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Mechanical Analysis and Haptic Simulation of the Catheter and Vessel Model for the MIS VR Operation Training System

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Abstract — **The specialized surgical technique MIS that permits vascular interventions through very small incisions and minimizes the patients' trauma and permits a faster recovery compared to traditional surgery and it permits vascular interventions through very small incisions. In this paper, we present the mechanical analysis and haptic simulation of the catheter and vessel model for the MIS VR operation training system, this is based on virtual reality technology for unskilled doctors with extremely similar environment in real vascular interventional surgery to assess the clinical usefulness, accuracy, and safety of telemanipulation for vascular interventional surgery. It can be used for the interns to do the operation in local or remote training. It consists of a master controller system and the catheter manipulator placed at the patient side. The master side is the Robotic Catheter Master System, and slave side is the Virtual Reality based Robotic Catheter System. We want to build the vessel model, realize the 3D image output and catheter control of the Virtual Reality System. This application allows generating realistic geometrical model of catheter and model of blood vessels, and force feeling of surgeons to touch, and manipulates virtual catheter inside vascular model through the same surgical operation mode used in actual one. Finally, we complete the analysis and simulation of catheter control and mechanical design of the Virtual Reality based Robotic Catheter System and the experimental results show that the system can be used for surgery training.**

Index Terms **— Virtual Reality based Robotic Catheter System, Training System, Minimally Invasive Surgery (MIS), Mechanical Analysis, Open Scene Graph (OSG)**

I. INTRODUCTION

Robot technology, computer technology and remote communication made rapid development in the medical surgical and telemedicine. Cardiovascular and cerebrovascular disease could be the first "killer" of more than 30 million patients each year. Vascular surgical intervention has become widely accepted and applied in many medical fields and breakthrough of the space limitations of conventional surgery, and it can enhance the capacity expansion of medical experts. Revolutionary surgical technique, surgeries are operated using precise medical devices and viewing equipments inserted through a small incision instead of making a large incision to expose the operation site. The main advantage of this technique is to reduce patients' pain and scarring and prolonged hospital stay. However, this surgery technique is complicated and requiring extensive training to achieve the competency, the catheter passes are extremely intricate and delicate. For practical and ethical reasons, realistic virtual reality simulators provides the possibility of promising a method compared to the other available alternatives such as anesthetized animals, human cadavers and patients.

Industry simulation training and model for greater patient safety had been developed about the superiority of simulated training and objective assessment for laparoscopic cholecystectomy and stenting of the Carotid artery [1]. Because simulation in medical training usually not consist with virtual reality simulation, so that we should change to VR equipment. The VR simulators enable novice unskilled doctors to learn basic wire or catheter handling skills and provide the expert practitioners the opportunities to new operating procedures before performing on the patient. Diagnosis and medical surgery are performed for minimum invasive surgery recently, a case report on microscopic micromanipulator system "NeuRobot" in Neurosurgery: the authors proved the feasibility of the telesurgical usage of NeuRobot in private network. Some other product have been developed in a few years, one of the most popular products 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, multiple degrees of freedom, force detection at the distal tip is very hard. Catheter Robotics Inc. has developed a remote catheter system called Amigo has a robotic sheath to steer catheters which is controlled at a nearby work station, in a manner similar to the Sensei system. In April 2010, it was used to ablate artificial flutter in Leicester UK [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. Simbionix ANGIO Mentor products are multidisciplinary endovascular surgical simulators that provide hands-on practice of endovascular procedures performed under fluoroscopy, in an extensive and complete virtual reality simulated environment. The ANGIO Mentor simulation result in a higher level of skills to provide patients the best care.

However, for the surgeon to give the operation, the damage from the X-ray in the CT scan process to the sick in the operation, it is difficult of getting the accurate 3D

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positioning information in the blood vessel to help the surgeon in the operation, and it is difficult for the surgeon to master the skill because most of the training system cannot imitate the reality operation and improve the experience so easily.

The training system cannot fit for a more complex environment as the model can be changed by users, and in this article, we want to design the Catheter Virtual Reality System and first carry out the test of remote operate between Japan and China by internet network, operate robot master part in Japan to control the slave part of robot in Beijing and performed cerebral angiography in dog. For the Robotic Catheter System, the guide wire can be inserted into blood vessels, and the surgeon can take the guide wire and complete the operation, the process is called catheter inserted, it is one of the important step for the catheter be guided to the special position by the image guide.

