Proceedings of 2013 ICME
International Conference on Complex Medical Engineering
May 25 - 28, Beijing, China

A VR-based Training System for Vascular Interventional Surgery

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Abstract - **The Vascular Interventional Surgery(VIS) 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, we present a training system based on virtual reality technology for unskilled doctors with extremely similar environment in real vascular interventional surgery. This application allows generating realistic geometrical 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 VIS. Finally, the experimental results show that the error rate is in an acceptable range and the system can be used for surgery training.**

Index Terms* - *Vascular Interventional Surgery, catheter model, blood vessel model, unskilled doctor training

I. INTRODUCTION

Minimally invasive surgery is a revolutionary surgical technique, in which 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. Therefore, the main advantage of this technique is to reduce trauma to healthy tissue since this trauma is the leading cause for patients' pain and scaring and prolonged hospital stay. In addition, fast recovery and short stay at hospital also reduce the cost of surgery and the radiation exposure. However, a critical disadvantage of this surgery technique is its complicated, requiring extensive training efforts of the surgeon to achieve the competency, because the arteries through which the catheter passes are extremely intricate and delicate. The reduplicative insertion of the catheter through several tests could tear a blood vessel at some region and cause bleeding instantaneously and excessive pressure could crack the blood vessels. There is a need to provide additional means to train students or junior interventionists in order to improve their necessary skill levels. A realistic and computerized simulation system could complement and enhance the traditional type of training with real patients. For practical and ethical reasons, realistic virtual reality simulators provides the promising a alternative method 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 patients.

The benefits of using virtual reality technology in vascular interventional surgery for unskilled doctor training have already been recognized by several research groups and many of companies working in this area. Several interventional surgery simulation systems have been reported in the literature[1-11]. However, in these researches, the virtual surgical training were researched on the virtual model of body organ not the vascular physical model. Moreover, some achievements in this area have not used real catheter as a controller to operate the virtual vascular interventional surgery [12-13]. Therefore, it is not convenient when surgeon drive the catheter for inserting and rotating because it does not accord with the custom of surgeons' operations.

Therefore, the objective of this paper is to present a doctor training system based on virtual reality technology with a new mechanical structure of catheter controller for vascular interventional surgery. 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 as follows. Section 2 introduces the algorithms and implementation methods of vascular model, catheter model and the interactive simulation between blood vessels model and catheter model. And the mechanical design of controller which is used to operate virtual catheter will be presented in section 3. Section 4 discusses the results of our virtual reality simulators. Section 5 comes to the concludes the paper.

II. MODELING OF THE VESSEL-CATHETER INTERACTION

This section describes how we model the blood vessels, catheter and the interactive simulation between vascular model and catheter.

A. Simulation algorithm of blood vessels

A core component of a virtual reality surgical simulators and training system is realistic geometrical vascular models which are the virtual representations of real blood vessels that display accurate deformable responses. To develop these

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models, the shape and the material properties of blood vessels should be measured and characterized in living condition and in their native locations due to the fact that models with incorrect material properties and shape could result in adverse training effects. In our case, we extract the geometrical parameters of real vascular structure from special patients.

In order to reconstruct the realistic three dimension vascular model, we apply median filter algorithm to reduce the noise of the CT images, then use local thresholding algorithm to realize the image segmentation of CT images, finally adopt the volume rendering technology to reconstruct the vascular model.

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. Set $\{x_{ij}(i,j) \in I^2\}$ 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}. The window of median filter often choose 3*3, 5*5 or 7*7.

Thresholding algorithm mainly bases on regional technology and sorts the image pixels using different characteristic threshold. The segment algorithm can be described as: First, set original image as f (x, y), next find T_1, T_2, T_3……T_N (N>1) according to corresponding algorithm in original images, then sort the images into several parts:

if $f(x, y) > T_N$, $g(x, y) = L_N$;

if $T_{N-1} < f(x, y) < T_N$, $g(x, y) = L_{N-1}$;

……

if $T_1 < f(x, y) < T_2$, $g(x, y) = L_1$;

if $f(x, y) < T_1$, $g(x, y) = L_0$.

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.

There are two main effective approaches to simulate deformation of human blood vessels precisely, finite element method (FEM) and mass-spring method (MSM). Compared to FEM, MSM presents better performance in computational time efficiency and adaptive ability to the topological structure of blood vessels. Also, MSM is precise enough in the simulation of blood vessels, which is demonstrated in reference [17]. Therefore, we used MSM to simulate the deformation of blood vessels.

The mass-spring model is a widely used mesh-free method in surgical simulation [15], which models the object as masses connected to each other with springs and dampers. Every 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. Hooke's law describes this force by a "spring equation" (1). 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.

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

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), where m is the 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.

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

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.

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

To obtain an exact solution of the differential equation (3), it has to be integrated in time. 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. It discretizes time by replacing the derivatives by differences between sufficiently small steps dt. The step dt is an additional parameter of the system which contributes heavily to its behaviour – a 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 (i.e. it will not be able to achieve a stable position).

