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Design of collision detection algorithms and force feedback for a virtual reality training intervention operation system

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Abstract –**Minimally invasive surgery (MIS) is a specialized surgical technique, the minimally invasive surgery compared to traditional surgery, not only can reduce the patient's pain, more can make the patients recover more quickly. But because the minimally invasive surgery is very complex, so the doctors need a lot of training to guarantee the realization of the surgery. In previous studies, we have developed a virtual reality training system. Based on CT image reconstruction of 3-d vessel model, we designed a 3 d model of the catheter. In order to provide the surgeon to meet the need of training sense of touch, we studied the force feedback and the collision detection algorithm. We design a system that contains three kinds of force: force feedback viscous force, friction force and impact force. Catheter force and viscous force between blood; Friction between the catheters means the power of the body and blood vessels; Catheter tip is the collision force between force and vessel. Then we develop a fast collision detection algorithm based on AABB bounding box (Axis Aligned) method. In this way, we can reduce the collision detection time, training in real time. Finally, we designed a few columns based on Phantom a control experiment. We also the contact force between the catheter and the blood vessels do the detailed analysis, combined with local collision detection algorithm to calculate the contact force and feedback to the operator through the Phantom handles.**

Index Terms –Virtual Reality, Minimally Invasive Surgery (MIS), Force Feedback, Collision Detection

I. INTRODUCTION

Cardiovascular and cerebrovascular disease is the leading cause of death. In 2008, 30% of the world's death is caused by cardiovascular disease. Compared with traditional open surgery, minimally invasive vascular interventional treatment of disease of heart head blood-vessel has more advantages. In minimally invasive surgery (MIS), the surgeon by operating precision medical equipment to insert catheter within the patient's blood vessels, rather than by open surgery. Its biggest advantage is can reduce the pain of patients, and to shorten the length of time [1].

In the past few years, some products have been developed. One of the most popular products is a robotic catheter placement system called Sensei Robotic Catheter System offered by Hansen Medical. It provides the physician with more stability and more force in catheter placement compared to manual techniques[2]. Catheter Robotics Inc. has developed a remote catheter system called Amigo. This system has a robotic sheath to steer catheters which is controlled at a nearby work station [3]. Magnetecs Inc. has produced their Catheter Guidance Control and Imaging (CGCI) system. It has 4 large magnets placed around the table, with customized catheters containing magnets in the tip. The catheter is moved and controlled by magnetic fields [4].

However, these products have their own shortcomings. Most of them do not conform to the surgical operation and their customs requires a wide range of training for professional knowledge, the proper execution of intervention. Current training possibilities including lectures, field use telecom case demonstration, observation program of the room and practice in mechanical model, use live animals intern vessel training, training to use the body [5] [6].Some relative to the current selection of products, to provide a training is a big advantage: training can avoid exposure to radiation; In the simulation environment, provided a practical training related technical skills at the same time, avoid to cause more damage to patients. Because of that, developing the simulation training system has great practical significance.

Although the simulation training system has a great advantage, but because the blood vessels is very fragile, in neurosurgery operation within the blood vessels, catheter and the contact force between the vessels is extremely important. In order to provide force feedback to doctors in the process of simulation, we design a method based on AABB, contains three kinds of force (the force feedback viscous force, friction force and contact force) fast collision detection algorithm. We design the part of the collision detection algorithm means that we do not detect the collision of the model, we only test some parts of the model.

In this way, we can save computing time and realize real-time training.

II. EXISTING COLLISION DETECTION METHODS

In short, in terms of geometry, collision detection is a problem of intersection test between the two different objects in a virtual environment [9]. According to the space, it can be divided into 2 d plane collision detection and collision detection of the third dimension. The plane collision detection is relatively simple, there have been some mature detection algorithm, but the space collision detection is much more complex. In virtual reality system, the main problem we face is how to deal with the contradiction between the accuracy and real-time performance. People in different systems, the real-time and accuracy requirements are different. In virtual reality operation system, the real-time performance is more important.