The training system 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 unskilled doctors to drive a real catheter for training courses directly and simulate surgeon's operating skills, insertion and rotation in real surgery. This paper is organized to introduce the algorithms and vascular model, catheter model and the interactive simulation between blood vessels model and catheter model, and give the mechanical analysis and haptic simulation of the catheter and vessel model for the MIS VR operation training system.

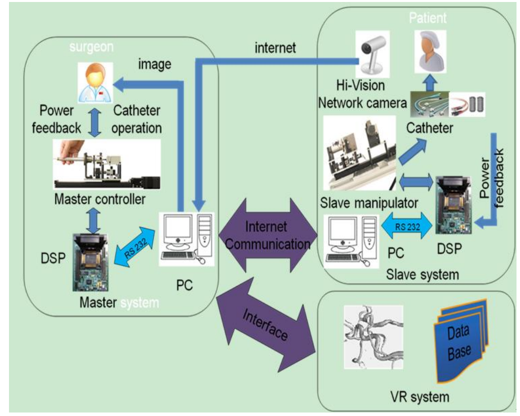


Fig. 1 the Structure of the Virtual Reality based Robotic Catheter System

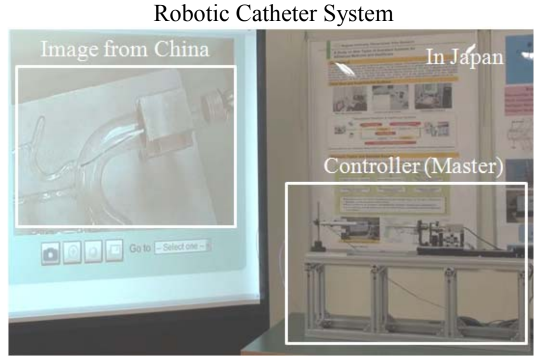


Fig. 2 The Robotic Catheter Master System

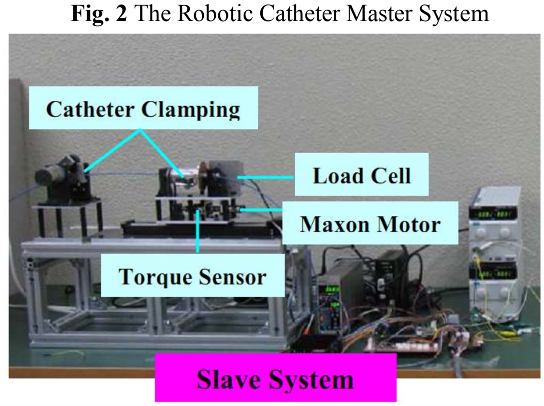


Fig. 3 The Robotic Catheter Slave System

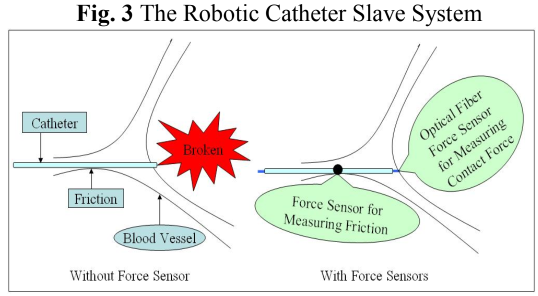


Fig. 4 Comparison of safety between two situations (Without force sensors and with force sensors)

II. THE STRUCTURE OF THE VR BASED ROBOTIC CATHETER SYSTEM

The Virtual Reality based Robotic Catheter System which could be used in operation training and remote catheter control, as shown in Fig. 1. We have designed the master-slave catheter operation system as shown in Fig. 2 and Fig. 3. In the master side, the 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 the catheter, and could be transmitted to the surgeon's hand in master side. Then the 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 follows the controller; it means that the catheter manipulator could keep the same motion with the operator's hand and this structure can realize the mechanical feedback to the surgeon. The catheter manipulator part is placed in the patient side inserted by using this mechanism. It contains two Degree of freedom, one is axial movement alone the frame, and the other one is radial movement. Two grapes are placed on this part. The surgeon can drive the catheter to move along both axial and radial when the catheter is clamped by front grasped. 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, in order to detect the contact force information between catheter and blood vessel, we developed an intelligent force sensor system for robotic catheter systems. By using the developed force sensor 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 operation, because the blood vessel is fragile. The Fig.4 shows the comparison of safety between without force sensors on catheter and with force sensors on the catheter.

