Proceedings of 2016 IEEE
International Conference on Mechatronics and Automation
August 7 - 10, Harbin, China

Force Feedback-based Robotic Catheter Training System for the Vascular Interventional Surgery

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***Abstract* - Virtual catheter training system is a typical application of Virtual reality(VR) technology in the medical field. Doctors must operate catheters through experience accurately in traditional minimally invasive surgery(MIS) to ensure the safety of the operation. In order to improve the operation skills we proposed the force feedback-based robotic catheter training system. In this paper, we can obtain force feedback through the catheter with CyberGlove. We established the high precise 3D model, and then we set up the mapping relationship between CyberGlove and the virtual hand, realizing the human-computer interaction. Based on the previous work, we created a virtual environment completed the collision detection and force feedback. In addition, the relevant verification experiment confirmed that the virtual environment makes surgery more immersive, the experimental result proved this system could simulate the real force feedback process, and the feedback force is 0.619N when the biggest variable value is 0.5mm.**

Index Terms - CyberGlove, VR, Collision Detection, Force Feedback

I. INTRODUCTION

Virtual Reality technology(VR) refers to computer technology as the core is used for simulating a 3d virtual environment and provide person with realistic experience such as vision, hearing and touch feeling, users can through necessary device and objects interact with the virtual world. Minimally invasive Surgery(MIS) by using modern medical device and related equipment does surgery in the human body. Compared with the traditional surgery, minimally invasive surgery has small trauma,less bleeding and short recovery time, alleviate the pain to the maximum extent. The development of virtual surgery simulation system can greatly save training time and expense, helps to cultivate novices as soon as possible to become a technical qualified doctors.

With the continuous development of virtual surgery technology, there has been a lot of virtual operation training systems in abroad, such as the university of California, on the basis of refitting the PHANTOM force feedback devices developed a virtual surgery system about abdomen, called VESTA, used for surgeons skills training and assessment[1]. O'Toole and his team used two PHANTOM equipments, realized arterial revascularization simulation system by building a haptic display channel[2]-[3]. Japanese Naoki Kusamoto used the phantom force feedback device established oral implants simulation system[4]-[7]. The domestic research on virtual surgery system is still in groping. Beihang University in 2003 developed a dental training fitting system, it allows us to detecting and cutting a tooth model, and also having the tooth diagnosis, tooth preparation functions[8].

There are also many desktop haptic interfaces such as the Sensable PHANTOM (http://www.sensable.com), the Novint Falcon (http://home.novint.com) and the Force Dimension DELTA (http://www.forcedimension.com).

However, there are also some disadvantages of these systems[9]-[11]. Most of the device they rely on do not conform to the custom of surgeon’s operations, and it needs training a lot of time to have a good command operation to the novice.

Training methods including practicing on mechanical models, using live animals and cadavers for training[12]. Virtual Reality training system provides some of these advantages compared to traditional: no radiation, more patient specific and less costs are associated. The simulation provides an environment where hands-on training can be safety[13]-[14]. Hence, developing virtual reality training system for vascular intervention surgery is crucial to us[15]-[18].

This paper using the CyberGlove as human-computer interaction tools, the modeling of virtual hand, interaction and control as the main research object to complete the surgery simulation. It based on the analysis and summary of virtual surgery training system, study the CyberGlove and virtual hand human-computer interaction technology in-depth and put forward the overall framework of virtual vascular interventional surgery training system. Through the establishment of virtual hand hierarchy and association, and the development of virtual hand controlled nodes, we solve the real-time control of virtual hand.Research specific contents are as follows:

1) According to the characteristics of the shape of a man's hand to building the static virtual hand. Using Maya to build hand modeling. And in line with characteristics of the joint movement add the skeleton model. Virtual hand model built by Maya is realistic and easy to interact with CyberGlove. And

978-1-5090-2394-3/16/$31.00 ©2016 IEEE

studied the building environment of virtual surgery.

