Kinematics Analysis of the Catheter for a Novel VR Robotic Catheter System

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Abstract – Compared to traditional surgery, MIS (minimally invasive surgery) as a specialized surgical technique has attracted more attention for its small incisions can minimize the trauma of patients and shorten the recovery time. Because of the complexity of the interventional surgery, the surgeon must be trained a lot to improve operation skills. In this paper, we will introduce a virtual reality robotic catheter system which can be used to train the interns to complete the operation. The virtual environment, including catheter model and vascular model, is established using 3 DS MAX 2012 software. PHANTOM premium 1.5 as the master side has been applied to control the movement of the catheter model in the virtual environment. During the real process of MIS, the catheter can realize radial movement and axial rotation. The position information obtained from the handle of the haptic device is chosen as the control variable to control the movement of the catheter in the virtual environment on two degrees of freedom. And we analyze the kinematics of the two degrees of freedom of the catheter. A proportional relationship between the control variable and the movement of the catheter is established. The experimental results prove that the traceability of the virtual reality system is high. That ensures the reliability and accuracy of the virtual interventional surgery.

Index Terms – MIS (minimally invasive surgery), Virtual reality, Robotic catheter system, Kinematics.

I. INTRODUCTION

Minimally invasive surgery is increasingly accepted and applied in many medical fields, due to the small incision produced in surgery procedure. The main advantage of this revolutionary surgical technique is to minimize the patients’ trauma and shorten the recovery time. Because of the complexity of interventional surgery, the surgeon must be trained a lot to improve surgical skills.

Traditional training methods include human cadavers, patients, anesthetized animals and human body models. However, they each have their own limitations. With the development of computer technique, the VR (virtual reality) technology has been applied in medical field [1]-[3]. The vascular interventional surgery training system based on virtual reality technique provides a novel method to solve this problem. The advantages of this training system are to represent the surgical scene intuitively, to repeat training without loss and risk, and to optimize operation plan in advance.

Several research groups and many companies have realized the benefits of using haptic device in minimally invasive surgery training. They devote themselves to developing the realistic virtual surgery system. So far many products have been developed. These virtual reality systems can improve the surgical skill and provide objective assessment for laparoscopic cholecystectomy and stenting of the carotid artery [4]. Arizona State University has developed a training system for orthopedic drill bone surgery. The system is aimed at the case that this kind of surgery needs high requirement of location and size for the force. The system has passed the validation of senior doctors. A case about microscopic micromanipulator system “NeuRobot” has proved the feasibility of the telesurgical usage of NeuRobot. One of the most influential research is a robotic catheter placement system called Sensei Robotic Catheter System [5], [6] proposed by Hansen Medical. This system provides the operator higher stability and more accurate force in the catheter placement. Compared to manual techniques, this system improves manipulation precise and reduces radiation exposure for the surgeon. Multiple degrees of freedom and force detection at the distal tip are the difficult points of the research. Catheter Robotics Inc. also developed a remote catheter system called Amigo. It has a robotic sheath to steer catheters which is controlled by a nearby work station. According to the report, in April 2010, this system was used to ablate artificial flutter in Leicester UK [7]. Magnatecs Inc. has developed Catheter Guidance Control and Imaging (CGCI) system. Four large magnets are placed around the table and there are magnets in the tip of customized catheters. The catheter is moved by magnetic fields, which is controlled at the nearby work station. Simbionix ANGIO Mentor products are multidisciplinary endovascular surgical simulators, and they can provide hands-on practice of endovascular procedures in virtual reality simulated environment. The surgeon can improve the operation skills using ANGIO Mentor simulation.