As shown in Fig. 5, we can test no more than 2 minutes to show the vessel 3D images, we transmit the DICOM3.0 image to the master side, the camera image show us the external information and the surgeon in the master remote side can carry out the operation according to the two kinds of 3D image and complete the next operation step. However, the 3D image should be converted by us, and it is our important work to overcome so many unpredictable factors and difficulties.

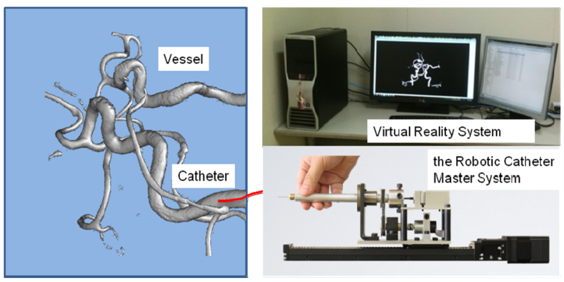


Fig. 5 Virtual Reality System

III. VR-BASED ROBOTIC CATHETER TRAINING SYSTEM

DICOM files can be exchanged between two entities that are capable of receiving image and patient data in DICOM format. 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 can use DCMTK to complete the image segmentation. It can be used in DICOM image segmentation, and next we can use Open Scene Graph (OSG) to realize 3D graphics.

We want to simulate the deformation of blood vessels. The mass-spring model is a widely used mesh-free method in surgical simulation, and models the object as masses connected to each other with springs and dampers. Each mass is represented respectively by its own coordinate, acceleration and velocity and deforms under the influence of inertial, spring and damping forces and the forces applied by the surgical catheter.

Various integration schemes have been tested [16] and Verlet integration emerged as the most suitable for application in MSS. Moreover, it is quite simple to implement. The step dt is an additional parameter of the system which contributes heavily to its behavior is too small step will result in lengthier computations while too big steps will result in divergence of the integration scheme and therefore the system itself. As see the three-dimension reconstruction images of the blood vessels have been shown in Fig. 6.

Catheter simulation 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 finite element modeling (FEM) methods. 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,. 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.

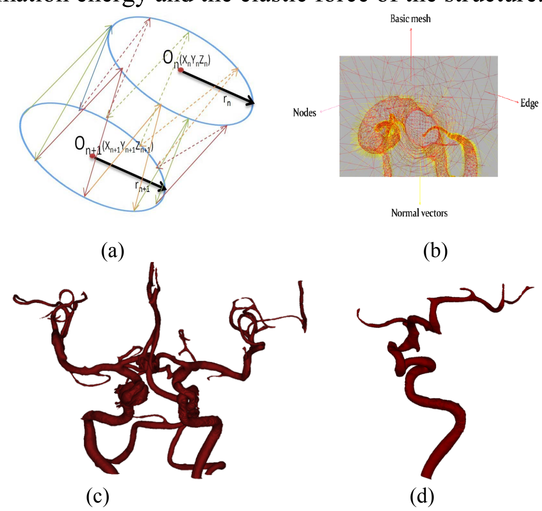


Fig. 6 Three-dimension reconstruction images of the blood vessels: (a) and (b) the mesh of the vessels (c) the whole structures of blood vessels. (d) specific blood vessel

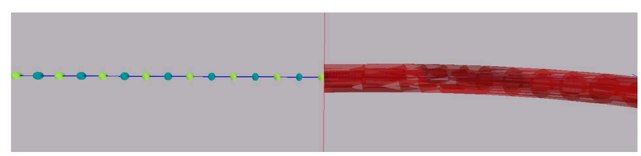


Fig. 7 Three-dimension reconstruction images of the catheter model

There is another important topic when considering training based on virtual reality technology and that is collision detection and response. The difficulties bounded with soft bodies such as blood vessel walls stem from their complicated reactions to external influences. Two kinds of collision detection methods are applied, broad phase and narrow phase. In terms of broad phase, bounding volume hierarchies (BVHs) are probably the most popular mechanisms. it is to recursively subdivide the object of interest and bounding volume for each of the resulting subset of primitives. Then, when checking for collisions, the hierarchy of the potentially colliding pair of objects is traversed from top to bottom. During the traversal, the bounding volumes are tested for overlap on every subdivision level. If no overlap is found, the objects surely cannot collide. If it is, the algorithms traverse the hierarchy further, but only through the children nodes where an overlap was detected.