2) Analyzed the hands skeleton and joints of the movement characteristics, we determined the degrees of freedom and movement law of joints, and to establish the internal level of virtual hand. Implements the dynamic control of virtual hand and interaction.

3) Based on the previous research, we analyzed collision detection algorithm and force feedback, then the blood vessels and catheter models completed the collision detection and force feedback.

This paper is organized as follows. Section II shows the whole system structure. Section III introduces the static builds and dynamic control of virtual hand. Section IV presents the constitution of collision detection and force feedback. Section V shows the result of the experiment. Section VI describes our further directions and concludes the paper.

II. The Overview Of The Training System

Intervention operation system can be divided into two parts: assisted vascular interventional surgery system and on the basis of it improved the doctor training system based on VR.

Assisted vascular interventional system has master and slave sides[19]-[20]. Doctor has an operation in the master side, the master controller collects the operation information and give it to PC. The PC in the master side through LAN or Internet communication gives the data to PC in the slave side. After received the data, the PC in the slave sides send control command to slave manipulator, to complete the catheter insertion movement and calculate the force feedback. The whole operation process is a closed loop. In addition, the slave sends collision information to master through the collision detection system to get the force sensing, and also the slave camera provides image information.

Vascular interventional surgery training system based on VR simulates surgery scenes by computer technology, according to the operation of the manipulator in master side, surgical instruments do the corresponding operation in virtual environment. When blood vessels and catheter collide in virtual environment, the vessel will produce soft tissue deformation, we can calculate the force feedback, and pass the force to the operator, realize the simulation of operation with the whole process. As shown in figure 1 as the assisted system and the structure diagram of VR whole system.

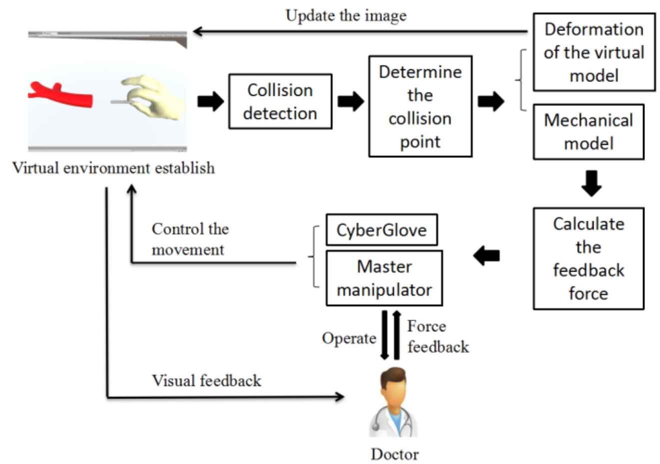


Fig1.The overall structure of the system

III. The Control Method Of The Virtual Hand

A. The degree of freedom(DOF) and the mapping relationship

A man's hand sophisticated bone structures is a multiple segments system.It is composed of 27 pieces of bone, consists of Carpal, Metacarpal and phalanges. There were a total of 8 pieces of carpal, arranged in two rows. Metacarpal, a total of 5 pieces, by thumb to the little finger in turn is called the I ~V metacarpal. Phalanges for 14 pieces, except the thumb only has two phalanges, other fingers have three phalanges, respectively called Phalange, Intel-Phalange and Distal Phalange.

Four neighbouring finger eaches has four degrees of freedom, including MPJ (J: joint, C: Carpal, M: Metacarpal, T: Thumb, P: Phalange, I: Inter-phalange, D: Distal phalange.) have two and it can bend, stretch, adduction and outreach. PIJ and DIJ each have 1 DOF, only can make bend and stretch movement. MCJ has one DOF for each. Thumb has five DOF, of which the TMCJ and TMPJ each have two, can make a bend, stretch, adduction and outreach, TIJ has one, only can make bend and stretch movement. Moreover, The wrist has six DOF in the three-dimensional space, so human hand with a total of 31DOF, as shown in table 1.