A. Space Decomposition

Collision detection method based on space decomposition, we first of all, the whole virtual space is divided into small units (uniform or non-uniform), only the geometrical element to occupy the same or neighbor cells are submitted to the geometrical intersection test. This family of collision detection methods performs well when the distribution of objects in the whole virtual space is sparse and even.

As shown in Fig. 1-a，the uniform space decomposition method divides the virtual space, and the space contains all the units into a uniform grid with equal volume cells. Although it is easy to implement, but because of the need to detect area is relatively large, so the potential collision detection cell, tend to consume a long time.The non-uniform space decomposition method decomposes the space into a multi-resolution tree structure as the k-d tree, Octree, or BSP tree, and the adjacent cells can lie on different levels. Fig. 1-b is an Octree, and the method needs more time to construct the decomposing tree but it is more efficient to find the potential collision cells due to the small detection area.

B. Bounding Volume Hierarchy

Bounding volume hierarchy (BVH) is another popular category of collision detection techniques. It uses simple-shaped approximating geometries to substitute the original objects, and the intersection test is firstly carried out between bounding boxes. Only when the bounding boxes are overlapped, the object geometric elements contained by them are submitted to the geometric intersection test. Compared to space decomposition, BVH is much more effective in a dynamic virtual environment.

A bounding box for a set of objects is a closed volume that completely contains the union of the objects. Simple-shaped volume helps to improve the efficiency of geometrical operations. According to the shape of bounding volumes, it can be divided into Sphere, Axis-Aligned Bounding Boxes (AABB), Oriented Bounding Box (OBB) and Discrete Orientation PolyOne (k-DOP) and as shown in Fig. 2.

Amongst the four bounding volumes, AABB is the most commonly used due to its simplicity and compactness. Simplicity not only facilitates constructing or updating the bounding boxes of the objects, but reduces the time complexity of computing the overlapping between bounding boxes. Another important advantage of the method is that it can apply to collision detection of soft models.

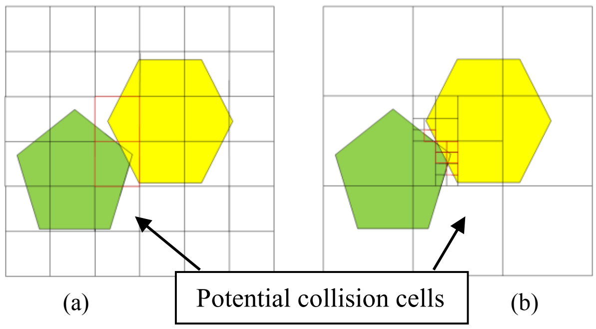


Fig.1 Uniform space decomposition method (a) and non-uniform space decomposition method (b), the red blocks are potential collision cells.

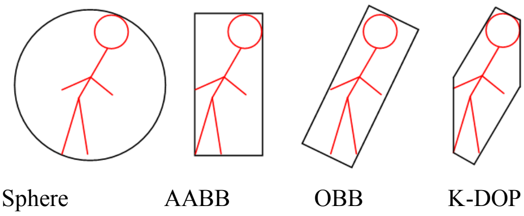


Fig.2 Four types of bounding volumes

III. IMPROVED COLLISION DETECTION ALGORITHM

As previously described, the AABB method is simple that can save computation time, in addition it can apply to soft models. Thus the collision detection algorithm we designed is based on AABB method.

Although the AABB method can save some computation time, it is hard to realize real time training if the model is too huge. And the vessel model is complex and branching, so it is time-consuming to detect the collision for the whole model. Thus we propose a fast partly collision detection algorithm as shown in Fig. 3 that just detect the collision of some key areas rather than the whole model.

