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Design of the Virtual Reality based Robotic Catheter System for Minimally Invasive Surgery Training

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Abstract **- Minimally Invasive Surgery (MIS) is a specialized surgical technique that permits vascular interventions through very small incisions. This minimizes the patients' trauma and permits a faster recovery compared to traditional surgery. However, the significant disadvantage of this surgery technique is its complexity; therefore, it requires extensive training before surgery. In this paper, for the VR system, we use the master side as the controller, and we use the open source code DCMTK to read the information of ".DCM" file and carry out the CT image segmentation for the Virtual Reality based Robotic Catheter System and we use Open Scene Graph (OSG) to realize the 3D image output and catheter control of the Virtual Reality System. We present virtual reality simulators for training with force feedback in minimally invasive surgery. This application allows generating realistic physical-based model of catheter and blood vessels, and enables surgeons to touch, feel and manipulate virtual catheter inside vascular model through the same surgical operation mode used in actual MIS. The experimental results show that the error rate is in an acceptable range and the simulators can be used for surgery training.**

Index Terms – minimally invasive surgery, virtual reality simulators, physical-based models

I. INTRODUCTION

The main advantage of the MIS technique is to reduce trauma to healthy tissue since this trauma is the leading cause for patient post-operative pain and prolonged hospital stay. Less hospital stay and rest periods also reduce the cost of surgery and are among other advantages of this method. However, a critical disadvantage of this surgery technique is its complexity, requiring a high training effort of the surgeon because the arteries through which the catheter passes are extremely complex and delicate. The repeated insertion of the catheter through several trials could tear a blood vessel at a junction and cause bleeding and excessive pressure could rupture the blood vessels.

For practical and ethical reasons, realistic virtual reality simulators provides the powerful aids compared to other available alternatives such as anesthetized animals, human cadavers and patients. The VR simulators enable novice doctors to learn basic wire or catheter handling skills and provide the expert practitioners the opportunities to rehearse new operation procedures prior to performing on the patient.

Also there are some product have been developed in a few years, One of the most popular product is a robotic catheter placement system called Sensei Robotic Catheter System [1-3] offered by Hansen Medical. The Sensei provides the physician with more stability and more force in catheter placement with the Artisan sheath compared to manual techniques, allowing for more precise manipulation with less radiation exposure to the doctor, commensurate with higher procedural complications to the patient. Because of the sheath's multiple degrees of freedom, force detection at the distal tip is very hard. Catheter Robotics Inc. has developed a remote catheter system called Amigo. This system has a robotic sheath to steer catheters which is controlled at a nearby work station, in a manner similar to the Sensei system. The first in human use of this system was in April 2010 in Leicester UK, where it was used to ablate artificial flutter [4]. Magnatecs Inc. has produce their 'Catheter Guidance Control and Imaging' (CGCI) system. This has 4 large magnets placed around the table, with customized catheters containing magnets in the tip. The catheter is again moved by the magnetic fields and is controlled at a nearby work station. The system facilitates precise vector based navigation of magnetically-enabled guide wires for percutaneous coronary intervention (PCI) by using two permanent magnets located on opposite sides of the table to produce a controllable magnetic field.

Because minimally invasive techniques has unavoidable reduced the sense of touch compared to open surgery, surgeons have to rely more on the haptic feeling generated by the interaction between blood vessels and the catheter. Even if the color and texture of blood vessels convey crucial anatomical information visually, touch is still critical in the surgeries. The benefits of using haptic feedback devices in minimally invasive surgery training through simulation have already been recognized by several research groups and many of companies working in this area [1-11]. However, in these researches, the virtual surgical training were carried out without haptic feedback, or researched on the virtual model of body organ not the vascular physical model. Moreover, some achievements in this area used Phantom Omni or other haptic devices as a controller to operate the virtual minimally invasive surgery [12-13]. Nevertheless, it is not convenient when surgeon drive the catheter for inserting and rotating because it does not accord with the custom of surgeons' operations.

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In this paper, we prepare to develop a Virtual Reality based Robotic Catheter System, including the design of Catheter Operating System, 3D Image Generation, Information Interaction and Mechanics Model analysis, and at last we will set up the VR system to simulate the process of inserting the catheter. And present the virtual reality simulators based on a novel robotic catheter operating system for surgeons' training in minimally invasive surgery. The simulators can generate the realistic virtual reality environment of blood vessels according to patient's special computed tomography (CT) or magnetic resonance imaging (MRI), in addition, allow to simulate surgeon's operating skills to insert and rotate catheter like surgeon operates catheter directly and carry out the intervention with haptic interfaces with force feedback, which provides the surgeon with a sense of touch.