Human hand different parts of the joint can realize the different action, which is not the same level. For example, wrists can rotate and swing, while the fingers can flexion, adduction, and outreach, but it has different DOF in different parts of the joints. Hierarchy can reflect the level and the similarity between models, while the associated reflect the related relationship of the model. According to characteristics of human joints distribution of DOF, we can establish the hierarchical structure of the virtual hand.Virtual hand includes multiple layers, as shown in table 2, and the 3d human hand models are shown in figure 2.

B. skeleton animation

In general, real-time character animation technology can be divided into three types. The first kind is Joint Animation. Joint animation role model consists of several independent joints. Every joint is an independent grid model corresponds to a certain body joints, different joints according to the characteristics of the role organized into a hierarchy. The second kind is the Key frame Animation, it is also called Vertex Animation. Character animation in the key frame animation is composed of a series of gradient mesh models. The third kind is the skeletal Animation. Skeletal animation can be regarded as a combination of joint animation and vertex animation. It also has flexible in joint animation and vivid in vertex animation. Skeletal animation model is a mesh model. The interior of the mesh is a skeleton structure, as shown in figure 3. When the character skeleton movement, the body can

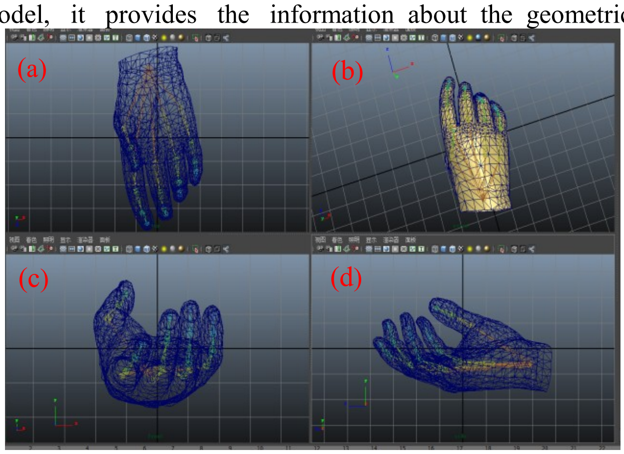
Table 1 the DOF's Distrubution of Hand's Joints

	C	TMC J	MCJ	TMP J	MP J	TIJ	PIJ	DIJ
Number of joints	1	1	4	1	4	1	4	4
Move DOF	3	0	0	0	0	0	0	0
Rotate DOF	3	2	1	2	2	1	1	1
Total DOF	6	2	4	2	8	1	4	4

Table 2 Virtual-hand's Layers

The hierarchical from top to down					
First	Wrist	Wrist	Wrist	Wrist	Wrist
Second	Thumb metacarpal	Metacarpal	Metacarpal	Metacarpal	Metacarpal
Third	Thumb	Index finger	Middle finger	ring finger	little finger
Forth	Thumb Phalange	Index finger phalange	Middle finger phalange	Ring finger phalange	little finger phalange
Fifth	Thumb distal phalange	Index finger Inter-phalange	Middle finger Inter-phalange	ring finger Inter-phalange	little finger Inter-phalange
Sixth		Index finger distal phalange	Middle finger distal phalange	Ring finger distal phalange	Little finger distal phalange

follow skeleton movement. Skeleton is a hierarchy structure made up of a certain number of bone, the arrangement and connection relationship of a bone have important influence on the whole skeleton movement. Each bone data contains its own animation data. Associated with each frame is a "Skin" model, it provides the information about the geometric



(a) Top view of the virtual hand model (b)The perspective view of the virtual hand model (c)Front view of the virtual hand model (d)The side view of the virtual hand model

