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A Training System for Vascular Interventional Surgeons based on Local Path Planning

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***Abstract*-Because the internal environment of the blood vessels in the brain is complex, and the cerebrovascular itself is very fragile, the catheter and guide wire are easy to puncture the cerebrovascular in the process of cerebrovascular interventional surgery, which brings great harm to patients. In order to reduce the number of collisions between catheter and guide wire with vascular wall and improve the safety of surgery. This paper proposes a local dynamic path planning based physician training system for vascular interventional surgery. The system uses the improved rapidly-exploring random tree (RRT) algorithm to plan the real-time local path of the catheter guide wire in the vascular interventional surgeon training system. Experimental results show that the algorithm has fast convergence speed and makes the planned path closer to the optimal path.**

Index Terms -Local path planning, Improve safety, Improve RRT algorithm, Optimal path

I. INTRODUCTION

Due to the development of society, people's life is speeding up and they are often living in unhealthy lifestyles, so the prevalence of cardiovascular and cerebrovascular diseases has been on the rise, which has seriously affected human health. Usually, the methods for treating cardiovascular and cerebrovascular diseases include drug therapy, traditional surgical treatment and vascular interventional surgery. Vascular interventional surgical treatment method is to use modern high-tech medical imaging means to obtain the image of the tissue at the lesion, and under the guidance of vascular interventional surgical instruments such as guide wires and catheters, to achieve the specified clinical diagnosis of the lesion along the blood vessels. Vascular intervention surgery has the advantages of small trauma, less blood loss, rapid recovery, less pain, high reliability, so it is more and more loved by people. However, doctors are exposed to X-ray radiation for a long time, which has great impact on their health. Moreover, the operation is difficult and the learning cycle is long. With the development of artificial intelligence technology and robotics technology, more and more people are investing in the research and development of vascular interventional surgery robots. The vascular interventional surgical robot can protect the doctor from X-ray radiation, improve the efficiency of the operation and the safety of the operation.

Because the cranial nerve blood vessel is narrow and curved and is very fragile, and the environment for cranial nerve intervention is complex, the catheter guidewire is very easy to puncture the blood vessel during the intervention process, resulting in intracranial hemorrhage for patients, which brings great risks to the cranial nerve intervention surgery. Generally speaking, the robot for vascular interventional surgery plans an optimal path from the surgical approach to the lesion position before the doctor's operation, which can greatly reduce the collision between the catheter guide wire and the blood vessel wall, shorten the operation time and greatly improve the safety of the operation. In the system of our laboratory research, the boundary of the blood vessel is regarded as an impenetrable obstacle, which is projected onto a two-dimensional plane in the form of a regular matrix grid, and then each obstacle and their relationship are distinguished by color values. The algorithm can make reasonable path planning for objects in virtual environment [1]. However, during the training of doctors, there are many factors that lead to the failure of the catheter guide wire to move along the original global path, and when the trajectory of the catheter guide wire is offset, the risk of puncturing the blood vessel is increased. Therefore, it is very necessary to add local dynamic path planning into the training system of vascular interventional surgeons. In order to solve the real-time problem of local dynamic path planning, the function of trajectory prediction is added to the system [2]. Trajectory prediction can predict the trajectory of the catheter guide wire at the next moment in advance, and when the predicted trajectory is abnormal, local path planning is initiated in advance.

Mentice of Sweden developed a training system for vascular interventional surgeons named Mentice VSIT in 2006 and upgraded the system from 2009 to 2012. The system uses the same surgical instruments as the real interventional surgery to simulate the interventional operation process, and uses the force feedback technology, which greatly improves the authenticity and effectiveness of the training system for vascular interventional surgeons [12]. In 2007, Simbionics Inc. of the United States developed the ANGIO Mentor system [13]. The system can select stents of appropriate size and specification according to the lesion position of patients. The team of Shanghai Jiaotong University designed an integrated vascular intervention surgery simulator with force feedback function [14].

In order to satisfy the needs of medical training, an auxiliary intervention simulation module was added in the simulator. Beijing Institute of Technology has developed a training system for vascular interventional surgery based on nonlinear force feedback. This training system aims to use virtual reality technology to help doctors and trainees master the skills of vascular interventional surgery quickly, efficiently and at low cost.