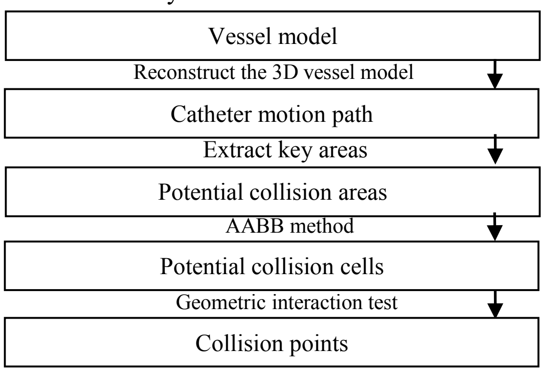


Fig.3 Reconstruction of 3D vessel model

In our previous research, we have reconstructed the 3D vessel model by CT images of a patient as shown in Fig. 4. By this model, we can get the information of the vessels as shown in Table. 1. Then we can use MATLAB to draw the centreline of the vessels as shown in Fig. 5 and the centreline is the similar motion path of the catheter, thus we can get the position of the catheter tip during the training.

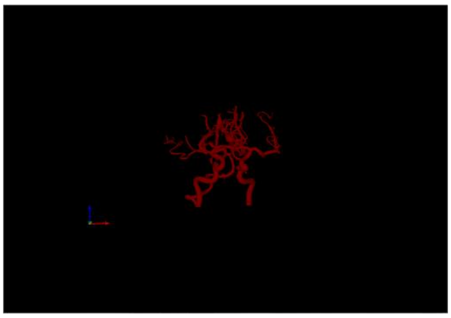


Fig.4 Reconstruction of 3D vessel model

Line	Point	X	Y	Z	R
1	1	86.346	121.446	2.25	2.144645
1	2	86.7679	121.446	2.520448	2.190143
1	3	87.1898	121.446	2.790895	2.154589
1	4	87.35913	121.446	3.199443	2.210748
1	5	87.77374	121.4223	3.465217	2.037205
1	6	88.09649	121.0995	3.672108	1.999683
1	7	88.22849	120.978	4.056728	2.195115
1	8	88.65039	120.978	4.327176	2.195115
1	9	88.686	120.978	4.808846	2.186951
1	10	88.98907	120.978	5.144271	2.09296
1	11	89.35058	120.7814	5.376009	2.15659
1	12	89.622	120.51	5.629694	2.244449
1	13	89.622	120.51	6.130833	2.102638
1	14	90.02776	120.51	6.410104	2.137772
1	15	90.36514	120.2349	6.626371	2.114259

Table.1 Position and radius of the vessel (Line means which vessel it is; Point stands for the points on the centreline of a vessel in order; X, Y, Z are coordinates of the point; R is the radius of the point).

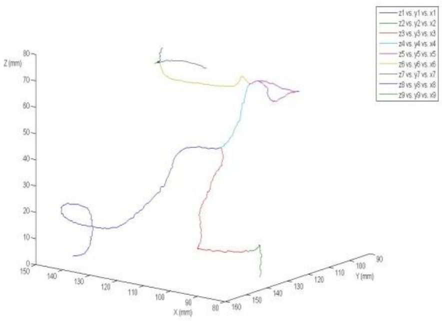


Fig.5 Centreline of 3D vessel model

The flowchart of the fast partly collision detection algorithm is shown in Fig. 6. In the algorithm, there are two important areas: Area I - the area around the catheter tip and Area II - the previous collision area. Area I is a dynamic area and it will change with the position of the catheter tip. Area II is some static areas but the amount of the areas is changeable.

As we know, the collision happens between the catheter and the vessels, thus there is no need to detect the collision of some areas if the catheter has not arrived. By the similar path of the catheter, we can get the position of the catheter tip, and then we just need to detect the collision from the catheter tip to the hatch of the vessel. In this area, the most important area is the area around the catheter tip (Area I), most collisions happen there and some of them are damaging to the vessel. Thus we need to keep getting the position of the catheter tip and detecting collision around the area as shown in the flowchart. Moreover we will detect the areas where a collision occurred previously (Area II). If a collision occurred in Area I, we will mark the collision point on the vessel and then we will keep detecting collision around the collision point until we delete the point.