II. THE VR BASED ROBOTIC CATHETER SYSTEM

We first proposed the structure of the Virtual Reality based Robotic Catheter System which could be used in operation training and remote catheter control, as shown in Fig. 1 and Fig. 2. In the master side, surgeon operates the handle to drive the catheter for inserting and rotating to clamp catheter directly, the control commands of the catheter operating system were transmitted to the slave side, after the slave side PC receiving the control commands from master side, the mechanism clamps the catheter to insert and rotate inside the blood vessel and at the same time simulate the surgeon's operating skill. The load cell was used for detecting the frictional force between catheter and blood vessel, the torque sensor and motor were used for detecting rotating information of catheter, and could be transmitted to the surgeon's hand in master side. Then surgeon can decide whether inserting or rotating the catheter depending on the feedback information and the visual information.

On the slave side, the catheter manipulator is as well as the controller; it means that the catheter manipulator could keep the same motion with the operator's hand. The operation will become visualized and easy to begin. On the other hand, this structure can realize the mechanical feedback to the surgeon. the catheter manipulator. This part is placed in the patient side. The catheter is inserted by using this mechanism. This part contains two DOFs, one is axial movement alone the frame, and the other one is radial movement. Two graspers are placed at this part. The surgeon can drive the catheter to move along both axial and radial when the catheter is clamped by front grasper. The catheter keeps its position and the catheter driven part can move freely when the catheter is clamped by second grasper.

During the operation of intravascular neurosurgery, it is significant to obtain the contact force information between catheter and blood vessel. In order to detect the contact force information between catheter and blood vessel, we developed an intelligent force sensors system for robotic catheter systems. By using the developed force sensors system, we can obtain the contact force information and feedback it to the surgeon. If there are no force sensors on the catheter, it is easy to damage the blood vessel during operating, because the blood vessel is fragile. The Fig. 3 shows the comparison of safety between without force sensors on catheter and with force sensors on catheter.

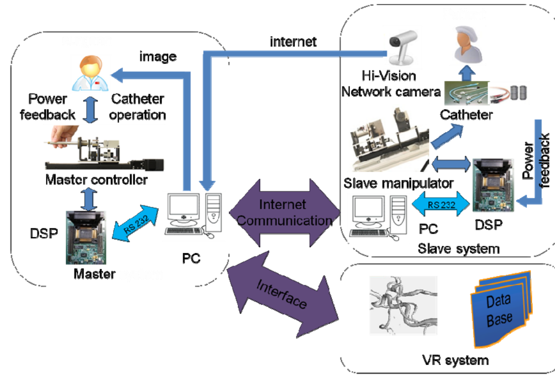


Fig. 1 the Structure of the Virtual Reality based Robotic Catheter System

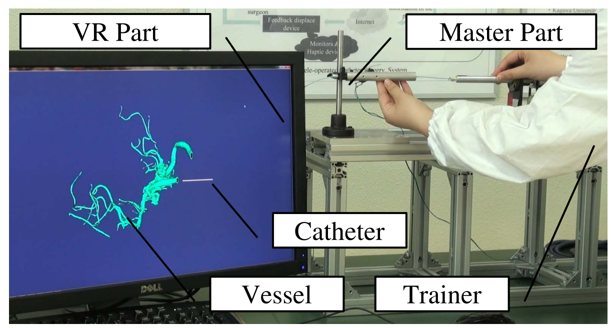


Fig. 2 Virtual Reality based Robotic Catheter System

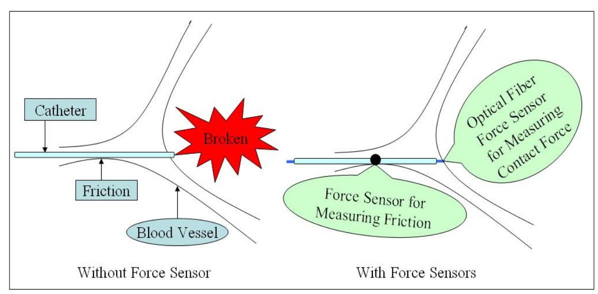


Fig. 3 Comparison of safety between two situations (Without force sensors and with force sensors)

III. 3D BLOOD VESSEL MODEL

In order to get the 3D image of the catheter inserting in the vessel blood, we have use DCMTK to read the information from the ".DCM" file. X-ray computed tomography (CT) is a medical imaging method employing tomography created by computer processing. Digital geometry processing is used to generate a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images taken around a single axis of rotation.