In our research a virtual reality robotic catheter system for vascular interventional surgery is proposed. This system is based on the master-slave robotic catheter system [8]-[10]. So the whole system can realize catheter remote operation, besides it can be used to train interns. The haptic device PHANTOM premium is chosen as the master side of the system for it can provide vivid haptic feedback. However, compared with the realistic surgery procedure, this master of the system lacks of operability. That will influence the training effect. In addition to this case, there is not a reasonable...
relationship between the operation of the haptic device handle and the kinematics of the catheter in the virtual environment. In order to improve the operability of the virtual reality system, we analyze the kinematics of the catheter on two degrees of freedom, and build a reasonable proportional relationship between the control variable and the catheter’s movement. The experimental results prove that the traceability of the virtual reality system is high. That ensures the reliability and accuracy of the virtual interventional surgery. As a result the operating precision of the virtual reality system is enhanced, which allows the unskilled interns to be trained successfully.

II. THE STRUCTURE OF THE VR ROBOTIC CATHETER SYSTEM

In order to realize operation training and remote catheter control, the Virtual Reality based Robotic Catheter System is proposed. As shown in Fig.1. The master-slave robotic catheter system can realize remote catheter control [11], [12]. The haptic device PHANTOM premium is applied as the master side. The surgeon operates handle to move along axial and radial directions. At the same time, the control commands will be transmitted to the PC of the slave side. Then the controller of the slave side controls the slave manipulator to clamp the catheter to insert and rotate the catheter, as if the surgeon operated the real catheter just beside the patient.

To ensure the safety of the remote control, a force sensing system is applied. When the catheter contacts the blood vessel wall, it can transmit the force feedback information to the master side [13]-[15]. The operator can feel the feedback force actually through the master side. Besides, the monitoring figures gained by the IP camera will be transmitted to the operator.

Based on the master-slave robotic catheter system [16], a virtual reality surgery training system is proposed. We build a virtual surgery environment through software design to simulate real surgery scene. The intern operates the handle of the master side to control the movement of the virtual catheter. The catheter in the virtual environment can realize insertion along axial direction and rotation along radial direction. When catheter contacts the blood vessel wall in the virtual environment, the model can produce deformation, and the intern will feel the feedback force [17]-[19]. The real surgery procedure is simulated in this way. During the process of training, the intern operates the handle on the master side to control the movement of the catheter in the virtual environment. If the catheter contacts the vessel, a feedback force will be transmitted to the intern through PHANTOM, then the intern can adjust the operation according to the visual and force feedback. Fig.2 shows the virtual reality system.

III. HARDWARE PLATFORM AND SOFTWARE DESIGN

A. Structure and Principle of the VR System

In order to achieve the goal of training interns, the VR Robotic Catheter System must imitate the actual medical procedure. Based on this purpose, the whole system is designed as Fig.3 shows. The software design is aimed at building the virtual environment, which includes the catheter model and the vascular model. When the catheter collides the vascular wall the model could produce deformation and a feedback force. The haptic device is the main hardware platform. Utilizing it the interaction between the virtual environment and the operator can be realized. The operator can control the movement of the catheter in virtual environment and the feedback force can be transmitted to the operator.

Fig.2 The Virtual Reality System

Fig.3 The Structure Diagram of Virtual Reality System
The hardware platform and the software design should be combined perfectly, only in this way the VR system can be integrated successfully [20]. The Fig. 4 shows the functional block diagram.

**B. Hardware Platform**

As the master side manipulated by the intern, the haptic device (PHANTOM Premium 1.5) is chosen and applied in this VR robotic catheter system [21]. Its main function is to track the movement location of the operator’s hand, at the same time, transmit the force/tactile information generated in the virtual environment to the operator by means of force feedback. The chief parameters of this device are shown in TABLE I.

**TABLE I**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input DOF</td>
<td>6 DOF</td>
</tr>
<tr>
<td>Output DOF</td>
<td>6 DOF</td>
</tr>
<tr>
<td>Workspace (mm)</td>
<td>381×267×191</td>
</tr>
<tr>
<td>3D distinguishability (mm)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Fig.5 has shown the whole PHANTOM premium platform.