Fig2. Virtual hand model in Maya

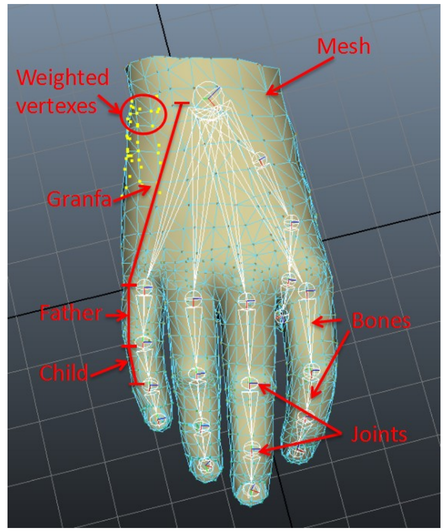


Fig3. Skeleton animation model

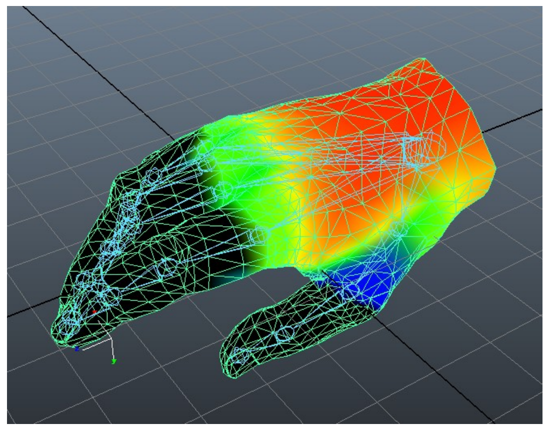


Fig4. The "skin" model of the virtual hand

model and material texture information needed to make animation[14]-[15], as shown in figure 4.

The essence of the "skin" algorithm is a kind of interpolation algorithm, the basic formula is:

$$v=\sum_{i=1}^{n}\omega_i C_i v_i \quad \text{where} \quad \sum_{i=1}^{n}\omega_i=1 , \qquad (3)$$

In this formula v_i is the vertices in the ith local coordinates of the associated skeleton subspace, c_i is the ith global transformation matrix of associated skeleton,is coordinates of the associated skeleton subspace, c_i is the ith global transformation matrix of associated skeleton,is the value of the ith associated skeleton, and their sum is 1.These steps have achieved a flexible virtual hand modeling, we use Maya created a lifelike virtual hand model by adopting the method of grid surfaces modeling, as shown in Fig5.