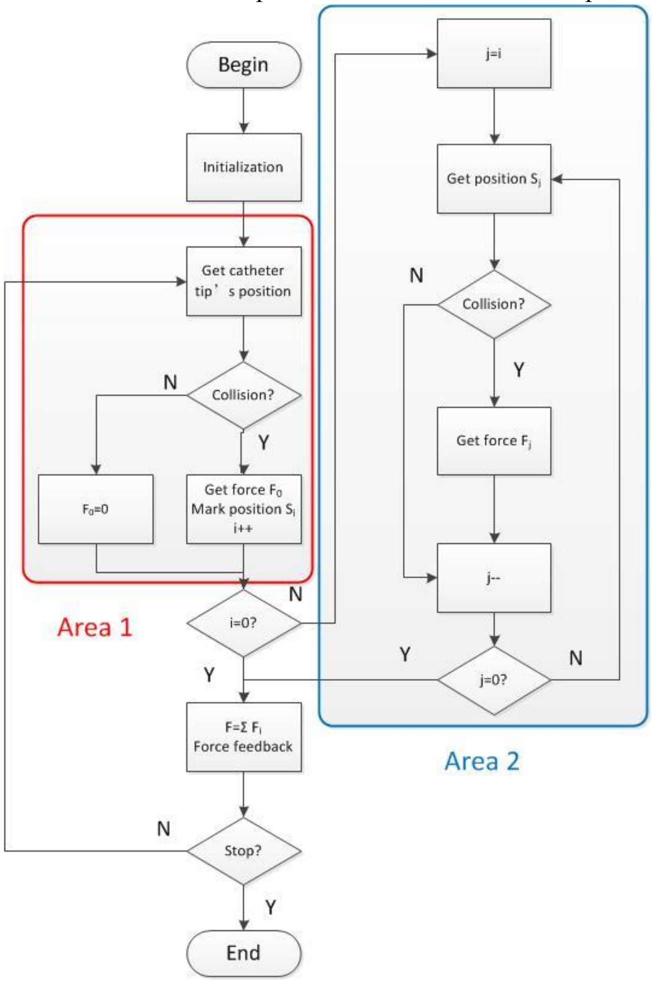


Fig.6 Flowchart of the fast partly collision detection algorithm

During the training, the surgeon push catheters, collision detection algorithm will detect collisions in region 1 and 2.When the surgeon pull catheter, the algorithm will only detect collisions in area 2.And if the catheter passes the marked collision point, the algorithm will delete the point and the amount of Area 2 will reduce. Then when the catheter pulls out of the vessel, the marked collision point will be all deleted and the amount of Area 2 will reduce to zero.

By using the collision detection algorithm in training system, we in the guarantee of potential collision cell at the same time to shorten the time required, after collection by adopting interactive tests to get the collision point.

V. Force Feedback Simulation Results

In order to testify our collision detection and force feedback, we used a haptic device Phantom Omni (as shown in Fig. 7) to control the catheter model and provide a force to the trainer.

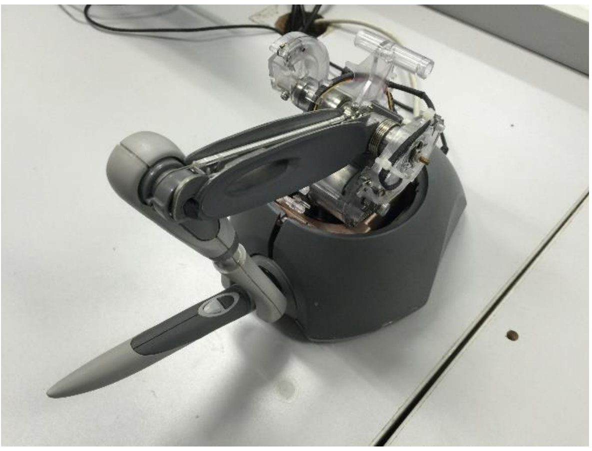


Fig.7 Sensable Phantom Omni

Due to the limit of the handle, we must design a switch. When the switch is on, the control information will be transmitted to the catheter model. And if the switch is off, the catheter model will keep its position. We designed two plans to control the catheter model to insert the vessel model. One plan used the change of handle's position to control and the other one used the handle's velocity.