Dynamic local path planning can greatly reduce the number of collisions between the catheter guide wire and the vascular wall, and improve the safety of the doctor training system for vascular interventional surgery. The innovation of this paper lies in the real-time local path planning for the catheter in the doctor training system using the improved RRT algorithm. According to the intravascular environment, the catheter plans a collision-free path from the predicted position X_n at the next moment to the sub-target point X_{ng} on the global path. The algorithm can guarantee the real-time performance of path planning. The planned path is closer to the optimal path and does not have too large a turn path.

This paper is divided into five parts. In the first part, we introduce vascular interventional surgery and the physician training system for vascular interventional surgery based on dynamic local path planning. The second part introduces the dynamic local path planning based on RRT algorithm. The third part introduces the dynamic local path planning based on the improved RRT algorithm. The fourth part is the experiment and analysis of catheter dynamic local path planning in the vascular intervention surgery doctor training system; The fifth part summarizes this article.

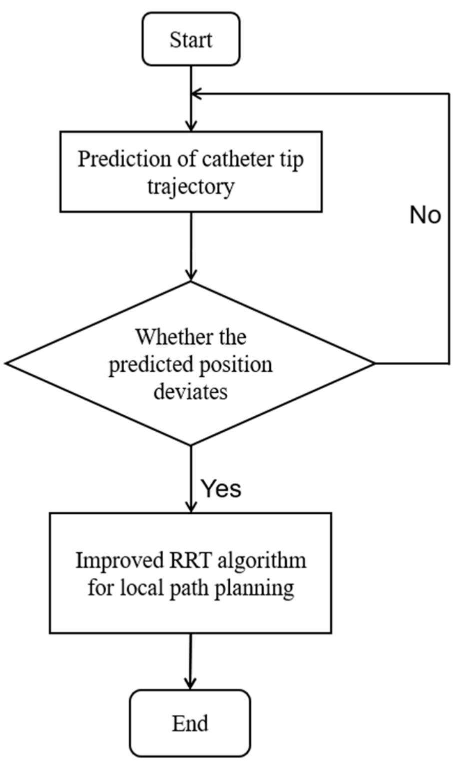

Fig. 1 Flow chart of dynamic local path planning for vascular interventional surgeon training system.

II. THE LOCAL PATH PLANNING BASED ON RRT ALGORITHM

Vascular intervention is the first choice for the treatment of cardiovascular and cerebrovascular diseases. However, during the vascular intervention, doctors will use DSA imaging equipment, which poses a great threat to the health of doctors. Therefore, the use of vascular interventional surgery robot is an inevitable trend of development. However, the blood vessels are very fragile and the environment is complex, so it is very demanding for the robot for vascular intervention surgery, and it is necessary to ensure the safety of the surgery. Preoperative path planning can plan an optimal global path, and then the catheter guidewire moves along the global path, which can greatly reduce the number of collisions with the blood vessel ratio and improve the safety of surgery. However, during the surgery, due to improper operation and unclear contrast images, the catheter guidewire will deviate from the global path, resulting in the failure of the vascular puncture surgery. Therefore, it is very necessary to study the local path planning. Local path planning allows for the correction of off-track catheter guidewires to the original trajectory.

Traditional path planning algorithms include artificial potential field algorithm, fuzzy rule algorithm, A* algorithm, genetic algorithm and neural network algorithm. However, all these methods need to model obstacles in a certain space. Their calculation complexity is high and the calculation time is long. The principle of RRT algorithm is very simple. The principle of this algorithm is to quickly expand a group of tree-like paths to explore areas in space, and then find a feasible path. Fig. 2 shows the random tree growth diagram of the traditional RRT algorithm.

X_{start} is the starting position and X_{goal} is the target position. The process of path space search starts from the starting point, and the line randomly scatters X_{rand}; Then find the nearest x near to $X_{rand;}$ Then advance stepsize along the direction from X_{near} to X_{rand} to get X_{new}; Detecting whether there is collision with obstacles in the map environment; If there is no collision, a space search expansion will be successfully completed.

RRT algorithm obtains the path from the starting position to the target position through multiple iterations. Fig. 3 shows the flow chart of each iteration of algorithm.