We should use the software Cmake to install the DCMTK to the VC++ package. We need install "DCMTK 3.5.4-source code packages", "DCMTK 3.5.4-support libraries for windows", "Cmake 2.8.4 (one of Packages compiled tools)".

Then we can use DCMTK to complete the image segmentation. Image grey value calculation formula can be shown in equation (1). According to the CT value of the DCM file which can present different parts of the human body, it is possible for us to change the grey value in the program and realize image segmentation.

$$G(V)=\begin{cases} 0, & V<C-\frac{W}{2} \\ \frac{g_m}{W}\left(V+\frac{W}{2}-C\right), & C-\frac{W}{2}\le V\le C+\frac{W}{2} \\ g_m & V>C+\frac{W}{2} \end{cases} \quad (1)$$

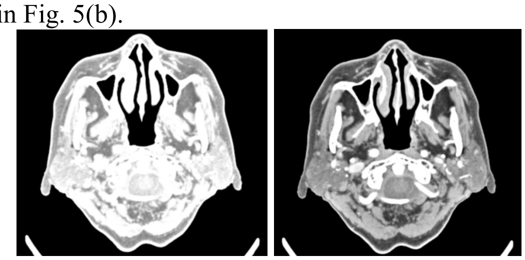
where, V means image data, G(v) means Value displayed, gm is the maximum value displayed, w is the display window wide, c is the window level.

A core component of a virtual reality surgical simulators and training system is realistic physical-based vascular models which are the virtual representations of real blood vessels that display accurate displacement and force response. To develop these models, the shape and the material properties of blood vessels should be measured and characterized in living condition and in their native locations. Models with incorrect material properties and shape could result in adverse training effects. The median filter is a nonlinear digital filtering technique, often used to remove noise which could be generated in several ways. In this case, the noise is generated by the process of image collecting. Median filtering is very widely used in digital image processing because, under certain conditions, it preserves edges while removing noise. And it is always used in pre-processing step. The main idea of the median filter is to run through the signal entry by entry, replacing each entry with the median of neighboring entries. The pattern of neighbors is called the "window", which slides, entry by entry, over the entire signal.

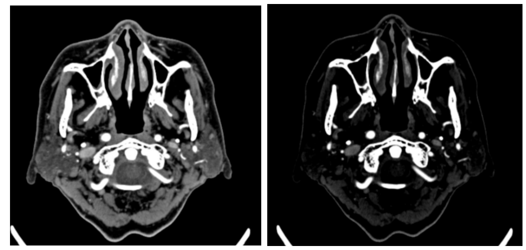
$$Z_{ij}=Med\left\{X_{(i+r),(j+s)},(r,s)\in S_{ij}, \quad i,j\in I^2\right\} \quad (2)$$

where Set X_{ij} dedicate the grey level of each point of image, S_{ij} is filtering window and Z_{ij} means the mid-value of window in S_{ij}.

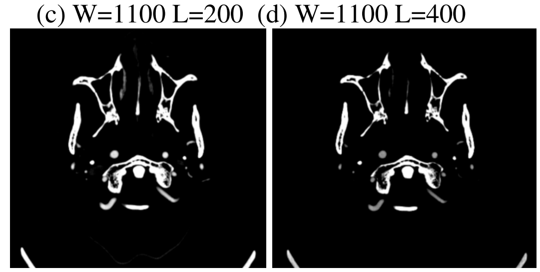
As shown in Fig. 4, we use Windows-Leveling method get the 2D image. We can adjust the value of the Window and leveling to divide the vessel from the image. Fig. 8 show us the 2D image of the vessel, we can get the center coordinates and save into ".txt" file, then draw the vascular section after segmentation as shown in Fig. 5(a) and the vascular surface as shown in Fig. 5(b).