Position control plan:

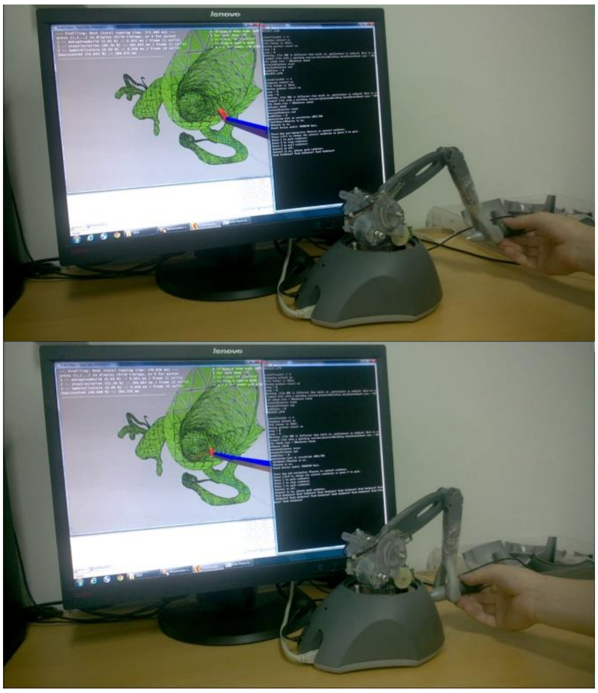
In this plan, computer will get a handle's position X1 when trainer turn on the switch and get a other position X2 when trainer turn off the switch. Then transmit the difference between the two positions to virtual environment to control catheter model.

Velocity control plan:

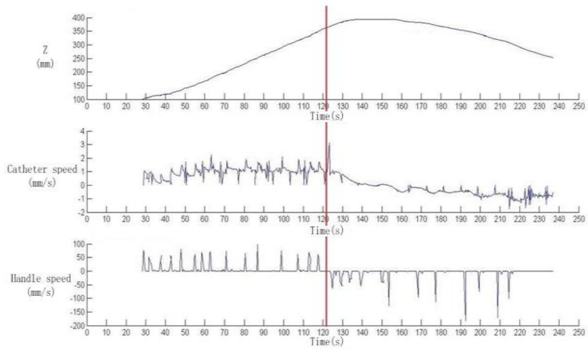
In this plan, computer will keep getting handle's velocity all the time and use the velocity information to control catheter model if the switch is on.

Position control plan is simpler than velocity control plan for the computer because it just needs two positions for once control. But position control plan is troublesome to trainer because it must turn on and turn off the switch every time. So in order to make our system more humane, we chose velocity control plan.

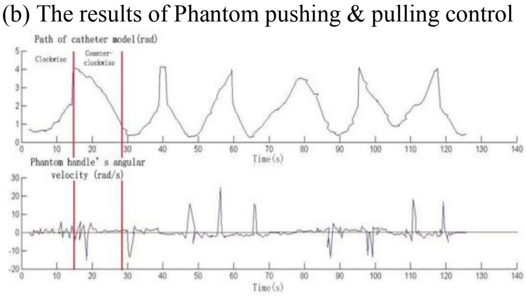
We designed a series of collision experiments between the catheter model and vessel model in virtual reality environment as shown in Fig. 9). The trainer operates the haptic device to control the catheter model to insert into the vessel model. And the catheter model can be subjected to two different sets of movement: insertion/retraction and rotation. Catheter will be manipulated to reach different parts of the blood vessels. And if the catheter collides with the vessels, the virtual reality system will get the collision information and send it to the haptic device, and then the haptic device will provide a force feedback to warn the trainer. Based on the force feedback and image information, the trainer decides to rotate or retract the catheter.



(a)Phantom control of pushing, pulling and rotating.



