

A Novel Path Planning Algorithm for the Vascular Interventional Surgical Robotic Doctor Training System

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Abstract - Cerebrovascular disease is a serious threat to people's health. Because of its small trauma, quick recovery and good effect, vascular interventional surgery is widely used. Through the use of VR (virtual reality) technology of vascular interventional surgery doctor training system, people can perform surgery simulation, which can improve the doctor's ability to operate surgery. Aiming at path planning problem of the cerebral vascular interventional surgery, this paper proposed a fast path planning algorithm. Firstly, the algorithm projects all obstacles in virtual scene onto the projection matrix of the scene, which uses different color values to express, then gets its surrounded around the barrier route, on the basis, obtains local obstacle avoidance path, generates the basic path, uses algorithm 2 to optimize, and obtains an optimal path planning from the initial point to end point. Finally, we conducted a verification experiment, obtained the error histogram between the real path and the path. The average error is 0.3 mm, due to operation error, the error will be further decreased, which conforms the need of the cerebral vascular interventional surgery.

Index Terms - Mimics, VR, Unity 3D, Path planning, Obstacle avoidance

I. INTRODUCTION

Minimally invasive vascular interventional surgery is that a doctor by catheterization patient's blood vessels, control its forward backward and rotating in the blood vessels, which implement the treatment of related diseases. Compared with traditional surgery, because of its small hurt, less pain and quick recovery, minimally invasive vascular interventional surgery can significantly reduce the pain of patients, so it has been widely used. Although people demand for minimally invasive vascular interventional surgery have been a continual growth, but at present, there are some drawbacks, which seriously restrict the minimally invasive vascular interventional surgery in the widely used and effective treatment. First of all, the doctor in the operating process will be exposed to radiation environment, which damages the doctor's health. Secondly, operation time is long, which is a huge test for the doctor's energy and physical strength. Finally, the cerebrovascular intervention operation requires a high claim of operational capability of the doctor, if the doctor generates improper operation; it will lead to a perforation, massive loss of blood, cause a variety of complications, and its serious consequences. The development of virtual surgery simulation system can greatly save training time and expense,

and help to cultivate novices to become technical qualified doctors.

With the progress of medical technology, the study of cerebral vascular interventional surgery robot makes great progress. At the beginning of the 21st century, Siemens has developed a new multiaxial Omni-directional robot angiography and treatment system---Artis zeego system. The robot system provided a better way which designed for the doctor's surgery, before and after surgery and operation optimization of path planning. In 2009, for the first time, the Mongolia Monash University in Australia applied the "automatic wave (auto wave)" technology to the organization in the study of deformation [1][2][3]. They use automatic wave propagation to simulate the deformation of corresponding organization; this greatly solves the organization large deformation problems. After years of research, shu-xiang guo, Kagawa University professor, Japan, designed a catheter control system that can realize the force feedback function, and the doctor used the master side of the operating device to drive the movement of the slave side device, so as to realize vascular interventional surgery [6]. In 2010, Fu Yili, Harbin Institute of Technology, developed the simulation training simulation system that satisfy the needs of the cerebrovascular intervention operation [7]. The simulation training system successful realized the catheter and blood vessel collision detection and mechanics analysis.

However, there are also some disadvantages of these systems [4][8][9][10]. Most of the devices 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 for the novice. Training methods include practicing on mechanical models, and using live animals and cadavers for training [11]. 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 [5][12][13]. Hence, developing virtual reality training system for vascular intervention surgery is crucial to us [14]-[17].

This article uses Unity 3d as the carrier of virtual environment. The master side of cerebrovascular intervention operation system and virtual environment uses RS232 interface to realize the data transmission. Operators operate the master side to realize the accompany movement of catheter

in virtual environment, realize visualization training environment, and realize the human-computer interaction. The specific contents of the study are as follows:

1) By human cerebral CTA data imported to the Mimics, we got 3-D reconstruction model of cerebrovascular, and gave its physical properties, then we imported it into the Unity 3d, and built a virtual operation environment.