(a) W=1800 L=-500 (b) W=1500 L=-200

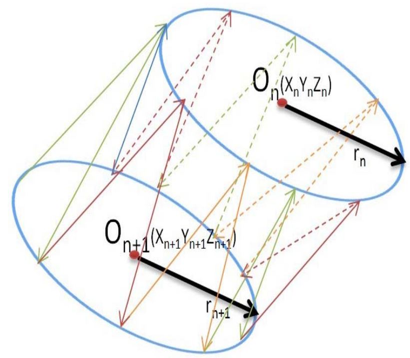


(c) W=1100 L=200 (d) W=1100 L=400

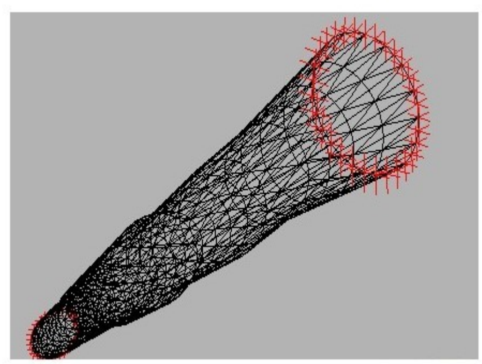


(e) W=500 L=200 (f) W=500 L=400

Fig. 4 2D image by W-L method



(a) Vascular section after segmentation



(b) vascular surface

Fig. 5 Vascular section 3D model by using OSG

Volume rendering methods generate images of a 3D volumetric data set without explicitly extracting geometric surfaces from the data. These techniques use an optical model to map data values to optical properties, such as color and opacity. During rendering, optical properties are accumulated along each viewing ray to form an image of the data. We use texture mapping to apply images, or textures, to geometric objects. Volume aligned texturing produces images of reasonable quality, though there is often a noticeable transition when the volume is rotated.

The three-dimension reconstruction images of the blood vessels have been shown in Fig. 6: (a) for the multi-branched blood vessels and we can choose a part of them as research topic shown in (b).

(a) the whole structures of blood vessels

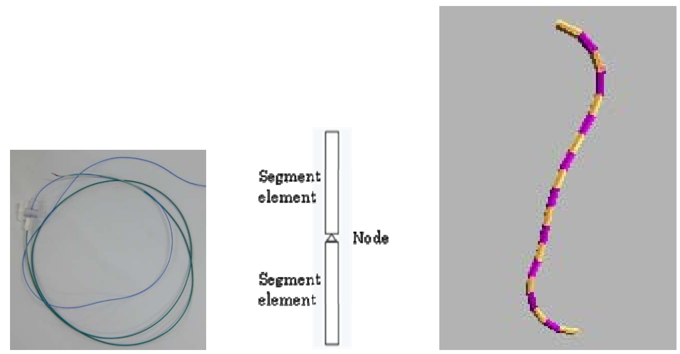
(b) specific blood vessel

Fig. 6 3-D reconstruction images of the blood vessels

IV. Modeling of the Catheter

The actual catheter used in minimally invasive surgery is shown in Fig. 7 (a). The catheter can be subjected to two different sets of movement during manipulation: insertion/retraction and rotation. Using translation and rotation, the user can manipulate the catheter to reach different parts of the blood vessels.

The approaches of the catheter simulation have been presented by several research groups [22]. The algorithms can be classified as physical or geometrical methods. Geometrical methods, such as splines and snakes, are based on a simplified physical principle to achieve the simulation results. Thus, calculation rate of the virtual model using this algorithm is fast but without physical properties. The main physical approaches to soft tissue modeling are the mass-spring, multi-body dynamics and the finite element modeling (FEM) methods. FEM is the most realistic method for modeling the tissue deformable behavior if the properties of the model are correctly chosen. It describes a shape as a set of basic geometrical elements and the model is defined by the choice of its elements, its shape function, and other global parameters. So the FEM is a suitable technique for solving the simulation problem. Based on the catheter structure, the guide wire is discretized as a chain of small and elastic cylindrical segments, as shown in Fig. 7 (b). Each one is connected to its neighbors at joints known as nodes. The small cylindrical segment is also called the beam element. Two successive beam elements form one bend element. With these elements we can evaluate the deformation energy and the elastic force of the structure. The virtual catheter is shown in Fig. 7 (c).