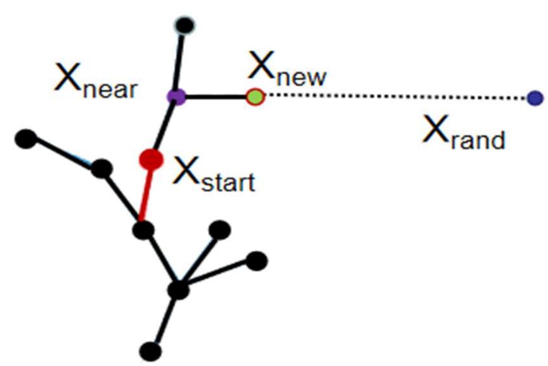

Fig. 2 The random tree growth diagram of the traditional RRT algorithm.

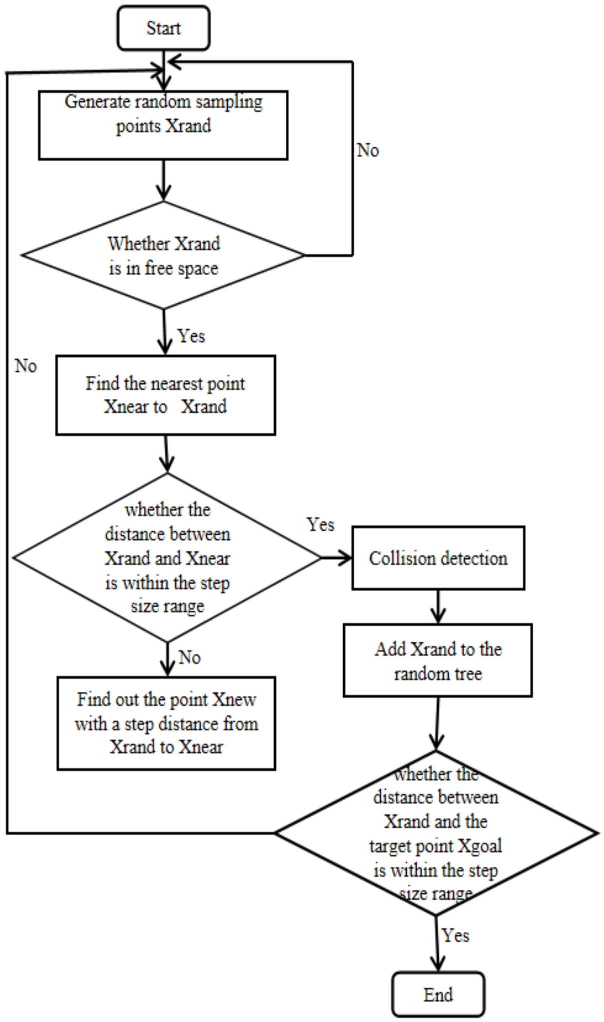

Fig. 3 The flow chart of each iteration of algorithm

From the above process, we can see that the algorithm is iterative before reaching the convergence condition, so as long as there is an effective path between the starting point and the end point of the planning, as long as there are enough iterations, then the sampling points are enough, the denser the random tree grows, and the area that can be explored is wide enough, so it is inevitable to find an effective path. However, because the sampling points are random every time, the algorithm can't guarantee that the found path is optimal, and the same starting point and end point are planned many times, and the planned path is different every time.

III. Improved RRT algorithm

An improved RRT algorithm is proposed based on the traditional RRT. The algorithm uses a mixture of node connection screening strategy and extension point selection strategy. It can control the growth direction of random tree, improve the convergence speed of algorithm and improve the efficiency of catheter path planning in doctor training system.

A. Expansion point selection strategy

The principle of extended point selection strategy is to simulate the attraction of target point to catheter tip in artificial potential field method, and improve the random sampling function in RRT algorithm. This strategy can guide the growth direction of the expansion tree, so as to explore the target as soon as possible, making the growth of the expansion tree more directional, eliminating the need to do a lot of unnecessary expansion, greatly reducing the planning time and saving resources. The new leaf node is determined by the random point X_{rand} and the target point X_{goal}, which is used to guide the tree to expand to the target point. Fig. 4 is a schematic diagram of expansion point selection strategy.

Define a constant l when the distance between the obstacle and the target point is less than l, use the above method to guide the expansion of the expansion tree. Otherwise, it is still expanding in the random direction. In this way, the randomness of the expansion tree is kept, and it can be expanded to the target faster.