2) We analyzed the 3-D reconstruction model of cerebrovascular. In order to realize the data transmission, we wrote the interface program of the master side and the virtual environment.

3) Based on the above work, we realized the path planning of catheter in the blood vessels, and made the catheter movement in setting the path.

This paper is organized as follows. Section II shows the whole system structure. Section III describes the establishment of the virtual environment. Section IV shows catheter path planning algorithm. Section V shows the result of the experiment. Section VI describes concludes the paper and our further directions.

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. The figure 1 is the overall structure of the system.

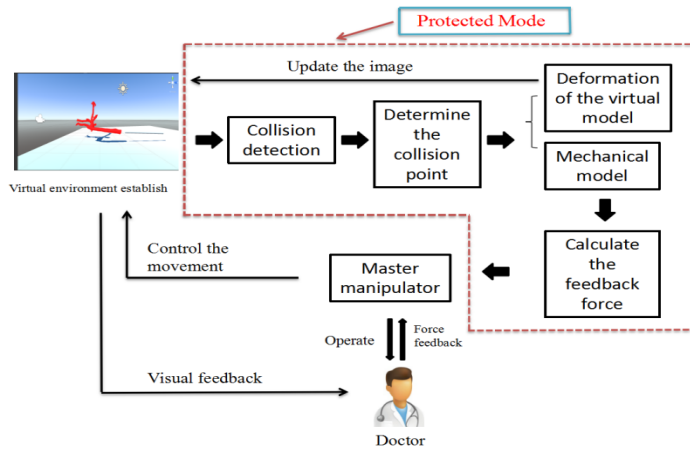


Fig1. The overall structure of the system

Assisted vascular interventional system has master and slave sides [18]-[20]. Doctor has an operation in the master side; the master controller collects the operation information and gives 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 side 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.

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. After setting the motion path of catheter, when we operate catheter in master side of training system, the

catheter in virtual environment will do following motion in real-time, which can achieve the purpose of training.

III. THE ESTABLISHMENT OF THE VIRTUAL ENVIRONMENT

A. Establishment of three dimensional model of cerebral vessels

What the Belgian Materialise company developed 3-D interactive digital medical imaging control system, namely Mimics, is software that can set of highly integrated and easy to use 3-d image generation, editing and processing software. This paper selected the brain as the research object. The figure 2 is CT angiography original figure. We bring the CTA data of brain into the Mimics, use its internal own threshold segmentation, in turn the mask editor and regional growth to operate, which serves as the CT image preprocessing, and then conducted 3-D reconstruction of cerebrovascular on the basis of shear deformation method. Finally through 3-D images of the regeneration of translation, scaling, we can accurately get cerebrovascular images. The figure 3 is after treatment of cerebrovascular

B. Model import

We brought the cerebrovascular model from Mimics into Maya, cut, reduced grid and finally got a cerebrovascular model that we needed. The figure 4 shows the rendering results. We brought the model that we have managed into the Unity 3D, joined the catheter in the virtual environment, and prepared the way for subsequent processing. The figure 5 is the interface that brought the cerebrovascular model into the Unity 3D.

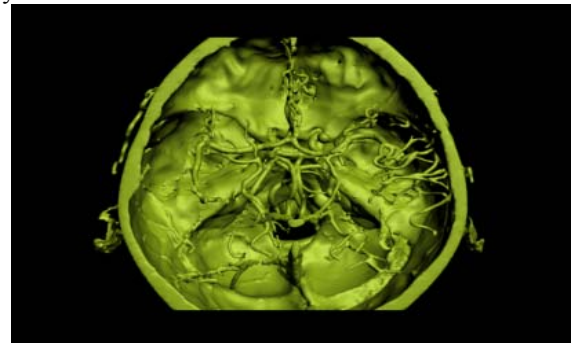


Fig2. CT angiography original figure

C. Protection module

In order to make the training more safe and reliable, we set the protection module, when the force feedback is more than the set value, the device will warn, and remind trainer to stop the operation.

