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Analysis of the Haptic Collision and Deformation of the Blood Vessel Model for the Microsurgery Training System

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***Abstract*—As we know that MIS permits vascular interventions through very small incisions and minimizes the patients' trauma and permits a faster recovery compared. In this document, we present the mechanical and haptic simulation of the MIS VR operation training system. Virtual reality technology for doctors can improve the accuracy and safety of real vascular interventional surgery for vascular interventional surgery in local or remote training. It consists of a master controller system at surgery side and the catheter manipulator placed at the patient side. For the slave side Virtual Reality based Robotic Catheter System, we want to realize the 3D image and catheter control of the Virtual Reality System allows generating realistic geometrical model of catheter and model of blood vessels, and force feeling of surgeons. Finally, we complete the analysis and simulation of the model haptic deformation, develop the catheter control and mechanical design of the Virtual Reality based Robotic Catheter System and the experimental results show the mechanical and haptic analysis of the VR training system.**

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

I. Introduction

THIS document is about the study of mechanical and haptic simulation of the MIS VR operation training system. As all we know that Cardiovascular and cerebrovascular disease could be the first "killer" of so many patients each year. And the technology of vascular surgical intervention has become widely accepted and applied in many medical fields and in the space limitations of conventional surgery, which can enhance the capacity expansion of medical experts. 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. This technique can 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 for laparoscopic cholecystectomy and stenting of the Carotid artery [1]. 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 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. So that we should change to VR equipment as the reason of the simulation in medical training usually not consist with virtual reality simulation, however 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]. 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.

In this paper, we want to design the Catheter Virtual Reality System. 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

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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.

II. Structure of VR based Robotic Catheter System

The Virtual Reality based Robotic Catheter System which could be used in operation training and remote catheter controlling; the surgeon should reference to the vessel image and complete the operation, as shown in Fig. 1. In order to assist the surgeon to complete the operation, we have designed the master-slave catheter operation system as shown in Fig. 2 and Fig. 3. On the master side, the surgeon operates the handle to drive the catheter for inserting and rotating to clamp catheter directly, 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. 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.

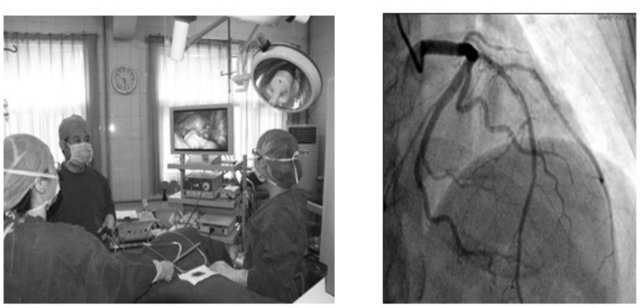


Fig. 1 the Catheter Operation with vessel imaging.

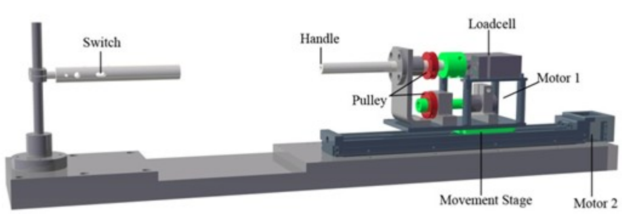


Fig. 2 The Robotic Catheter Master System

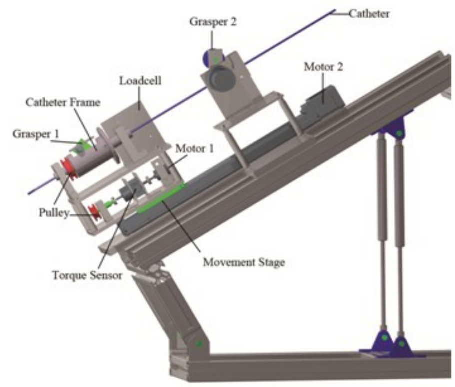


Fig. 3 The Robotic Catheter Slave System

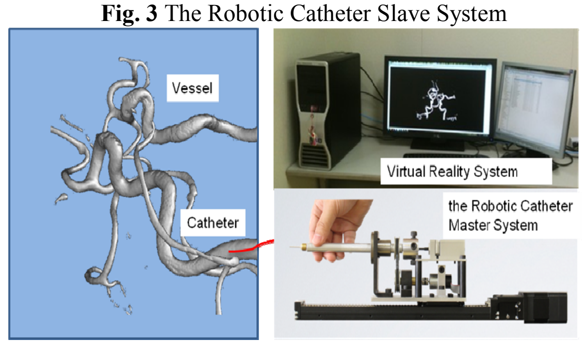


Fig. 4 Virtual Reality System

The catheter manipulator part contains two Degree of freedom, one is axial movement alone the frame, and the other one is radial movement. 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.