The principle of artificial potential field is shown in formula (1).

$$U = \begin{cases} \frac{1}{2} K (\frac{1}{D} - \frac{1}{D_0})^2 \\ 0, \ D > D_0 \end{cases} \tag{1}$$

In this formula, U is the repulsive potential field function, K is the repulsive coefficient, D is the distance between catheter and vessel wall, and D_0 is the action range of repulsive force field.

According to the principle of artificial potential field method, we also establish a repulsive field S for all obstacles in the RRT algorithm. As shown in the formula (2)

$$S = \begin{cases} \frac{1}{2} K_s (\frac{1}{d} - \frac{1}{d_0})^2 \\ 0, \ d > d_0 \end{cases} \tag{2}$$

In the formula, S is the repulsive force field function, K_s is the repulsive force field coefficient, d is the distance between the obstacle and the target point, and d_0 is a predetermined constant. The repulsive force field of obstacles far away from the target point is larger. We stipulate that X_{new} in the repulsion field cannot be added to the extension tree T, thus compressing the search space, which means that the algorithm can be extended to the target as soon as possible.

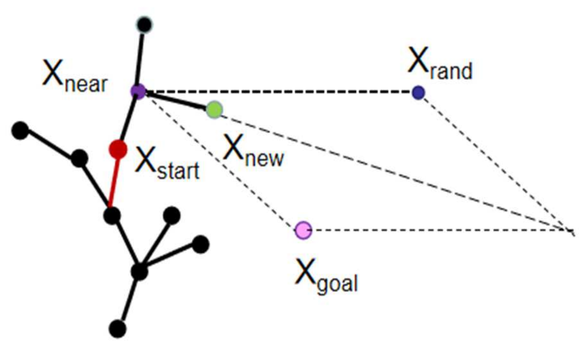

Fig. 4 The schematic diagram of expansion point selection strategy

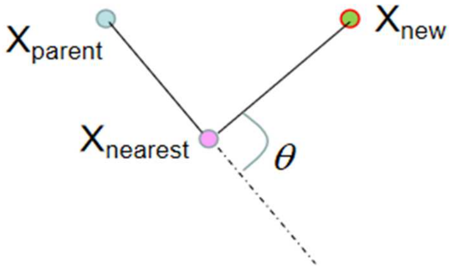

Fig. 5 The included angle θ

When the algorithm generates a new node X_{new}, first judge whether it is in the range of obstacle repulsion field, and if it is in the range of repulsive force field, the point will be abandoned for the next iteration. If not, collision detection is performed. If the collision detection is passed, this point is added to the tree T, and whether it meets the constraint of $| X_{new}–X_{goal} | < d$ is detected. If the constraint is met, the next iteration attempts to extend directly to the target point.

B. Node connection filtering strategy

The optimal path obtained by RRT algorithm improved by extended point selection strategy may have a big turning path. Therefore, we solve this problem through the strategy of node connection filtering. The principle of node connection screening strategy is: every time a new node X_{new} is generated by random tree expansion, it is judged whether the included angle θ between the connection between X_{new} and X_{near} and the connection between X_{near} and X_{near}'s parent node X_{parent} is too large. If it is too large, X_{new} will not be added to the random tree. The included angle θ is shown in Fig. 5. Formula(3) shows the calculation method of angle θ.

$$\theta = arccos\left(\frac{D_1^2+D_2^2-D_3^2}{2*D_1*D_2}\right) + arccos\left(\frac{D_1^2+D_3^2-D_2^2}{2*D_1*D_3}\right) \quad (3)$$

In which D1 represents the distance from X_{new} to X_{parent}, D2 represents the distance from X_{near} to X_{parent} and D3 represents the distance from X_{near} to X_{new}. In the process of reselecting the parent node, it is judged whether the included angle θ between X_{new} and X_{near} and X_{near} and its parent node is too large, and if it is too large, X_{near} will be abandoned as X_{new}'s parent node.

According to the kinematics formula and Kalman filter algorithm, the position of the catheter tip at the next time is obtained [2]. When the predicted position deviates from the global path beyond the threshold, the improved RRT algorithm is used to plan the local path.

IV. Experimental Results

A. The experiment establishment

This experiment is carried out by Matlab simulation and the training system of interventional surgeons in our laboratory. Firstly, we get the simulated vessel wall in the training system of vascular interventional surgeons by edge detection. Then the edge coordinates of the vascular wall are extracted. Finally, the images of blood vessel edges are put into Matlab for simulation experiments of traditional RRT and improved RRT. The goal and task of the two experiments are the same, that is, planning the path from the same starting position to the same sub-target position. The simulation results are shown in Fig. 6-Fig.15.