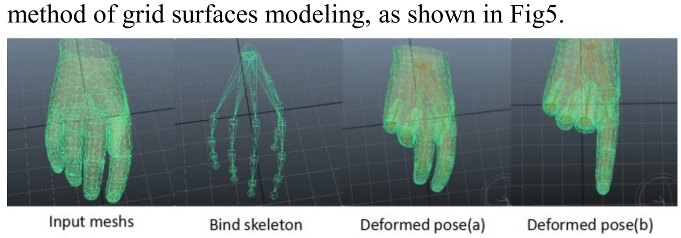


Fig5. Results of skeleton binding and deformed poses of given mesh

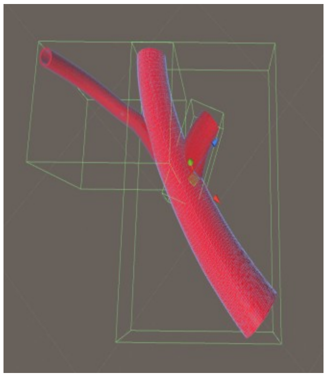


Fig6. The AABB tree of the virtual vascular

IV. Collision Detection And Force Feedback

A. Collision Detection

Collision detection is the foundation of a virtual reality system, and it is the premise to calculate the force feedback. Collision detection of real-time, stability and accuracy will affect the subsequent processing of virtual reality system, which are more likely to have a significant impact on the performance of the entire surgical simulation. The current collision detection is: collision detection algorithm based on bounding box, the collision detection algorithm based on distance calculation, and the collision detection algorithm based on voronoi diagram. The collision detection algorithm based on bounding boxes is: along the Axis of Bounding Box AABB (Axis-Aligned Bounding Box) , surrounded the ball (Sphere), along arbitrary direction surrounded the box OBB (Oriented Bounding Box). Unity collider we used is the specific application of bounding box collision detection, it contains two main colliders: prototype collider and mesh collider. Prototype collider has simple geometric objects appearance, such as box, sphere, capsule collider etc. Mesh collider is based on object 3d model mesh to realize collision detection and prototype computing resource consumption is relatively lower, suitable for low accuracy collision detection. Mesh collider is much bigger than prototype of computing costs, but also much more precise. We used AABB in this paper, the result of establishing the AABB bounding box tree of the virtual vascular is shown in Fig6.

B.Force Feedback

The calculation of force feedback is used mostly spring-damper model, and use it to calculate the surface normal. This way is simple calculation,when force sensing to reappear the refresh rate for more than 1 KHz.

In the process of interaction, when the virtual surgical instruments and virtual soft tissue surface contact, the virtual model of soft tissue deformation[17]-[18]. As shown in figure 7.When virtual surgical instruments can be obtained the balance, we can get the displacement of HIP relative to SCP , namely "puncture depth x". By the spring-damper force feedback calculation model, the virtual surgical instruments by reaction to the end of the mathematical expression are:

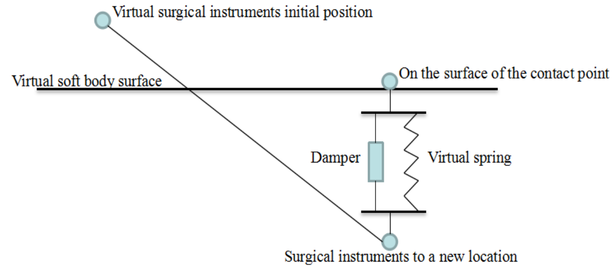


Fig7.The model of the force feedback

$$F(t) = Kx + D\dot{x} \tag{4}$$

Where K is spring elasticity coefficient; D is spring damping coefficient; x is the surface displacement of the contact point.

Among them, the direction of the feedback force F(t) and the displacement of x in the opposite direction. Due to the different biomechanical properties of soft tissue, by adjusting the elasticity coefficient K and the damping coefficient D can be used to simulate the physical properties of different virtual soft tissue, so as to simulate the human body surface characteristics of the soft tissue.

According to the above model, combined with the structure of the blood vessel walls, we get the following calculation model:

$$F = E \cdot S \cdot \Delta X / X \tag{5}$$

Where E is the modulus of elasticity of the blood vessel walls, S is the area of contact, X for the thickness of the blood vessel walls, ΔX for the variable value of the shape of blood vessel walls.

Through model calculation, force feedback sent back to the master manipulator, and then take advantage of magnetorheological fluid(MRF) damper to realize force feedback. As shown in figure 8, it is designed for use of MRF damper. When the conductor in the piston rod energized, it will generate a magnetic field, we can control the magnetic field intensity through the control of current size. We will drive the movement of the piston rod when we operate the catheter, so that the piston body of the cylinder movement, meanwhile the MRF cutting magnetic induction lines, forming the resistance of the piston body movement. When the magnetic field intensity changes the viscous coefficient of MRF, the piston body motions resistance also changed accordingly, so it will realize the force feedback.

V. Experiments And Results

The main equipment used in this experiment is as follows:

1)The master-slave vascular interventional system

The master-slave vascular interventional system is developed to depend on MRF to realize the force feedback. The master side used the mechanical structure of the cylinder, the cylinder inside is MRF and piston, the sleeve connected with the piston, catheter connected to the casing through the jig, so operation catheter can move the piston in the cylinder, when MRF viscosity changes, the piston thrust affected, in