Finally, when the traversal gets to the bottom level of the hierarchy and still detects overlaps, the primitives stored in these nodes are finally tested for mutual intersection. Actually, any BVHs are generally a good solution for complex scenes because they are easily used for self-intersection tests and quite convenient. For the narrow phase, two stages are performed for collision detection, first checking to see if any vertex in the blood vessel model lies within the catheter model then again checking if a vertex of the catheter model lies within the virtual vascular model. We finally get the 3D model As shown in Fig.7.

IV. Mechanical Analysis of the Catheter and Vessel Model

In order to testify our physical model of blood vessel and catheter, first of all, we give the analysis of the vessel, by a "spring equation" (1). The movement of the particles can be described by Newtonian mechanics. When only one spring and one particle is accounted for, it takes the form of equation (2), Equation(3) shows the actual form that needs to be solved for every particle i in a general MSS, with F^e representing external forces acting on the particle, F_{ij} the force computed using equation (1) and N_i the set of particles, to which particle i is connected by a spring. To obtain an exact solution of the differential equation (3), it has to be integrated in time.

$$F_{ij} = k\left(\left|l_{ij}\right| - \left|l_{ij}^0\right|\right)\frac{l_{ij}}{\left|l_{ij}\right|} \tag{1}$$

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{2}$$

$$m_i\ddot{x}_i + c\dot{x}_i + \sum_{\forall j \in N_i} F_{ij} = F_i^e \tag{3}$$

where F is the resulting force, k is the stiffness of the spring, l_{ij} is the length of the spring connecting i-th and j-th particle while the zero superscript again denotes the rest pose. m is mass of the observed particle, c is the damping coefficient of the spring, k is again the stiffness coefficient and x is the position of the particle, with appropriate time derivatives.

The mechanical of the blood vessel can be used in three model, Maxwell model, Voigt mode, Kelvin model, as shown in Fig. 8. For the Maxwell model, response of a Maxwell element can be present in (4) and at time t the deformation is (5)

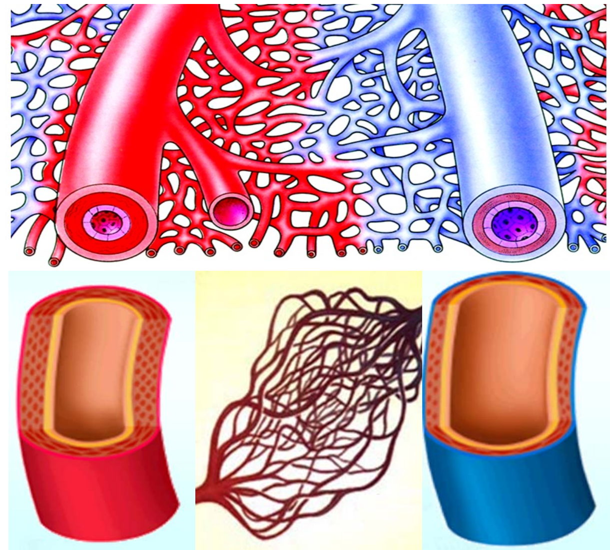
$$\varepsilon = \varepsilon_1 + \varepsilon_2 = \frac{\sigma}{E} + \frac{\sigma}{\eta}\cdot t = \sigma\left[\frac{1}{E} + \frac{t}{\eta}\right] \tag{4}$$

$$\sigma_1 = E\cdot\varepsilon_1 = \sigma_2 = \eta\cdot\frac{d\varepsilon_2}{dt} = \eta\cdot\frac{d\left(\varepsilon - \varepsilon_1\right)}{dt}$$

