 

\[ (10) \]

Table 3 The value of coefficients of equations

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Equation(8)</th>
<th>Equation(9)</th>
<th>Equation(10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_1 )</td>
<td>10.7570425295675</td>
<td>-0.0458112493682241</td>
<td>-0.95427920247375</td>
</tr>
<tr>
<td>( p_2 )</td>
<td>-6.2231000295362</td>
<td>0.0305859086041285</td>
<td>-0.00040828206997</td>
</tr>
<tr>
<td>( p_3 )</td>
<td>0.883370687657208</td>
<td>-0.0053257402443182</td>
<td>5.0887796790768E-7</td>
</tr>
<tr>
<td>( p_4 )</td>
<td>0.0845715414615174</td>
<td>0.00252181091481388</td>
<td>0.53713351929736</td>
</tr>
<tr>
<td>( p_5 )</td>
<td>0.21111906361302</td>
<td>9.16606495805341E-5</td>
<td>-0.09473057030645</td>
</tr>
<tr>
<td>( p_6 )</td>
<td>-0.065179068967355</td>
<td>-1.33274067712188</td>
<td>0.0056726005368227</td>
</tr>
<tr>
<td>( p_7 )</td>
<td>-0.53162177825006</td>
<td>0.58614950947635</td>
<td>-0.0030486476487092</td>
</tr>
<tr>
<td>( p_8 )</td>
<td>0.109381479887936</td>
<td>-0.0838985792444168</td>
<td>5.40292719857216E-6</td>
</tr>
<tr>
<td>( p_9 )</td>
<td>-0.232557786813228</td>
<td>0.0097017809662687</td>
<td>-0.00321731563738</td>
</tr>
<tr>
<td>( p_{10} )</td>
<td>0.348570133405462</td>
<td>-0.000294944754168809</td>
<td>0.0178453979823655</td>
</tr>
<tr>
<td>( p_{11} )</td>
<td>-0.108690893060829</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 illustrates the computing results that the coefficients preserve multiple significant digits since this the result calculated by computer and if we change one of them would cause huge error. That’s why we remain all of significant digits. These models are calculated by 1stOpt with the method of Levenberg-Marquardt (LM) and Universal Global Optimization (UGO) which promise the effectiveness of models. Meanwhile, we have several parameters to quantitatively describe the reliability of these models which are Root of Mean Square Error (RSME), Sum of Square Error (SSE), Correlation Coef. (R), R-Square and Determination Coef. (DC). Among these parameters, the RSME which should be close to 0 and R which should be close to 1, are the main reference. Their value are shown in table 4.

Table 4 The value of parameters to evaluate models

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Equation(8)</th>
<th>Equation(9)</th>
<th>Equation(10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSME</td>
<td>0.0719066734362812</td>
<td>0.146661155168206</td>
<td>0.321042004075031</td>
</tr>
<tr>
<td>SSE</td>
<td>0.25852848423359</td>
<td>0.1306355820764445</td>
<td>13.3988358894671</td>
</tr>
<tr>
<td>R</td>
<td>0.990543521676876</td>
<td>0.96783309427638</td>
<td>0.901552180541117</td>
</tr>
<tr>
<td>R-Square</td>
<td>0.9811764683336027</td>
<td>0.936701314837653</td>
<td>0.812976654764552</td>
</tr>
<tr>
<td>DC</td>
<td>0.981176463920649</td>
<td>0.93665717341804</td>
<td>0.812976166195218</td>
</tr>
</tbody>
</table>

We can find two error models of displacement can satisfy the demands while model of degree has a little error since the surface is quite complex, but these three models are accurate enough generally.

5. Conclusion

In this paper, we tested motion signals capture accuracy of master manipulator, in respect of axial displacement, circumferential rotation and axial velocity for vascular interventional robot, and the experimental results meet the requirements of the project which indicate that the master manipulator can accurately capture the motion signal from doctors, which also shows that the design and processing of mechanism structure is reasonable. Moreover, we also established error models of axial displacement and the rotation angle, providing an important error reference for the follow-up work of the project, such as the design of virtual training system and the research of error compensation.

However, there are still some problems should be improved. Firstly, while testing, we find that the roll of the friction wheel is occasionally not very fluent. This is because wheels is made of vulcanizate which exists deformation, making
wheels become rough circles and will influence the capture accuracy. If the manipulator could be assembled by professional assembly personnel, it would be better. Secondly, we’d better test more times at each displacement or angle so that we can get adequate and comprehensive data which will make error model more reliability.

Acknowledgments

This research work supported by National Science Foundation of China (Grant No.91748122), National Science Foundation for Young Scientists of China (Grant No.61603237), Shanghai Pujiang Program (Grant No.17PJ1402900) and Science and Technology Commission of Shanghai Municipality (16111107802, 16111108202).

References