(b) The results of Phantom pushing & pulling control



(c) The results of Phantom Rotary control

Fig.8 The experiments of Phantom controlling and their results

The Fig.8 shows the Phantom control catheter model as the axial movement of the experimental data. In this experiment, we operate catheter alternately model made a clockwise and counter-clockwise. Can be seen from the diagram, when the Phantom handle rotation speed is positive, catheter model front do clockwise rotation, when the Phantom handle rotation speed negative, catheter model front-end counter-clockwise.

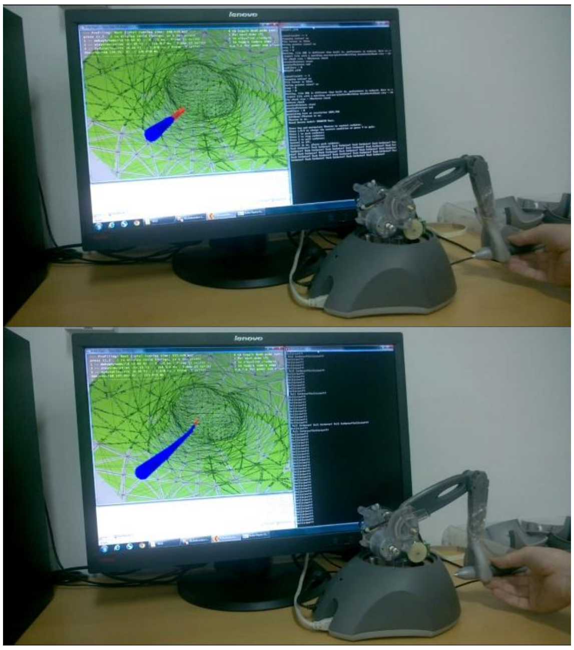


Fig.9 The experiments of collision test based on Phantom

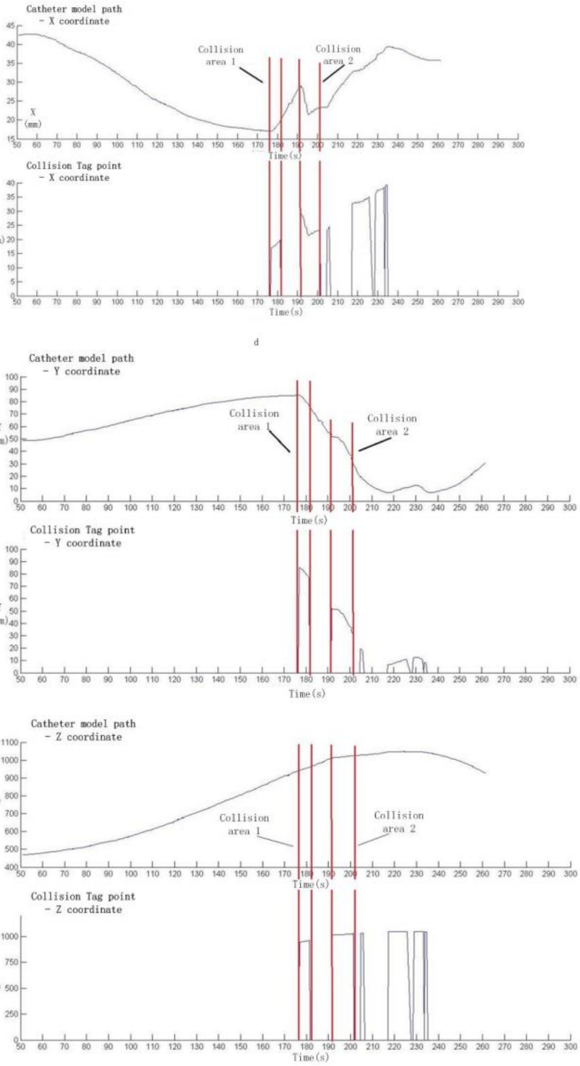
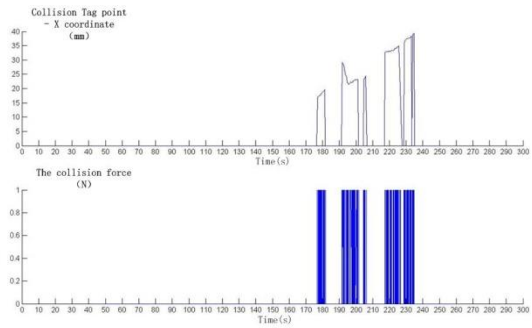
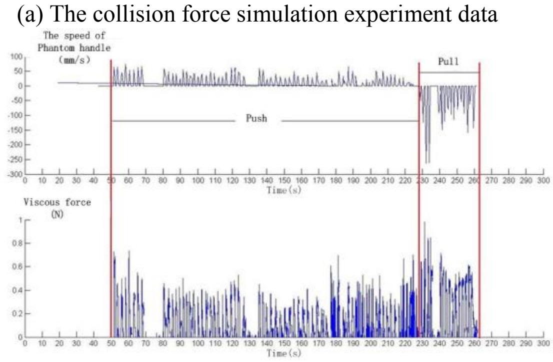