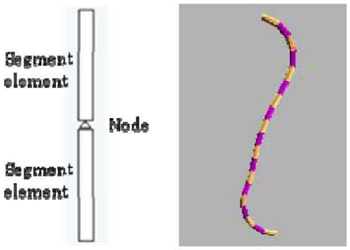
The three-dimension reconstruction images of the blood vessels have been shown in Fig. 1: (a) for the multi-branched blood vessels and we can choose a part of them as research topic shown in (b).

(a) (b)

Fig 1. three-dimension reconstruction images of the blood vessels: (a) the whole structures of blood vessels. (b) specific blood vessel

B. Simulation algorithm of catheter model

The approaches of the catheter simulation have been presented by several research groups [15]. 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 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, as shown in Fig. 2 (a). 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. 2 (b).



(a) (b)

Fig 2. the simulation images of catheter: (a) the segment element image. (b) the virtual catheter image

We used the methods of reference [18] to realize the physical model of the catheter because this virtual model runs more accurate and stable in simulation of catheter. In order to obtain the physical characters of the catheter, the operation of insertion and rotation should be considered, when the catheter is driven into the blood vessel.

When the segment element is stretched or compressed, it generates elastic forces on its nodes. The direction of the force is in the direction of segment element and its magnitude follow Hooke's law:

$$f_e=k_s(r_c-r_0) \tag{4}$$

where r_c and r_0 are the current and the original lengths of the segment element, respectively. The force vector can be evaluated by following vector equation.

C. Collision detection

Apart from the models themselves, 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. In this case, 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. The idea is to recursively subdivide the object of interest and compute a 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. As 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. Since every triangle stores an outward-facing normal $\boldsymbol{n}_i$, a point on the triangle $\boldsymbol{t}_i$(this can be any one of the vertices), and given a colliding vertex $\boldsymbol{v}$, a vertex can be said to be inside an object if for every triangle in the rigid object $(\boldsymbol{p}-\boldsymbol{t}_i)\cdot\boldsymbol{n}_i<0$. The minimum collision depth is just the largest scalar value from $(\boldsymbol{p}-\boldsymbol{t}_i)\cdot\boldsymbol{n}_i$ if the intersecting test passes for all triangles.

III. THE MECHANICAL DESIGN OF CONTROLLER

The conceptual principle of the controller which is applied to operate virtual catheter inside blood vessel model has been shown in Fig. 3.

The catheter can be subjected to two different sets of movement during manipulation: insertion/retraction and rotation. According to translation and rotation of catheter, 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. 4. 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 off-axis illumination by the LED helps to put the tiny textures on the surface in sharp contrast. The CMOS sensor typically comprises 18 pixel × 18 pixel (324 pixels in total). The mouse works by comparing the images of the surface that are refreshed approximately every 1500th of a second. As it is too computationally taxing to compare the images at all 324 possible overlaps, a 5 pixel × 5 pixel window, taken from the center of the second image, is normally used for the overlap matching process. This window is moved relative to the first image and the chip rates how well each of the 324 pixels matches up. These ratings are added to an overall score for the overlap. 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.

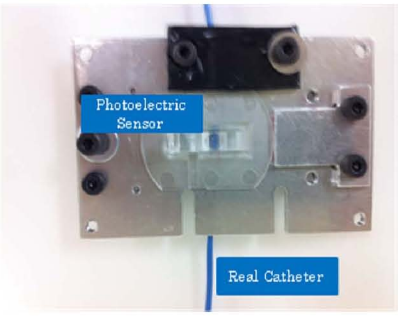


Fig. 3. Conceptual principle of the controller

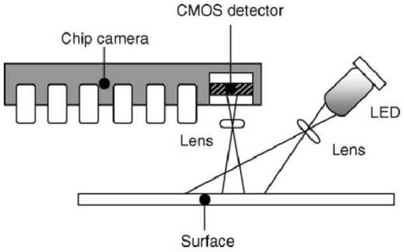


Fig. 4. Schematic description of the working components of an optical mouse

The unit of data measured by a photoelectric sensor is pixel not millimeter. Therefore, next step is to convert pixel unit into millimeter unit. Some experiments have been carried out to find the relationship between pixel data and real displacement of catheter, as equation 5 shows:

$$\begin{cases} U = a \cdot X \\ \theta = b \cdot Y \end{cases} \tag{5}$$

where X and Y are the sensor outputs in vertical and horizontal direction and U and θ are real displacements in Cartesian coordinate system. Moreover, a and b are two constants measured by experiments. Then it is more easier to calculate the velocity and acceleration as equation 6 shows:

$$Speed = \frac{U(k) - U(k-1)}{\Delta T} \tag{6}$$

There are two obvious advantages in mechanical design of this controller compared to other training system based on virtual reality technology. The first one is the fact that 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. Therefore, 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.

IV. EXPERIMENTAL RESULTS

To testify our simulation model of blood vessel and catheter, 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 has been shown in Fig. 5.