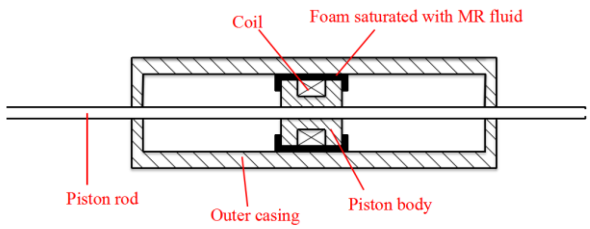


Fig8. The damper designed for use of MRF

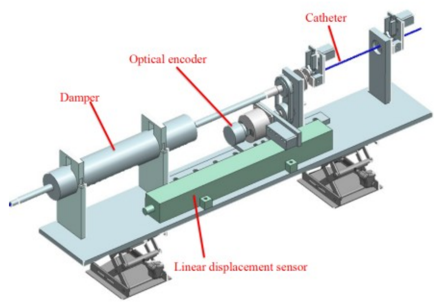


Fig9.The master side in the system

Fig10. Embedded bending sensor in CyberGlove

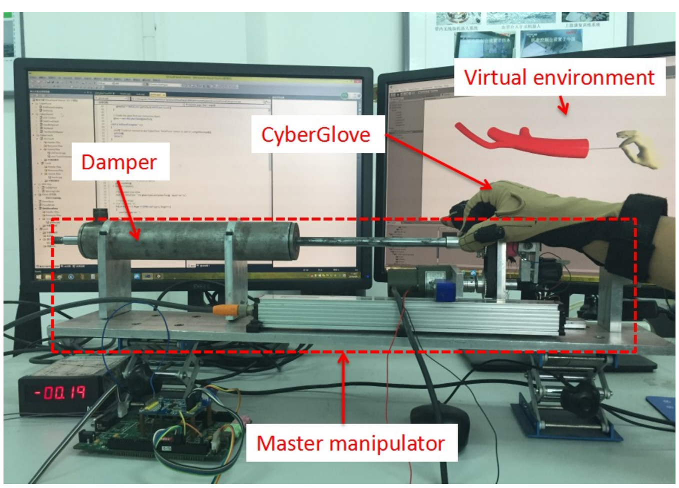
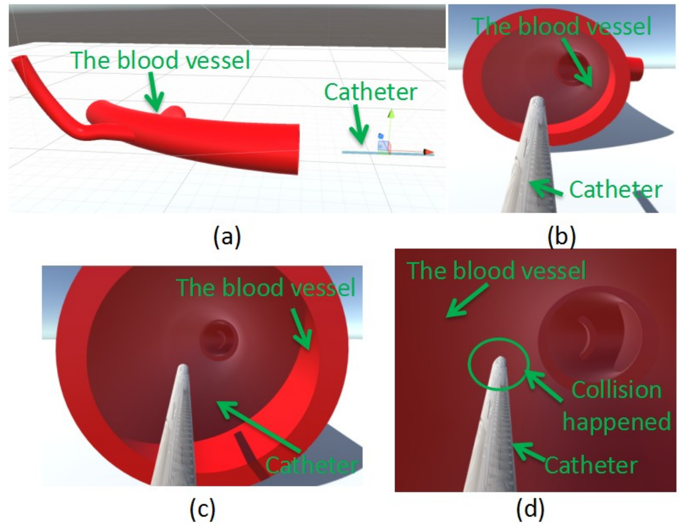


Fig11. The whole structure of the training system

order to let the person feel force feedback, as shown in Fig9. The slave robot is used to control the movement towards the catheter, and the master one is used to control the slave.

2) CyberGlove



(a)The overall structure of the blood vessel and the catheter; (b)Catheter start to insert into blood vessel; (c)The catheter is inserting into the blood vessel; (d)The collision happened between the catheter and blood vessel.