1) Collision Detection

This module involves collision of the catheter and blood vessel in the virtual environment. When it occurs to collision, the place will appear the feedback force. Because the blood vessel is a soft model, it will occur soft tissue deformation. Considering all the factors, this study adopts the collision detection method based on AABB bounding box. It is suitable for dealing with the collision problem of complex scenes with a large number of objects, and the calculation is relatively simple. The method can satisfy the requirements of the soft

tissue deformation and the real-time performance of the force feedback.



Fig3. After treatment of cerebrovascular

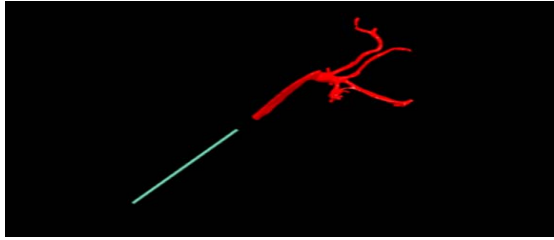


Fig4. The rendering results

The collision detection algorithm can be divided into two stages: the first stage is the global search phase, that is, the first step is that the algorithm excludes the obvious disjoint objects; The second stage is the local detection phase, that is, after the global search for the possible intersection of the object for further detection. The local detection stage can be divided into two layers, namely, the gradual refinement layer and the exact intersection layer. Firstly, the algorithm traverses the hierarchical bounding box tree of the object, and detects whether the nodes intersect with each other until the leaf nodes of the bounding box tree; Then, the intersection of the objects surrounded by the bounding box of the leaf nodes is precisely detected, and the collision point is determined. The exact intersection detection of the basic voxel is completed exactly.

2) Calculation of force feedback model

When the catheter motions in the blood vessel, it will produce force includes resistance of blood flow, and contact force. The contact force can be divided into two types, one is elastic that it occurs to the catheter along the surface normal direction, another is the friction between the contact surfaces and the front end of the catheter, and the two kinds of force form together the contact force by the catheter. According to the corresponding theorem and the model, the calculation formula as shown in formula 1.

$$\begin{aligned} F_{\text{feedback force}} &= f + F_{\text{collision}} + F_{\text{friction}} \\ &= \pi(R^2 - r^2) * \eta * v * l + E * \\ &\quad S * \frac{\Delta X}{X} + C_n + \text{sgn}(v) \end{aligned} \quad (1)$$

In the above formula R is the tube diameter, r is the inner diameter, v is velocity of the catheter movement, and l is the length of catheter inserted into the blood.

IV PATH PLANNING ALGORITHM OF CATHETER

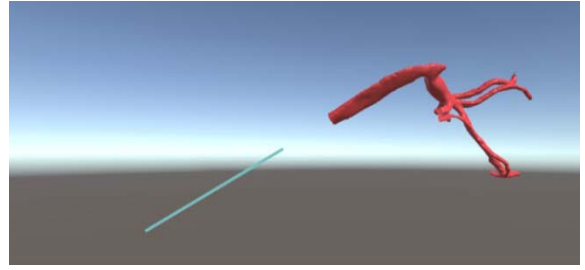


Fig5. The interface that brought the cerebrovascular model into the Unity 3D

A. Algorithm thought

In normal circumstances, when we encounter obstacles, we will attempt to bypass obstacles, and walk in the direction of the destination. In the 3D virtual scene, the projection map of 3D virtual scene is organized in the form of regular matrix grid, and we projected an obstacle that cannot be traversed in the scene onto the 2D plane. Moreover, in order to distinguish the different obstacles in the 3D scene, we fill each obstacle in the image with different color values. As shown the green line in figure 6 (a). In fact, if there is no obstacle on the vision, activists will choose walking routes of close around obstructions, as shown the green line in figure 6 (b), and according to this idea, path planning algorithm is proposed.