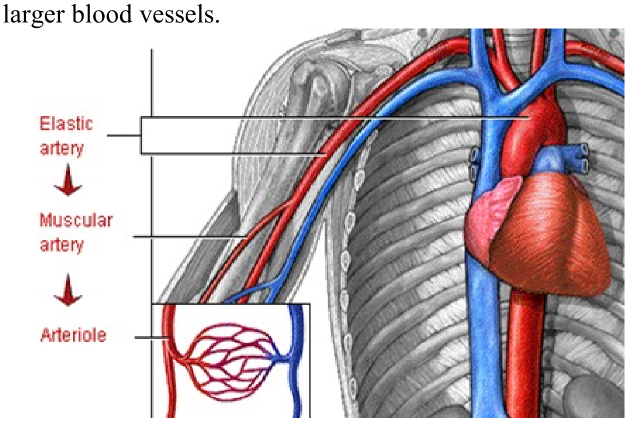
As shown in Fig. 4, we set up the VR training system and theand the surgeon in the master remote side can carry out the operation according to the two kinds of 3D image and complete the next operation step. However, the 3D image should be converted by us, and it is important to overcome the mechanical and haptic analysis of the vessel model.

III. Principle of Mechanical and haptic Analysis of the Catheter and Vessel Model

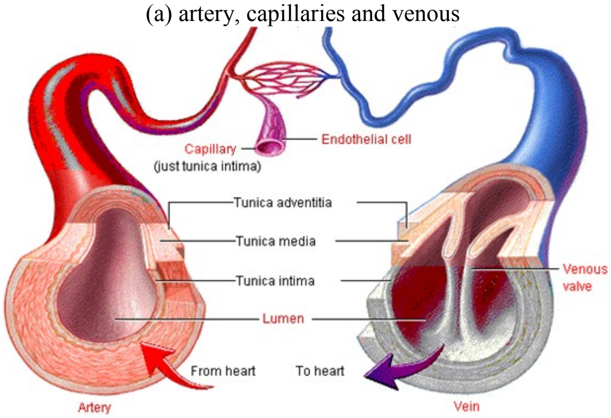
The blood vessels are the part of the circulatory system that transports blood throughout the body. There are three major types of blood vessels: the arteries, which carry the blood away from the heart; the capillaries, which enable the actual exchange of water and chemicals between the blood and the tissues; and the veins, which carry blood from the capillaries back toward the heart, As shown in Fig.5.

The arteries and veins have three layers, the middle layer is thicker in the arteries than it is in the veins: Tunica intima (the thinnest layer) is a single layer of simple squamous endothelial cells glued by a polysaccharide intercellular matrix, surrounded by a thin layer of subendothelial connective tissue interlaced with a number of circularly arranged elastic bands called the internal elastic lamina.

Tunica media (the thickest layer in arteries) is circularly arranged elastic fiber, connective tissue, polysaccharide substances, the second and third layer are separated by another thick elastic band called external elastic lamina. The tunica media may (especially in arteries) be rich in vascular smooth muscle, which controls the caliber of the vessel. Tunica adventitia (the thickest layer in veins) entirely made of connective tissue. It also contains nerves that supply the vessel as well as nutrient capillaries (vasa vasorum) in the larger blood vessels.