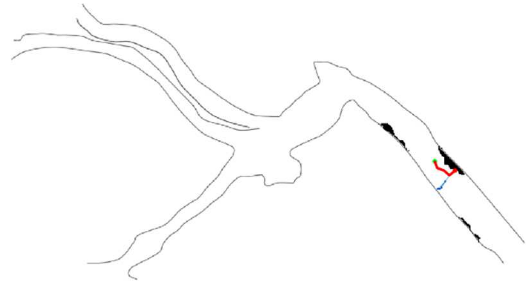

Fig. 6 The first experimental results of the traditional RRT algorithm

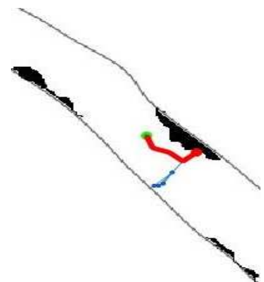

Fig. 7 The partial enlargement of the first experiment

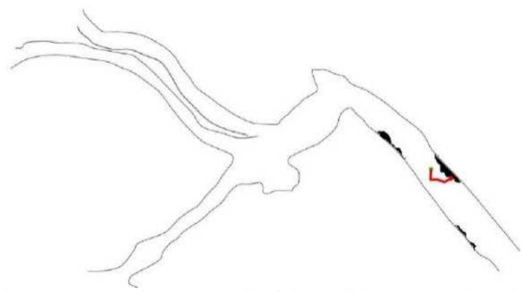

Fig. 8 The second experimental result of the traditional RRT algorithm

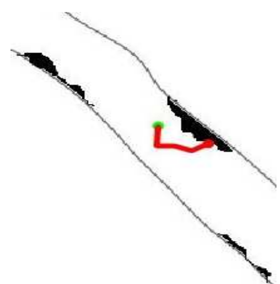

Fig. 9 The partial enlargement of the second experiment

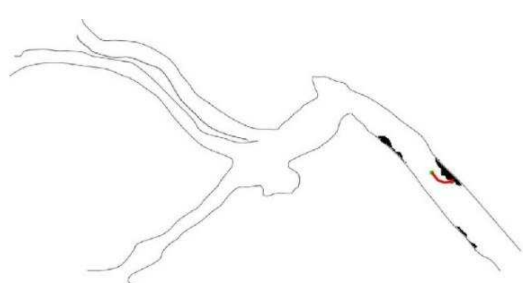

Fig. 10 The third experimental result of the traditional RRT algorithm

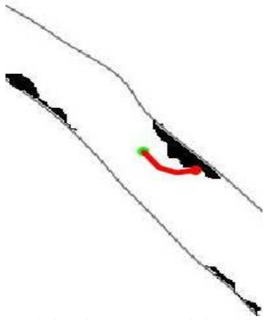

Fig. 11 The partial enlargement of the third experiment

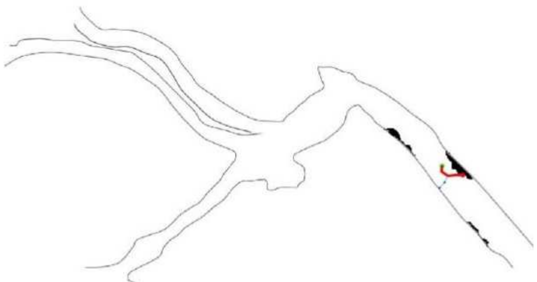

Fig. 12 The fourth experimental result of the traditional RRT algorithm

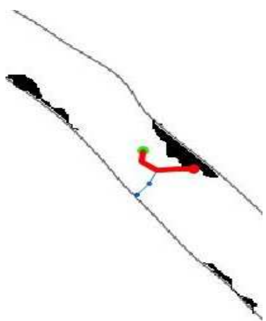

Fig. 13 The partial enlargement of the forth experiment

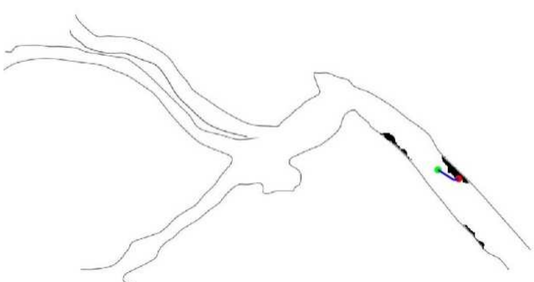

Fig. 14 The results of improved RRT algorithm

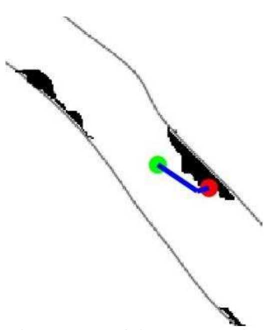

Fig. 15 The partial enlargement of the Improved RRT algorithm result

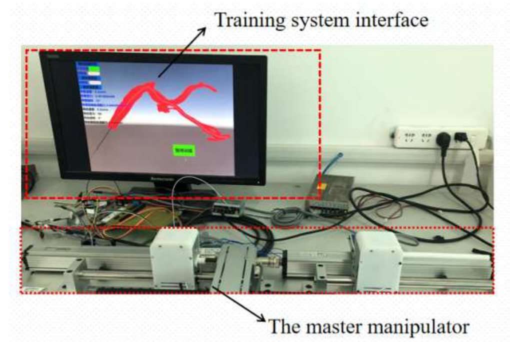

Fig. 16 The training system for vascular interventional surgeons

TABLE I
COMPARISON TABLE OF PLANNING TIME AND PATH LENGTH

Experiment	Planning time	Path length
First	1.4s	4.749cm
Second	1.1s	5.323cm
Third	1s	4.027cm
Forth	1.16s	4.528cm
Improved	0.704s	3.846cm

Fig. 6 shows the first experimental results of the traditional RRT algorithm. Fig. 7 shows the partial enlargement of the first experiment. Fig. 8 shows the second experimental result of the traditional RRT algorithm. Fig. 9 shows the partial enlargement of the second experiment. Fig. 10 shows the third experimental result of the traditional RRT algorithm. Fig. 11 shows the partial enlargement of the third experiment. Fig. 12 shows the fourth experimental result of the traditional RRT algorithm. Fig. 13 shows the partial enlargement of the third experiment. According to the results of these four experiments, we can see that for the same target task, the planned path is different every time. And some paths have larger turning angles and are not optimal paths.

Fig. 14 shows the Matlab experimental simulation of local path planning based on improved RRT algorithm. Fig. 15 shows the partial enlargement of the improve RRT algorithm result. Through the experiment, we can see that the local path obtained by the node connection filtering strategy does not turn at a large angle. And the planned path is better than the local path planned by the traditional RRT algorithm.