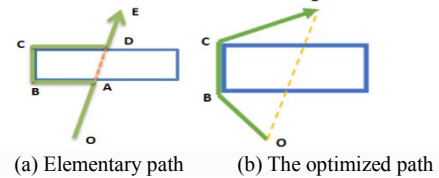


Fig6. Algorithm idea sketch

B. Algorithm design

In order to implement the algorithm, firstly, the algorithm projects all obstacles in virtual scene onto the projection matrix of the scene, which uses different color values to express, then gets its surrounded around the barrier route. The following algorithm consists of two parts: the algorithm generates the basic path and stores in the basic path list, and then we get the path planning with the proposed algorithm.

1) Generating of surrounded by line barrier route

The route of the obstacle is a circle around the obstacle which is stored in the form of a circular list. A boundary point is a node with at least one neighbouring element representing an obstacle. As shown the green loop in figure 7.



Fig7. Line barrier bounding box sketch

The Line barrier bounding box can be scanned by scanning the scene projection matrix, when finished; the surround path is stored in the form of a cyclic chained table according to the color value. Thus, if there is a predetermined route traversing the obstacle, the corresponding barrier surround route can be found by scanning the color values obtained, then by the in

and out of the two points across the barrier area in circularly linked list, and in circularly linked list, the algorithm finds two initial paths around the obstacle, selecting one of them as the initial path around the barrier.

2) Generating the basic path

The main task of the basic path generation algorithm is that find a basic path around the barrier in the scene projection matrix. As shown in figure 8, the line is O->A->B->C->D->E.

The basic ideas are that draw a straight line between the starting point to destination, along the straight line from the beginning of the starting point, point by point to read the value of the corresponding points in the scene projection matrix; if the object is obstacles, the algorithm finds two boundary point through the obstacles, according to the colour value from the circulation link the local path, read around the obstacles in the table, and put it into the path list; if the object is not an obstacle, the algorithm do not make processing, read the next point and continue; if it is a destination, the algorithm end. Algorithm 2 is shown below.

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- Step 1: Read the starting point O, end point E, and the starting point O is added to the end of PL that the initial path list is empty
 - Step 2: Along a straight line O - E in the projection matrix of the scene to read the next node, if the point is not the end point E, turn to step 3; otherwise, turn to step 5.
 - Step 3: To detect the node values, if is 0, turn to step 2.
 - Step 4: If it is the barrier, find out two boundary points through the obstacles (as shown in figure A、D), according to the colour value, Read local path around the obstacles from the circulation link, added it into the path list PL.
 - Step 5: Add the end point P to the end of the path list PL, algorithm end.
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3) Path planning algorithm

According to the above method, we presented a simplified algorithm. The basic idea is that the basic path has been generated in OABCDE 4.2.2, ABCD is a local path composed of pixels, the algorithm will stretch OA along the A->B, when encounter another obstacle point, SF enter into the path list PL, start from the F point along the E->B stretch, so processing, until arrive T points, algorithm end. Algorithm 2 is as follows.

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- Step 1: Read the first two nodes of the path list PL, the former node is the front, the middle node is the mid, if the mid is the end point the end, algorithm end, turn to step 6;
 - Step 2: Read the next node of the path list PL, if the node is the end point the end, algorithm end, turn to step 6; otherwise the node assigned to back;
 - Step 3: If the mid is located between the front and the back, in the path list PL delete the mid, the value of the back assigned to the mid, turn to step 2;
 - Step 4: If the mid is not between the front and the back, and there is no obstacle between the front and the back,

then the path list PL delete mid, the value of the back assigned to the mid, turn to step 2;

- Step 5: If the mid is between the front and the back, and there is obstacle between front and back, the boundary points of the obstacles are added to the front and the mid of the corresponding path list PL, and the boundary value is assigned to the front, turn to step 2
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Our approach is based on quasi-static mechanics in order to ensure a realistic modeling of guidewire propagation. When changing the location of the catheter, we proposed a dynamic adaptive adjustment strategy to deal with a large radius of curvature and small blood vessels. We joined the protection mechanism in the process of the advance of the catheter. When a collision occurs in the walls of blood vessels and the Catheter, it will produce the collision force, the interface of virtual environment that we established will show the size of the force, when the force reaches the critical value set, the master side operation of catheter trainer will stop push , which will play a protective effect. In the process of simulation, the local coordinates will be attached to the catheter up local displacement calculation; main steps of one simulation loop in our approach are summarized in Algorithm3.