(a) artery, capillaries and venous



(b) Detail structure

Fig. 5 Vessel structure, (a) artery, (b) capillaries and (c) venous

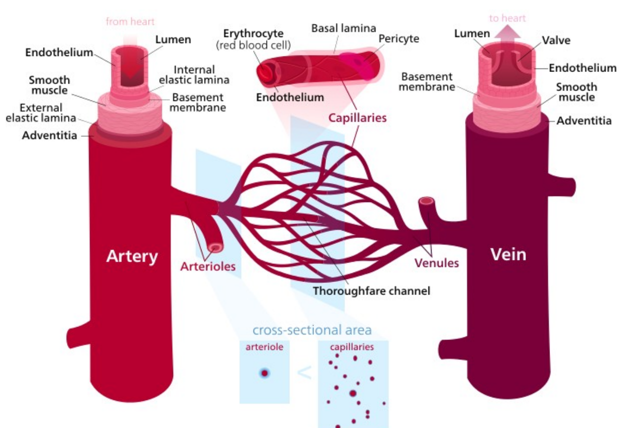


Fig. 6 blood to be pumped around the body

When blood vessels connect to form a region of diffuse vascular supply it is called an anastomosis. Anastomoses provide critical alternative routes for blood to flow in case of blockages.There is a layer of muscle surrounding the arteries and the veins which help contract and expand the vessels. This creates enough pressure for blood to be pumped around the body.

Blood vessels play a huge role in virtually every medical condition. Cancer, for example, cannot progress unless the tumor causes angiogenesis (formation of new blood vessels) to supply the malignant cells' metabolic demand. Atherosclerosis, the formation of lipid lumps (atheromas) in the blood vessel wall, is the most common cardiovascular disease, the main cause of death in the Western world. Blood vessel permeability is increased in inflammation. Damage, due to trauma or spontaneously, may lead to hemorrhage due to mechanical damage to the vessel endothelium. In contrast, occlusion of the blood vessel by atherosclerotic plaque, by an embolised blood clot or a foreign body leads to downstream ischemia (insufficient blood supply) and possibly necrosis. Vessel occlusion tends to be a positive feedback system; an occluded vessel creates eddies in the normally laminar flow or plug flow blood currents. These eddies create abnormal fluid velocity gradients which push blood elements such as cholesterol or chylomicron bodies to the endothelium. These deposit onto the arterial walls which are already partially occluded and build upon the blockage.

In order to testify the 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. 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.

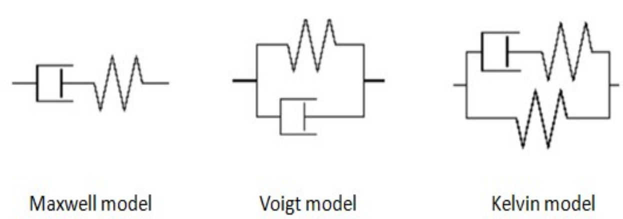


Fig. 7 Three basic models and the characteristics: Maxwell model, Voigt model and Kelvin model

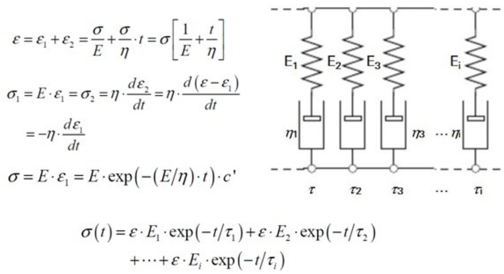


Fig. 8 Designed Maxwell model

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)

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

$$\begin{aligned} \sigma_1 &= E\cdot\varepsilon_1 = \sigma_2 = \eta\cdot\frac{d\varepsilon_2}{dt} = \eta\cdot\frac{d(\varepsilon-\varepsilon_1)}{dt} \\ &= -\eta\cdot\frac{d\varepsilon_1}{dt} \\ \varepsilon_1 + \varepsilon_2 &= \varepsilon \end{aligned} \tag{5}$$

then we have the solution of this differential equation

$$\begin{aligned} -\eta\cdot\frac{d\varepsilon_1}{dt} &= E\cdot\varepsilon_1 \\ \frac{d\varepsilon_1}{\varepsilon_1} &= -\frac{E}{\eta}\cdot dt \\ \ln\varepsilon_1 &= -\frac{E}{\eta}\cdot t + c \\ \varepsilon_1 &= \exp\left(-(E/\eta)\cdot t\right)\cdot c' \\ \sigma &= E\cdot\varepsilon_1 = E\cdot\exp\left(-(E/\eta)\cdot t\right)\cdot c' \end{aligned} \tag{6}$$