Finally, we carried out the experiment in the training system of vascular interventional surgeons in our laboratory. Improve the implementation of RRT algorithm by adding C# script in unity. As shown in Fig. 16, it is the training system for vascular interventional surgeons in our laboratory. This experiment includes two parts in the training system. The first part is four experiments of local path planning of traditional RRT algorithm in the doctor training system. The second part is the experiment of local path planning of improved RRT algorithm in the doctor training system. Nodes will be generated in the process of planning paths by RRT algorithm in the training system. The length of local path can be obtained by using these nodes according to the distance between points and points.

B. *Analysis of Experimental Results*

According to the four experimental results of local path planning based on traditional RRT algorithm and the experimental result of improved RRT algorithm are compared, as shown in Table I. The previous four experiments in the table are the experiments of traditional RRT algorithm in the doctor training system. The last experiment in the table is the experiment of the improved RRT algorithm in the doctor training system. The improved RRT algorithm can greatly shorten the time of path planning and ensure the real-time performance of local path planning, and the path planned by the improved algorithm is shorter than that planned by the traditional algorithm, and there is no big corner.

Through data analysis, the improved RRT algorithm can greatly shorten the time and path of local path planning, which is more in line with the local path planning of catheter in the training system of vascular interventional surgeons.

V. Conclusions And Future Work

In this paper, we proposed a catheter local path planning based on RRT algorithm in the vascular intervention surgery doctor training system. When the trajectory of the catheter was abnormal, the path of the catheter was corrected by local path planning. This method can reduce the times of collision between catheter and vessel wall, and greatly improve the safety. The experimental results showed that the improved algorithm had fast convergence speed, reduced the time of path planning, and also shortened the distance of the planned local path. In the future, we will continue to optimize for path smoothing.

Acknowledgment

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