**C. Software Design**

1) **Establishment of the Virtual Environment**

The virtual environment of the virtual vascular interventional surgery system is developed based on 3 DS MAX 2012 software on Windows platform. It completes the establishment and rendering of the virtual environment [22], including vascular model and catheter model. The virtual environment is shown in Fig.6. The red model is part of the vascular, which has some branches. The blue model is the catheter model. It is in cylindrical shape. These models are built in millimeter.

2) **Software Flow Design**

The programming language of Visual C + + 6.0 has been chosen to complete the whole procedure, in order to realize control and perception of the virtual object by applying the
haptic device. The overall software flow chart for the virtual reality robotic catheter system is shown in Fig.7.

IV. KINEMATICS ANALYSIS AND SIMULATION RESULTS

According to the above structure and principle of the system, integrating software and hardware equipment properly, we complete setting up the experimental platform of the system. Fig.8 shows the platform. In this system, PHANTOM premium 1.5 is used as the human-computer interactive interface device. When the operator controls the haptic device to move along the axial direction and rotate along radial direction, the catheter model in the virtual environment will track the movement of the device at the same time. If the catheter collides the vascular, according to collision detection algorithm and physical model, the contact force will be calculated out and feedback to the operator in real-time. Then the operator will produce a feeling of real operation procedure.

The spring-damer model is chosen to calculate the contact force along the normal direction between the catheter and the vascular wall. Before the vascular wall is broken, the calculation formula of feedback force is as follow.

$$F_{\text{vascular}} = k_{\text{vascular}} \cdot x - \rho_{\text{vascular}} \cdot v \cdot I$$

(1)

where $k_{\text{vascular}}$ is the elastic coefficient, $\rho_{\text{vascular}}$ is the viscosity coefficient, $v$ is the velocity of the catheter, $x$ is the deformation of soft tissue, $l$ is the length of the catheter inserted into the vascular.

The friction force along axial direction is calculated as follows referring to Karnoppp model. When there is no relative sliding, the friction is static, and when relative sliding occurs it turns to sliding friction.

$$F_{\text{vascular}} = \begin{cases} \frac{k}{\Delta v} \cdot \Delta v, & 0 < v < \Delta v \\ \left| C_v \cdot \text{sgn}(v) + \rho v / l \right| & v \geq \Delta v \end{cases}$$

(2)

where $k$ is a coefficient, $c_v$ is the sliding friction of the catheter, $\Delta v$ is the critical value of velocity.

Before calculating the feedback force, the movement control of the virtual catheter plays an important role in the representation of real operation procedure. Ignore the collision force and the friction, we only analyze the movement of the catheter. In real operation procedure, the movement of the catheter has two degrees of freedom, that moving along the axis direction and rotating along the radial direction [18]. So, from the PHANTOM premium device we obtain the position information of two degrees of freedom. Fig.6 has shown the freedom of the haptic device. There are six degrees of freedom in this haptic device, axial movement along X-axis, Y-axis and Z-axis, radial rotation along X-axis, Y-axis and Z-axis. We choose the position information on X-axis and Y-axis as the control variables. According to the proper proportion relationship, the position information can be transmitted to the virtual catheter, and the movement control of the virtual catheter can be realized.

As Fig.9 shows, one degree of freedom is that the catheter model moves forward and backward along axial direction. The position information of X-axis gained from the handle of PHANTOM premium device is set as the control signal. The position information achieved from the haptic device is position vector in centimeter, and we set it as quantity information in millimeter. Positive number represents the catheter moving along positive X-axis, and negative number represents the catheter moving along negative X-axis. In order to improve the operability of the VR system, the relationship between the movement amount of the catheter model and the control variable is built as follow.

$$S = k_1 \cdot P_{(x)}$$

(3)

where, $S$ means the displacement of the catheter model in virtual environment, $k_1$ is the proportional coefficient, $P_{(x)}$ means the X-axis position information of PHANTOM premium device.
The other degree of freedom is that the catheter rotates along radial direction. As Fig.10 shows. We set the position information of Y-axis as the control variable. The information obtained from the haptic device is position information in centimeter. However, the rotation is angular metric. Then we consider the position information obtained as quantity information, and set it into angular unit. Positive number represents the catheter rotates clockwise and negative number represents the catheter rotates anticlockwise. The maximal workspace along Y-axis is 267, as TABLE I shows, cannot reach 360, the amount of rotating one circle. So a proportional relation is a must. The relationship between the rotation angle of the catheter model and the control variable is as equation shows.