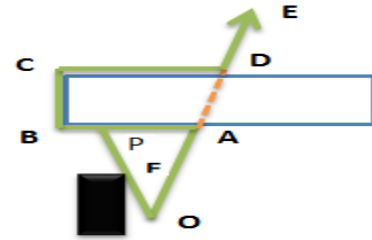


Fig8. Algorithm diagram

Algorithm 3: Guide simulation

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- Import the vascular model
 - Initialize guide
 - Preprocess
 - While simulating do
 - Step 1: Wait for control signal
 - Step 2: Update position
 - Step 3: Update local coordinates
 - Step 4: Collision detection and force feedback
 - When the force exceeds the critical value, stop the operation
 - Step 5: Update positions
 - End while
-

V. EXPERIMENTS AND RESULTS

A. Master-slave interventional vascular surgery system

The master side operator in this topic mainly includes a highly adjustable floor, the solid shaft incremental photoelectric encoder, photoelectric encoder hollow shaft, permanent magnets, support, guide rail, bearing, coil and photoelectric encoder mounting plate. We can adjust the height of the master side operator by adjusting the bottom.

The catheter has two parts, the first half is fixed with roll, and the other half is fixed with the inside of the hollow shaft encoder shaft, which is connected with bearing. When the

catheters rotates, it can drive the hollow shaft encoder rotate together, and because the slide used in the system is Japan's ball type slide rail, the frictional force is very small, so it can be ignored. As shown in figure 9. Two guide rails are used for fixed catheter, and their role is that they can avoid the catheter produce error because of the improper operation. When have an operation, locomotive catheter will drive the solid shaft photoelectric encoder to do follow movement, and then the orthogonal decoding unit can display the digital of the specific distance of the locomotive catheter. However, as long as the doctor rotates the second part of the catheter, the hollow shaft encoder will display rotation Angle. This system uses the electromagnetic induction as a force feedback device, and can avoid the error of inertia at the same time; the influence of MRF on friction is avoided.

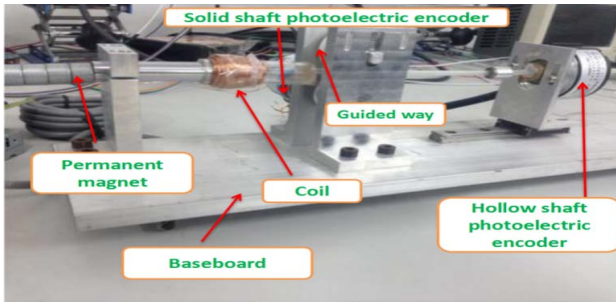


Fig9. The master manipulator

The hardware of the system are composed of computer and interactive devices, interactive devices is the force feedback devices, which is connected to the operator, and the key equipment of the virtual environment has input and output function. We used Windows 10 as the operating system in the virtual surgery system of this research, the cerebral CTA data was imported to the Mimics, which would deal with these CTA data, and when the 3D model was optimized by Maya and then imported into Unity 3D. Finally, we set the path planning algorithm to realize the path planning of the catheter.