(a) (b) (c)

Fig. 7. Catheter model: (a) the real catheter image. (b) the segment element image. (c) the virtual catheter image

When the segment element is bended, bend forces will be generated to resist this deformation. According to the character of the catheter, the segment element is almost incompressible, so bend angle must also be small. Therefore, the bend force and energy can be evaluated approximately by:

$$f_b = k_b B_b^T B_b x_b \tag{3}$$

$$W_b = \frac{k_b x_b^T B_b^T B_b x_b}{2} \tag{4}$$

$$x_b = \begin{Bmatrix} x_0 \\ x_1 \\ x_2 \end{Bmatrix}, f_b = \begin{Bmatrix} f_b^0 \\ f_b^1 \\ f_b^2 \end{Bmatrix}, B_b = \begin{bmatrix} -2I & I & I \end{bmatrix} \tag{5}$$

$$k_b = \overline{k_b} / r_0 \tag{6}$$

After obtaining the equation of the deformation energy of each element, we try to obtain the energy equation of the whole object by integrating all elements together.

When there is a rotation, there is torsion force (T) passing the connecting node.

$$T = k_t \Delta\theta \tag{7}$$

The torsion equilibrium for each beam of the guide wire can be established.

$$k_t \left(\Delta\theta_{i+1} - \Delta\theta_i \right) = T_i \tag{8}$$

Where $\Delta\theta_{i+1}$ and $\Delta\theta_i$ are twist angles at the two nodes of the beam element of the guide wire.

V. Experiments and Results

We designed a series of collision experiments between the catheter and vessel to compare the simulation results of the physics-based modeling of the catheter with the real output of the force measured by contact force sensor in the slave side. We predefined area T as the target collision area in vessels in the EVE model, which is shown in Fig. 8, and used the Robotic Catheter Operating System to control the catheter inserting and retracting in the specific vessel AB, then record the feedback force information from load cell in the slave side. We did the experiment at a specific angle of incidence and made the catheter inserted into the catheter in a state of uniform motion. Then we measured the angle of incidence and the velocity of the specific uniform motion of catheter in order to utilize them to virtual reality environment to make sure the same conditions between actual and VR environment.

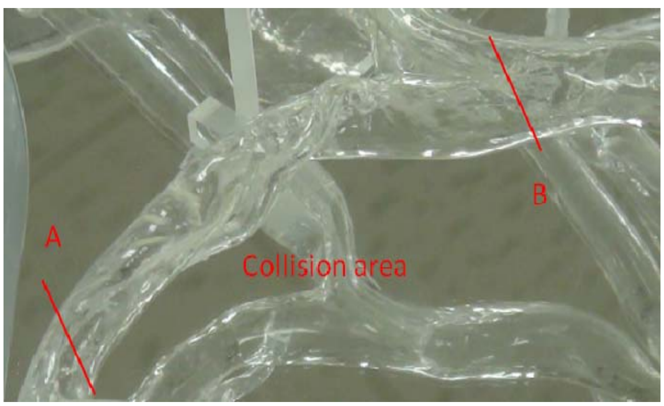
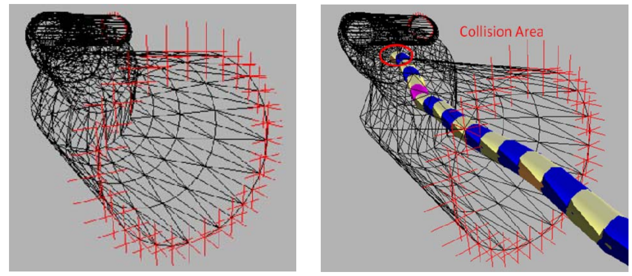


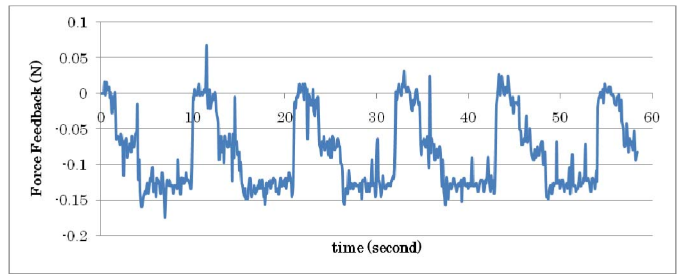
Fig. 8 Collision area in the specific vessel segment

We also simulated the physics-based model of the vessel T using the same radius, elastic coefficient and damper elastic with the EVE model, and drove the virtual catheter to insert and retract to contact the blood vessel in VR environment in the T target collision area. Fig. 9 (a) shows the simulation of target collision area T in specific vessels in virtual reality environment. In order to see more detailed deform information of blood vessel, the various rendering works are canceled. When catheter arrival at T area and have a collision with the vessel, we can get the simulated output of the catheter by using the physics-based modeling of the catheter and blood vessel through the deformation condition of the catheter and blood vessel, which is shown in Fig. 9(b).