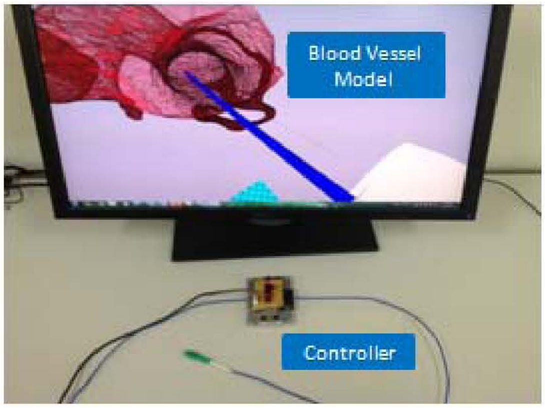


Fig. 5. The whole structure of VR-based training system

During the training procedure, doctors operate the controller to drive catheter to insert or rotate, at the same time, the controlling instructions of the catheter operating system are transmitted to the virtual reality environment. The catheter in virtual reality environment can insert or rotate according to the controlling commands from the controller. Based on the three-dimension vascular information, doctors can decide whether to insert or rotate the catheter. Fig. 6 shows the status of tip of catheter which is tracked in a yellow circle inside the blood vessel model when inserting and rotating the controller to control virtual catheter passing through a curve part and Fig.7 shows the three-dimensional coordinates' changes of tip of virtual catheter when passing through the curve part.

V. CONCLUSION AND FURTHER WORK

A doctor training system based on virtual reality technology for vascular interventional surgery has been presented in this paper. The training system can generate the realistic virtual reality environment of blood vessels according to patient's special computed tomography or magnetic resonance imaging files, 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. There are two obvious advantages in mechanical design of this controller compared to other training system based on virtual reality technology. The first one is the fact that 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. Therefore, 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.

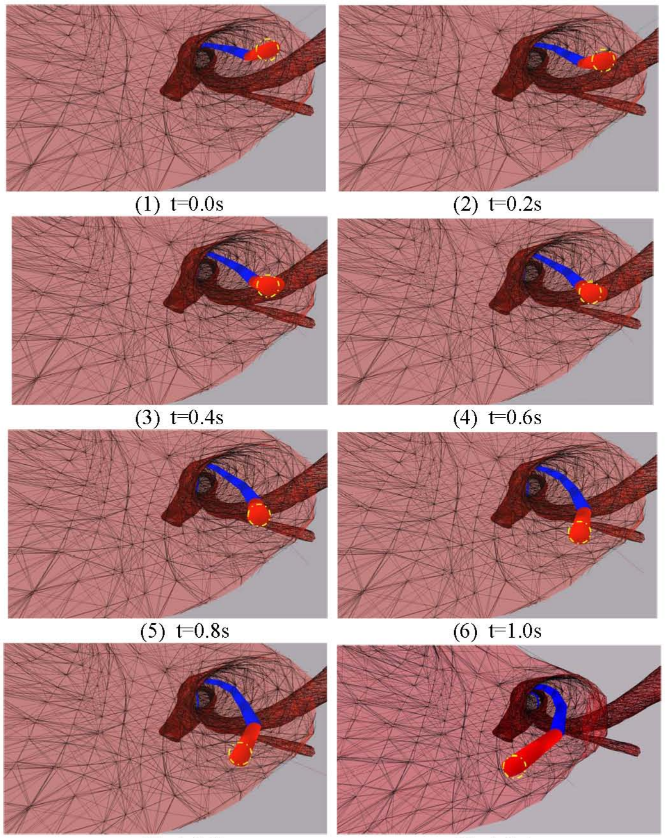

(1) t=0.0s (2) t=0.2s
(3) t=0.4s (4) t=0.6s
(5) t=0.8s (6) t=1.0s
(7) t=1.2s (8) t=1.4s

Fig. 6. Inserting process of catheter inside vascular structure

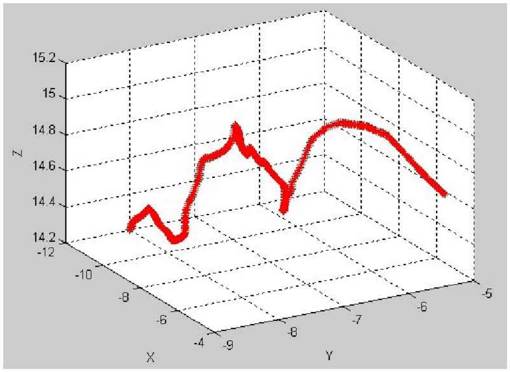


Fig. 7. Coordinates of tip of catheter in Fig. 6

Obviously, providing a realistic training environment in which trainees act as if they are operating on an actual patient is the simulators' essential goal. In order to achieve better training effect, force feedback should be added in this training system.

ACKNOWLEDGMENT

This research is supported by Kagawa University Characteristic Prior Research fund 2012.

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