Fig12. The whole process of the experiment

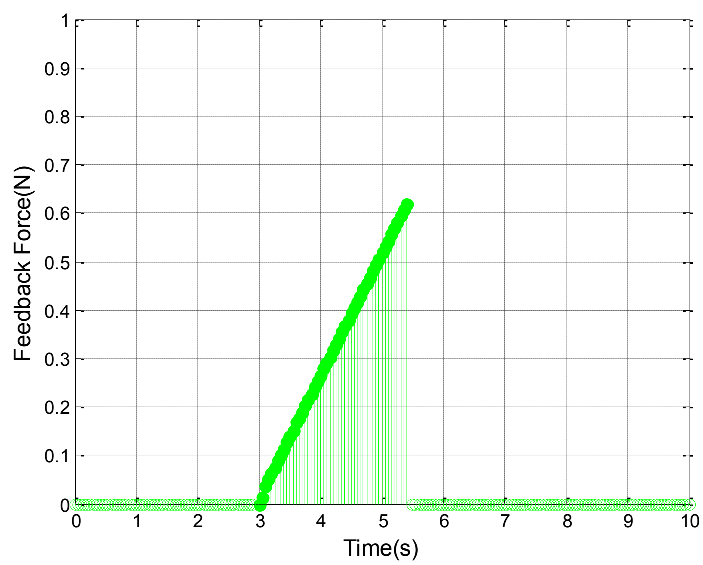


Fig13. The curve of force feedback

Figure 10 is used in the text of the CyberGlove, this series of CyberGlove use 22 embedded bending sensors measuring average finger flexion degree. On CyberGlove each finger have a motor, palm also has one too, in total it has 6 motors, we use it to prompting the collision occurs, when catheter model met the vascular, the vibration of the CyberGlove will give a feedback, alert doctors stop continue to insert catheter.

We use virtual reality development platform Unity3d and Visual Studio 2010, combined with the CyberGlove SDK and Maya, the system Window8 x64 on realization of CyberGlove and the real time of virtual hand interaction function. The whole system is as shown in Fig 11.

In this experiment, we simulated the whole operation process of the catheter movement, and detected the collision with blood vessel,as shown in figure 12, at the same time we calculated the force feedback. In general cases, the elastic modulus of blood vessels is 500 kPa, the thickness of the blood vessels is 0.5 mm. We assume that the biggest variable of blood vessels equals to vessel wall thickness, namely 0.5mm, when the variable value is more than 0.5 mm, thinking that blood vessel punctured, not feedback the force information to the master side. To simplify the computing workload, we took the cross sectional area of the catheter instead of the contact area to calculate the feedback force.

Figure 13 expressed as the calculation of the force feedback through catheter movement. At the beginning of the test, the catheter is outside the blood vessel, so there is no force feedback, namely the feedback force is zero, after collision, the feedback force of the catheter into the rapid change, when the biggest variable value of the vascular $\Delta X = 0.5mm$, the feedback force F=0.619N, more than this, catheter is punctured, feedback force back to zero.

VI. Conclusion And Future Work

In this paper, we proposed a catheter training system based on force feedback, in order to improve the doctor's surgery skills and facticity of the system. We used virtual reality platform Unity and modeling tool Maya to build a lifelike virtual hand and scene, and then we completed the interaction with the CyberGlove and the virtual hand model. Finally, we realized the collision detection and force feedback on the training system. Doctors operated the catheter with CyberGlove to obtain feedback force from the system, in this way the master side sent the manipulate information to the virtual model. When collision between the catheter and the vascular happened, PC could calculate the force feedback and then sent the message to the doctor. In this case, the virtual surgery training system is proved more accurate and immersive compared to traditional training system. The experimental result indicated that the proposed force feedback method has good effect. In the result, we can see the feedback force is 0.619N, when the biggest variable value of the vascular is 0.5mm. This paper proposed the training system in modern computer technology application of the medical field, increasing the diversity of the medical treatment method.

In the future work, we will use the proposed catheter training system to train unskilled doctors.

Acknowledgment

This research is supported by National High Technology Research Development Plan (863 Plan: 2015AA040102) and General Research Program of the Natural Science Foundation of Tianjin (13JCYBJC38600) .

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