\[ \omega = k_2 \cdot P_{(y)} \]  

(4)

where, \( \omega \) means the rotation angle of the catheter in virtual environment, \( k_2 \) is a proportional coefficient, \( P_{(y)} \) means the Y-axis position information.

Utilizing the experimental platform of the virtual reality system, we carry out a series of experiments. As Fig.9 shows, the operator is doing virtual vascular interventional surgery. The PHANTOM premium device is used as the human-computer interaction interface device. When the operator makes the handle move along X-axis in space, thereby the catheter model in virtual environment will move along axial direction. In a similar way, when the handle moves along Y-axis, then the catheter model will rotate in radial direction correspondingly. At the same time, a feedback force can be transmitted to the operator through the haptic device.

As shown in Fig.11, is the result of axial movement. Y-axis represents the displacement, and X-axis represents time. We move the handle of the haptic device along X-axis direction slowly in a constant speed. We measure the actual displacement of the handle along X-axis, and the blue curve shows the displacement of the handle after scale conversion. The red curve shows the real movement of the catheter model in virtual environment. The data curve has proved the operability of axial movement. Positive displacement represents the catheter moving forward, and negative displacement represents the catheter moving backward.

Fig.12 has shown the result of radial movement. Y-axis represents the angle, and X-axis represents time. We move the handle along Y-axis direction slowly in a constant speed. We measure the movement of the handle along Y-axis, and the blue curve shows the angle, that is the data after scale conversion. The red one shows the rotation angle of the catheter in virtual environment. The data curve has proved the operability of rotation. Positive angle represents the catheter rotating clockwise, and negative angle represents the catheter rotating anticlockwise. The catheter can rotate one circle. During the experiment, accidental error is unavoidable. This case does not affect the stability of the entire system.

Based on the above results, we can get the conclusion that the catheter in virtual environment is able to move along axial direction and rotate along radial direction under the control of haptic dive. This system conforms to the requirement of freedom. Moreover, it realizes more accurate movement control. The traceability of the virtual reality system conforms with the surgical requirement.

### V. CONCLUSION AND FUTURE WORK

The virtual reality robotic catheter system is used to train interns to improve operation skills. The system is proposed based on the master-slave robotic catheter system. Utilizing it the interns can rise operation experience in using the robotic catheter system. The virtual environment and the haptic device are the main parts in this system. The virtual environment of the virtual reality system is composed of two parts, the vascular model and the catheter model. The vascular model is set as the static environment; the catheter is the object to be controlled. 3 DS MAX 2012 is chosen to build and render models. PHANTOM premium 1.5 is applied as the master side to control the movement of the catheter model. This haptic device can transmit the contact force to the operator. When the catheter collides the vascular, the operator can feel a feedback force. Then the real surgical scene will be reappeared.

The virtual reality system is designed to simulate operation procedure. In real operation procedure, the motion of the catheter has two degrees of freedom, insertion along axial direction and rotation along radial direction, the catheter model in virtual environment is the same. In our research, the position information on X-axis and Y-axis of the haptic device...
are chosen as the control variables, the position information on X-axis controls movement along axial direction, the position information on Y-axis controls movement along radial direction.

In order to improve the accuracy of position control, we have analyzed kinematics of the catheter in two degrees of freedom and built a proportional relation between the control variable and the movement variable. Plus and minus represent the direction of the movement. The experimental results show that this virtual reality system can realize accurate operability. However, there is still a lot of work to complete before this system can be put into use. The physical model of the VR System is being built. It is one of the key points in this research. Next, we will use bullet to finish physical model and improve the practicability of this system.

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