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

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

For the vessel model, Blood flow is the continuous circulation of blood in the cardiovascular system. This process ensures the transportation of nutrients, hormones, waste, O2 and CO2 to different body parts to maintain cell-level metabolism, the regulation of the pH, osmotic pressure and temperature for the whole body, and the protection from microbial and mechanical harms. The science dedicated to describe the physics of blood flow is called hemodynamics. For the basic understanding it is important to be familiar with anatomy of the cardiovascular system and hydrodynamics. However it is crucial to mention that, blood is not a Newtonian fluid, and blood vessels are not rigid tubes, so classic hydrodynamics is not capable to explain hemodynamics. We can also consider the deformation by the flow force of the blood, when the heart infect on the blood vessel. The flow of blood can be present as follows

$$Q = K\frac{r^4}{L}(P_1 - P_2) \tag{8}$$

$$Q = \frac{\pi(P_1 - P_2)r^4}{8\eta L} \tag{9}$$

The general principle concerns the conservation of energy. Recall the laws of thermodynamics, it states that the rate of change of the total energy of a system is equal to the rate at which applied force do work on it. When there are no applied forces, the total energy is constant i.e. energy is conserved. We can introduce the idea of a streamline. Consider a steady flow in which its boundary consists of a streamline. If we assume that the fluid is constrained to remain on the streamline and if we assume the two ends of a finite length of the tube are at different levels and the fluid is flowing up from an initial velocity u_1 and a cross sectional area A_1 to a level Z_2 with velocity u_2 and area A_2, therefore we can have the Bernoulli's equation given as follows:

$$p_1 + 0.5\rho(u_1) + \rho g Z_1 = p_2 + 0.5\rho(u_2) + \rho g Z_2 \tag{10}$$

where p is the pressure, u is the velocity, Z is the height.

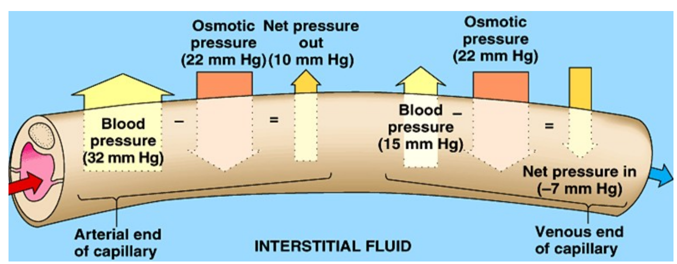


Fig. 9 Pressure model of the blood flow

Regardless of site, blood pressure is related to the wall tension of the vessel according to the Young–Laplace equation (assuming that the thickness of the vessel wall is very small as compared to the diameter of the lumen) :

$$\sigma_\theta = \frac{p_r}{t} \tag{11}$$

whereP is the blood pressure, t is the wall thickness, r is the inside radius of the cylinder. σ_θ is the cylinder stress or "hoop stress".

For the thin-walled assumption to be valid the vessel must have a wall thickness of no more than about one-tenth (often cited as one twentieth) of its radius.

The cylinder stress, in turn, is the average force exerted circumferentially (perpendicular both to the axis and to the radius of the object) in the cylinder wall, and can be described as:

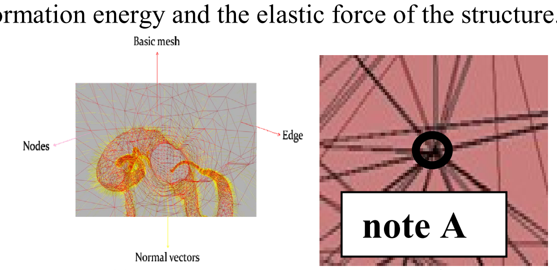
$$\sigma_\theta = \frac{F}{tl} \tag{12}$$

where F is the force exerted circumferentially on an area of the cylinder wall that has the following two lengths as sides, t is the radial thickness of the cylinder, l is the axial length of the cylinder.

IV. Reconstruction of the 3D Vessel Model with DICOM Files

We want to simulate the deformation of blood vessels with DICOM files. After the DICOM image segmentation, and we can use Open Scene Graph (OSG) to realize 3D graphics. 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 and integration emerged as the most suitable for application. As see the three-dimension reconstruction images of the blood vessels have been shown in Fig. 10. Catheter simulation algorithms can be classified as physical or geometrical methods. Thus, calculation rate of the virtual model using this algorithm is fast but without physical properties. The main physical approaches finite element modeling (FEM) methods describes a shape as a set of basic geometrical elements and 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. With these elements we can evaluate the deformation energy and the elastic force of the structure.