Fig.10 The results of the collision point extraction (In three dimensions X, Y and Z)

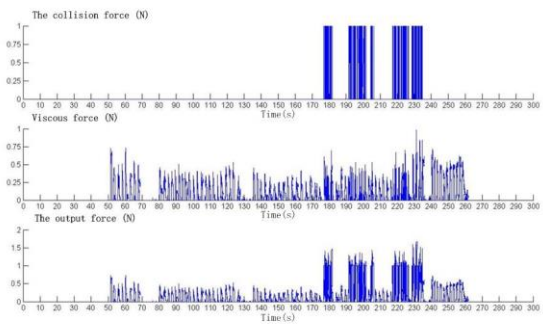
In this experiment we get the collision point coordinates of catheter path and extraction for comparing. In the collision zone 1 and collision zone 2, the catheter in the X axis direction changes a lot, which show that catheter front wall collision, leading to the force and the change in direction. From the Y direction, we can see if the direction catheter for big changes, only in the area 2 from stagnation, shows no collision in this direction. In Z direction, the catheter in the direction (the Z axis) sports ground to a halt, explain catheter front-end is blocked, and the impact is more dangerous.



(a) The collision force simulation experiment data



(a) The viscous force simulation experiment data



(c) Total output force simulation experiment data

Fig.11 The results of tactile feedback experiment

Finally, we carried out force feedback experiments. Collision force aspect, catheter model collision moment and the output in the Phantom collision force are basically identical. Viscous force, whether catheter forward or backward, viscous force is same as the catheter model velocity change trend. Finally the collision force and viscous force superposition get total output force feedback to the operator.

VI. CONCLUSIONS

In this article, we designed and implemented a virtual reality training system, the system USES a fast collision detection algorithm based on AABB method. In collision detection algorithm, there are two key areas: the area and the area around 1 - catheter tip 2 - before the collision zone. Area 1 is a dynamic area, the area with the changes and the location of the catheter tip. Area 2 is the number of some static area change. By the collision algorithm, we guarantee at the same time to test the collision point, shorten the time required.

In order to provide the surgeon touch, we design a fast collision detection algorithm, and the algorithm contains three kinds of force: force feedback viscous force, friction force and impact force. Catheter force and viscous force between blood; Friction between the catheter means the power of the body and blood vessels; Catheter tip is the collision force between force and vessel.

By the new collision detection algorithm and force feedback, virtual reality training system is more realistic and will be more helpful to the surgeon to obtain the expertise quickly.

The force feedback module designed in this chapter is the Phantom force feedback devices, through the Phantom transfer operator intubation operation information to the virtual environment, in order to realize the control of duct model. In this chapter for catheter axial and rotational control respectively designed two kinds of control scheme, and choose suitable for the solution of this system, after comparing the speed control. In addition, this chapter of the catheter and the contact force between blood vessels to make the detailed analysis, and design the related calculation formula, the local collision detection algorithm of the fourth chapter calculates the catheter model and the contact force between the vascular model and feedback to the operator through the Phantom handles.

In the future work, we will add proportion to collision detection areas - Area II to make the collision detection more quickly and effective.

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