$$= -\eta\cdot\frac{d\varepsilon_1}{dt} \tag{5}$$

$$\varepsilon_1 + \varepsilon_2 = \varepsilon$$

then we have the solution of this differential equation



(a)artery (b) capillaries (c) venous

Fig. 8 Vessel structure, (a) artery, (b) capillaries and (c) venous

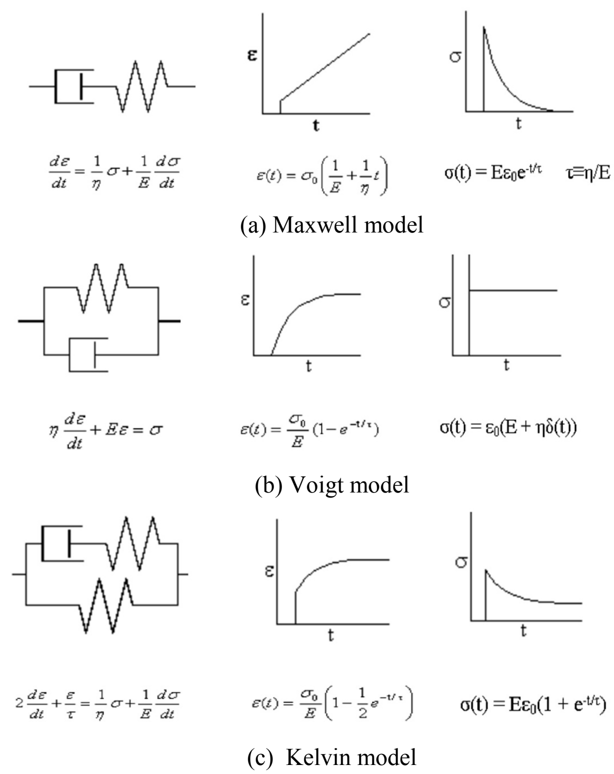


Fig. 9 Three basic models and the characteristics

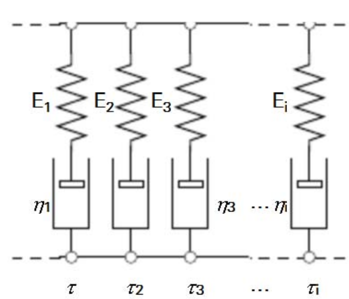


Fig. 10 Designed Maxwell model

$$-\eta \cdot \frac{d\varepsilon_1}{dt} = E \cdot \varepsilon_1$$

$$\frac{d\varepsilon_1}{\varepsilon_1} = -\frac{E}{\eta} \cdot dt$$

$$\ln \varepsilon_1 = -\frac{E}{\eta} \cdot t + c \tag{6}$$

$$\varepsilon_1 = \exp\left(-\left(E/\eta\right) \cdot t\right) \cdot c'$$

$$\sigma = E \cdot \varepsilon_1 = E \cdot \exp\left(-\left(E/\eta\right) \cdot t\right) \cdot c'$$

Both models, the Maxwell element and the Kelvin-Voigt element, are limited in their representation of the actual viscoelastic behavior; the former is able to describe stress relaxation.

According to those basic models, we design the model as shown in Fig.8, and this system we can described by follows

$$\begin{aligned} \sigma(t) = {} & \varepsilon \cdot E_1 \cdot \exp\left(-t/\tau_1\right) + \varepsilon \cdot E_2 \cdot \exp\left(-t/\tau_2\right) \\ & + \cdots + \varepsilon \cdot E_i \cdot \exp\left(-t/\tau_i\right) \end{aligned} \tag{7}$$

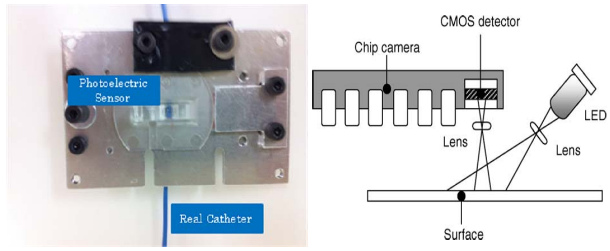
V. Dynamic Mechanical Behavior Analysis and Haptic Simulation Results

In order to testify our physical model of blood vessel and catheter, and prove the possibility of the dynamic mechanical behaviour, we designed a series of collision experiments between the catheter and vessel to compare the simulation results of the physics-based modelling of the catheter with the real output of the force measured by contact force sensor in the slave side.