B. the verification experiment between the actual motion path of the catheter and planning path

In this training system, the movement of the virtual catheter includes the axial forward and backward movement, and the figure 12 is the corresponding three dimensional figure of between the actual motion path of the catheter and planning path. The blue line is the path planning, and the red line is the actual path. In this experiment, we first recorded a number at the initial end, after catheter to forward motion, when perform an operation, the doctor operates appropriate surgery by catheter for forward, backward and rotating. In this paper, firstly, we set the path planning of catheter through the algorithm to make the catheter along the set path movement; secondly, we designed the verification experiment between the actual motion path of the catheter and planning path to verify the actual effect of the path planning of the catheter; finally, we analyzed the error between the actual motion path of the catheter and planning path and the results show in figure 13. The figure 11 is the whole structure of the training system.

We can see in three-dimensional figure, as time goes by, the curve is extended, when get to the last dot, reach destination, after catheter for backward movement, return to

the original position. Because the path is the path of the program, the curves of the forward and backward movement overlap. In this process, the displacement of measured values was measured by photoelectric encoder in master side. The point of actual path is obtained by Unity 3D, and we used these points to reconstruct the actual path. The data of virtual terminal is measured by Unity 3D. Red line represents the actual path of the master side operation, and the blue line represents the path planning. So we can see from the picture 12, the curve of the actual path is consistent with the curve of the path planning.

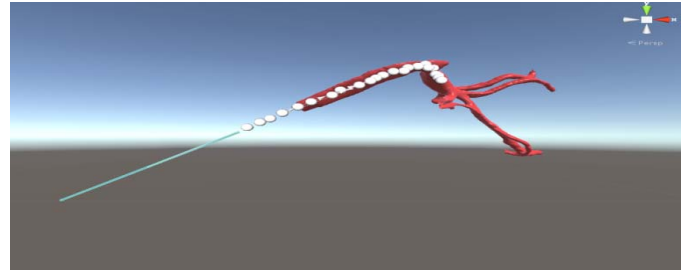


Fig10. Path planning display

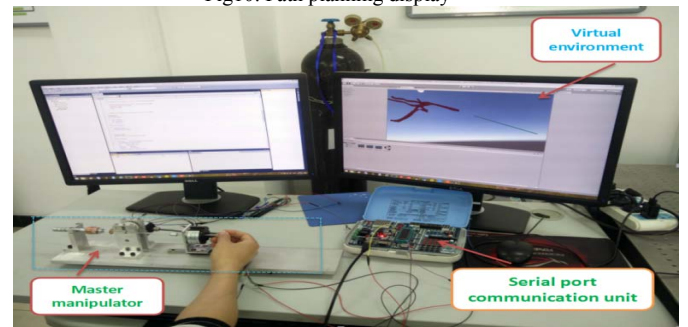


Fig11. The whole structure of the training system

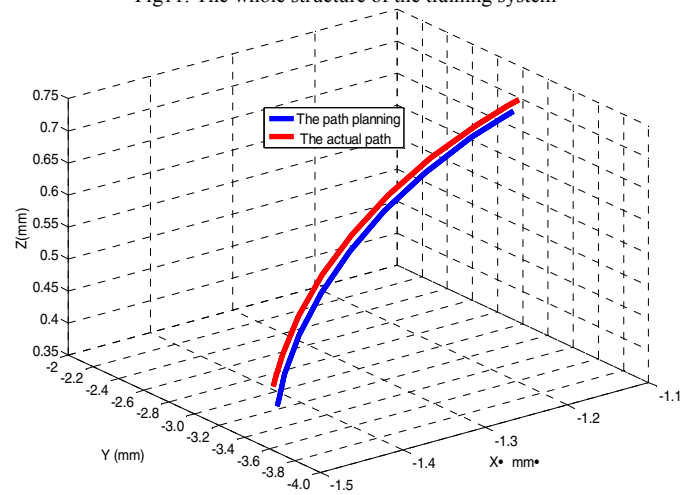


Fig12. The curves of the actual path and the path planning

After the experiment was accomplished, we concreted analyzed three-dimensional figure of between the actual motion path of the catheter and planning path. As shown in Figure 13. We can see from histogram that the maximum error is 1 mm, the average error is about 0.3 mm, and in the process of experiment, due to accidental factors, so there will appear error. After the doctor train many times, as the doctor operation proficiency in ascension, the corresponding error

can be further reduced, which conforms the needs of the vascular interventional surgery.