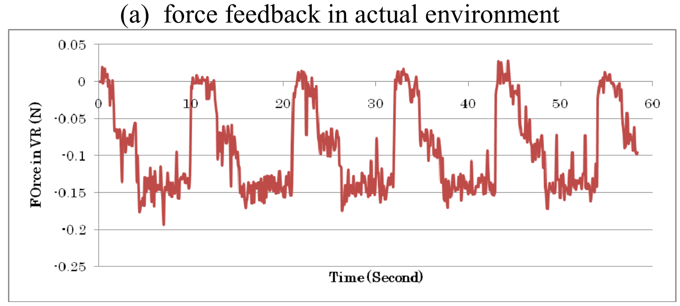


(a) (b)

Fig. 9 the collision images in virtual reality environment: (a) the original collision area AB. (b) the deformation of the collision area AB



(a) force feedback in actual environment



(b) the calculated force in VR system

Fig. 10 Compare of the force feedback detected by load cell and calculated by VR system

We compared the results between the actual output and virtual data. Fig. 10(a) shows the force feedback detected by load cell and Fig. 10(b) shows the calculated force in virtual reality environment.

The results show that force trend line between actual and virtual reality environment is similar and the error rate can be controlled between 7% and 18%. The errors may be generated in several reasons. The first one is the catheter-vessels interactions in virtual reality environment. There are many other complex interactions between the catheter and the vascular vessels occurred during catheter inserted into the EVE model. The second reason is the process of deformation turns to be a little rigid, and it may generate calculation error of elastic force.

When we use the VR system for training, we should calibrate the position of the catheter in the 3D vessel model, and make the master side consist with the VR side, as shown in Fig. 11 and Fig. 12, we can see the displacement error of the catheter is small, so that, we can say that the system is suitable for the training.

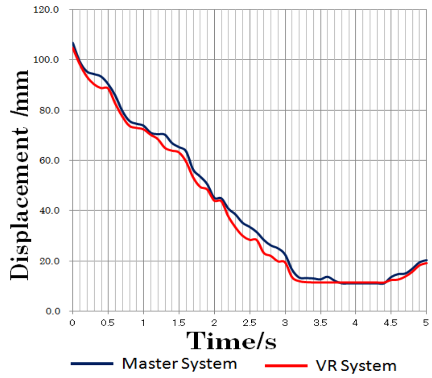


Fig. 11 Moving when the catheter is in backward

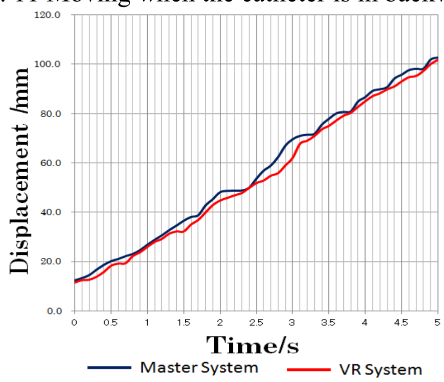


Fig. 12 Moving when the catheter is in forward

V. CONCLUSIONS

In this paper, the novel robotic catheter operating system has good maneuverability, it can simulate surgeon's operating skill to insert and rotate catheter. The characteristic evaluations (rotating motion and inserting motion) have also been done to verify the validity of the system, the experimental results indicated that the stability and responsibility of system were good, the robotic catheter system was fitting to be used for training unskilled surgeons to do the operation of intravascular neurosurgery. The open source code DCMTK toolkit was used to read the information of ".DCM" file and carry out the CT image segmentation for the Virtual Reality based Robotic Catheter System. Then, we use Open Scene Graph (OSG) to realize the 3D image output of the skill.

The catheter using a series of small and elastic cylindrical segments and reconstruct the vascular model using median filter algorithm, local thresholding algorithm and volume rendering. Based on the virtual model of catheter and blood vessels, we analyze and apply physical-based theory and implementation for these models. And the experimental results show that by defining the material properties of the catheter and the blood vessels, the behavior of the catheter motion can be realistically simulated in a specific patient artery network, thereby allowing surgeons to train and rehearse new operative skills repeatedly.

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