(a) (b)

Fig. 10 Three-dimension reconstruction images of the blood vessels: (a) and (b) the mesh of the vessels

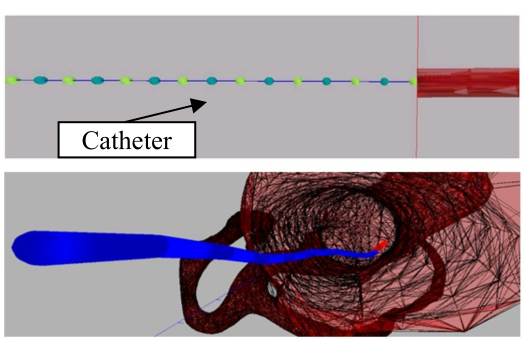


Fig. 11 3D reconstruction images of the catheter model

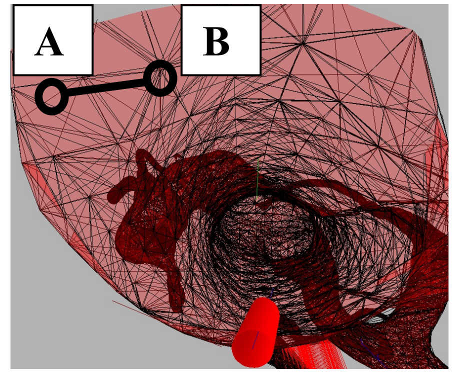
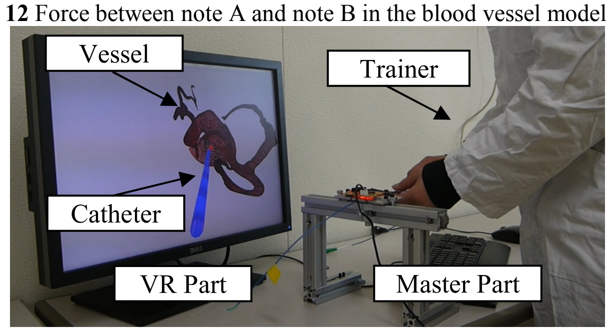
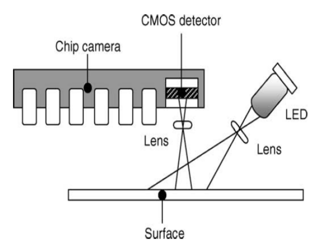
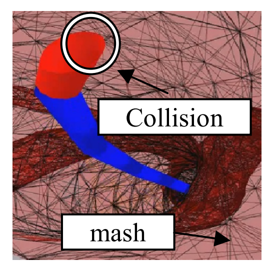


Fig. 12 Force between note A and note B in the blood vessel model

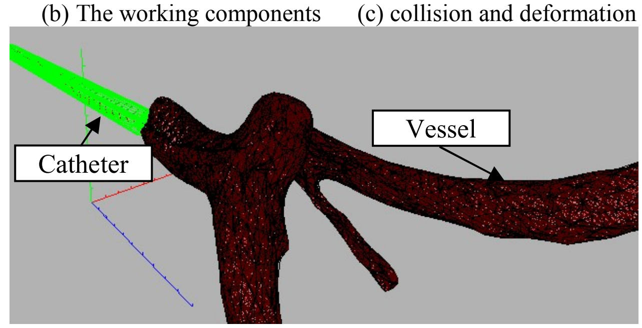


(a) Virtual Reality based Robotic Catheter System





(b) The working components (c) collision and deformation



(d) Simulation of the catheter Insertion and Rotation

Fig. 13 the catheter visual model inserting into the 3D vessel model

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. Bounding volume hierarchies (BVHs) are probably the most popular mechanisms to recursively subdivide the object of interest and bounding volume for each of the resulting subset of primitives. 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 overlap is found, 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. There are 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.11 and Fig.12.

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. 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 surgeon, he can operate the real catheter directly for their training courses and the measurement of displacement. 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. 13. 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 proposed the kind of Catheter Virtual Reality System which is used for the training of the interns to operate the Robotic Catheter System. For the VR parts, the novel robotic catheter operating system has good maneuverability and 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. We give the mechanical and haptic model of the vessel model, and 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. And In the future works, we would do more experiment for surgeon to use the Virtual Reality System to improve their experience.

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