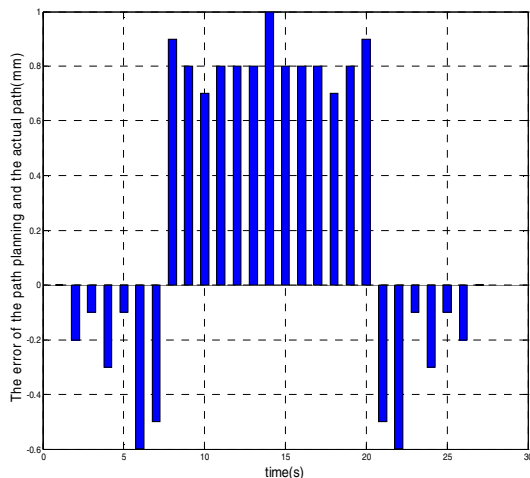


Fig13. The error histogram of the path planning and the actual path

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a novel path planning algorithm for the vascular interventional surgical robotic doctor training system. We brought the CTA data of brain into the Mimics, used its internal own threshold segmentation, in turn the mask editor and regional growth to operate, which served as the CT image preprocessing, conducted 3-D reconstruction of cerebrovascular, we used Maya to deal with the 3-D model, imported it into Unity 3D to conduct path planning, and aiming at path planning problem of the cerebral vascular interventional surgery, we proposed a path planning algorithm based on scene projection matrix. The algorithm makes full use of known environment information completely, obtains encircling route of around the barrier route by pre-treatment, on the basis, obtains local obstacle avoidance path, uses algorithm 2 to optimize. In order to test the effect of path planning, we conducted a verification experiment, obtained the error histogram between the real path and the path planning. The maximum error is 1mm and the average error is 0.3mm. Due to operation error, the error will be further decreased, the training system conforms the needs of the cerebral vascular interventional surgery.

In the future work, we will optimize the operation function, and improve the precision of the training system.

ACKNOWLEDGMENT

This research is supported by National High Technology Research Development Plan (863 Plan: 2015AA043202) Tianjin Key Laboratory for Control Theory and Application in Complicated Systems (TJKL-CTACS-201701).

REFERENCES

[1] Peterlík I, Sedef M, Basdogan C, et al. Cagatay basdogan real-time visio-haptic interaction with static soft tissue models having geometric and material nonlinearity[J]. *Computers & Graphics*. 2010, 34(6):43~54.

[2] F. Tendick, M. Downes, T. Goktekin, et al. "A Virtual Environment Bed for Training Laparoscopic Surgical Skills," *Presence: Tele-operators and Virtual Environments*, vol. 9, no.3, pp. 236-255, 2000.

[3] S. Hassan and J. Yoon, "Haptic assisted aircraft optimal assembly path planning scheme based on swarming and artificial potential field approach," *Adv. Eng. Softw.*, vol. 69, pp. 18-25, 2014.

[4] S. Y. Nakajima, T. Nozaki, and K. Ohnishi, "Heartbeat synchronization with haptic feedback for telesurgical robot," *IEEE Trans. Ind. Electron.*, vol. 61, no. 7, pp. 3753 - 3764, Jul. 2014.

[5] H. Kodama, C. Shi, M. Kojima, S. Ikeda, F. Arai, I. Takahashi, and T. Fukuda, "Catheter manipulation training system based on quantitative measurement of catheter insertion and rotation," *Adv. Robot.*, vol. 28, no. 19, pp. 1321-1328, 2014.

[6] J. Guo, S. Guo, N. Xiao, X. Ma, S. Yoshida, T. Tamiya and M. Kawanishi, A Novel Robotic Catheter System with Force and Visual Feedback for Vascular Interventional Surgery[J]. *International Journal of Mechatronics and Automation*, 2012, 2(1). 15~24.