The conceptual principle of the controller, the catheter can be subjected to two different sets of movement during manipulation: insertion/retraction and rotation. Catheter will be manipulated to reach different parts of the blood vessels. The photoelectric sensor is used to measure the information of displacement and rotation of catheter. The basic working principle of an optical mouse is described in Fig. 11. A single light emitting diode (LED) illuminates the surface at an angle. A lens is used to image the surface of the mouse pad onto a CMOS sensor located in the camera chip. The mouse works by comparing the images of the surface that are refreshed approximately every 1500th of a second. Once the chip has found the best overlap, it checks the scores of the eight pixels surrounding the center of the window. Finally, it sends the actual value of the displacement to the computer. Measurement accuracy is typically limited to the pixel spacing of the imaging sensor located in the chip.

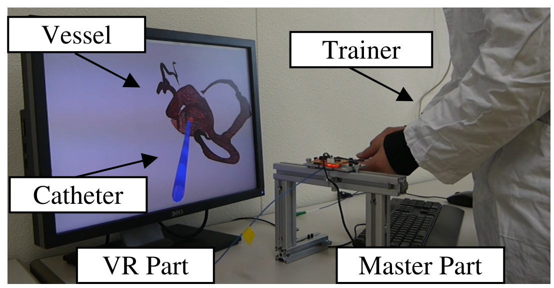
For the unskilled doctors can operate the real catheter directly for their training courses and the other one is that the measurement of displacement and rotation of catheter is contactless and the whole structure of this controller is simple and has better maneuverability and it is extremely competent to train unskilled doctors due to the fact that the operation on this controller is almost the same with the custom of surgeon's operations in actual surgery.

We designed a series of operation experiments between the controller and catheter model in virtual reality environment to compare the operation results. The whole structure of training system based on virtual reality technology and the simulation result and force in contact has been shown in Fig. 12.

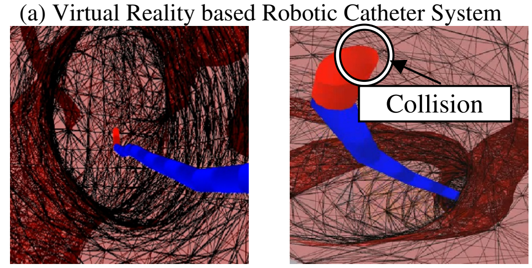


(a) Conceptual principle (b) The working components

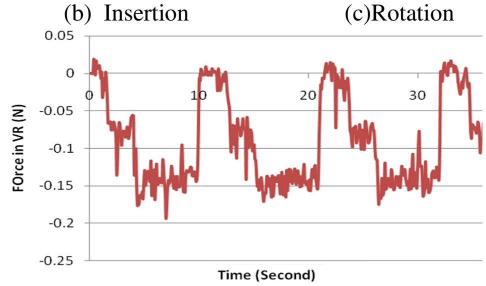
Fig. 11 Conceptual principle of the controller and Schematic description of the working components of an optical mouse



(a) Virtual Reality based Robotic Catheter System



(b) Insertion (c)Rotation



(d) The calculated force in VR system

Fig. 12 Two different catheter visual model inserting into the 3D vessel model

In the VR system, the catheter in a virtual reality environment can insert or rotate catheter according to the controlling instructions from master side. If the catheter contacts the blood vessel, the force feedback can be detected, stored and transmitted to the surgeon's hand. Based on the force feedback and monitoring image information, the virtual reality environment can be used for medical training.

V. CONCLUSIONS

In this paper, we introduced a new kind of Catheter Virtual Reality System which is used for the training of the interns to operate the Robotic Catheter System. The movement part of catheter manipulator keeps the same motion with the right handle of the controller. The right handles can measure two actions of the surgeon's hand, one is axial movement and the other one is radial movement. The handle is sustained by a bearing, and is linked to a load cell; a pulley is fixed on the handle.

For the VR parts, the open source code DCMTK toolkit was used to read the information about DICOM file and carry out the CT image segmentation for the Virtual Reality based Robotic Catheter System. Open Scene Graph (OSG) is used to realize the 3D image output of the skill. The novel robotic catheter operating system has good maneuverability, it can simulate surgeon's operating skill to insert and rotate catheter.

In order to testify our physical model of blood vessel and catheter, and prove the possibility of the dynamic mechanical behaviour, we designed a series of collision experiments between the catheter and vessel to compare the simulation results of the physics-based modelling of the vessel. 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 for training unskilled surgeons to do the operation.

In the future works, we will use the Virtual Reality System to help more unskilled surgeons improve their experience and make sure the safety of the operation by using the robotic catheter system.

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