[7] Ai Y, Pan B, Fu Y, et al. Design and development of simulation system for minimally invasive surgery robot[C]// *IEEE International Conference on Information and Automation*. IEEE, 2014:825-829.

[8] Jin Guo, Shuxiang Guo, Nan Xiao, and Baofeng Gao, "Virtual Reality Simulators based on a Novel Robotic Catheter Operating system for Training in Minimally Invasive Surgery", *Journal of Robotics and Mechatronics*, vol. 24, no. 4, pp. 649-655, 2012.

[9] Jin Guo, Shuxiang Guo, Nan Xiao, Thomas Deuteuille, "A VR-based Training System for Vascular Interventional Surgery," *Proceedings of 2013 ICME International Conference on Complex Medical Engineering (ICME CME 2013)*, pp.575-579, May. 25-28, Beijing, China, 2013.

[10] Jin Guo, Shuxiang Guo, Nan Xiao, Baofeng Gao, Xu Ma and Mohan Qu, "A Method of Decreasing Time Delay for A Tele-surgery System", *Proceedings of 2012 IEEE International Conference on Mechatronics and Automation*, pp.1191-1195, August 5-8, Chengdu, China, 2012.

[11] H. Kodama, C. Shi, M. Kojima, S. Ikeda, F. Arai, I. Takahashi, and T. Fukuda, "Catheter manipulation training system based on quantitative measurement of catheter insertion and rotation," *Adv. Robot.*, vol. 28, no. 19, pp. 1321-1328, 2014.

[12] N. Xiao, J. Guo, S. Guo and T. Tamiya, "A Robotic Catheter System with Real-time Force Feedback and Monitor," *Journal of Australasian Physical and Engineering Sciences in Medicine*. (In press), 2012.

[13] T. Tsujita, K. Sase, A. Konno, M. Nakayama, X. Chen, K. Abe, and M. Uchiyama, "Design and evaluation of an encountered-type haptic interface using MR fluid for surgical simulators," *Adv. Robot*, vol. 27, no. 7, pp. 7525-540, 2013.

[14] Y. C. Wu, J. S. Chen, "Toward the identification of EMG-signal and its bio-feedback application," *International Journal of Mechatronics and Automation*, vol. 1, no.2, pp.112-120, 2011.

[15] S. Guo, M. Qu, B. Gao, J. Guo, "Deformation of the Catheter and 3D Blood Vessel Model for a VR-based Catheter System", *Proceedings of 2013 IEEE International Conference on Mechatronics and Automation*, pp.861-866, August 4-7, Takamatsu, Japan, 2013.

[16] P. Chiang, Y. Cai, K. H. Mak, E. M. Soc, C. K. Chui, and J. Zheng, "A geometric approach to the modeling of the catheter-heart interaction for VR simulation of intra-cardiac intervention," *Computers & Graphics*, vol.35, no 5, pp. 1013-1022, October 2011.

[17] Yu Wang, Shuxiang Guo, Baofeng Gao, "Vascular Elasticity Determined Mass-spring Model for Virtual Reality Simulators," *International Journal of Mechatronics and Automation*, vol.5, no.1, pp1-10, 2015.

[18] X. Wang, M. Meng, "Perspective of Active Capsule Endoscope: Actuation and Localization," *International Journal of Mechatronics and Automation*, vol.1, no.1, pp. 38-45, 2011.

[19] Q. Pan, S. Guo, and T. Okada, "A Novel Hybrid Wireless Microrobot," *International Journal of Mechatronics and Automation*, vol.1, no.1, pp. 60-69, 2011.

[20] J. Guo, S. Guo, P. Wang, W. Wei and Y. Wang, "A Novel Type of Catheter Sidewall Tactile Sensor Array for Vascular Interventional Surgery," *Proceedings of the 2013 ICME International Conference on Complex Medical Engineering*, pp. 264-267, 2013.