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Spacecraft environmental path planning method based on improved artificial potential field

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Abstract. Spacecraft is the primary means of transportation for human exploration of outer space. With the advancement of science and technology, existing space exploration can no longer satisfy people's desire to explore, in the future, further and deeper space exploration is the goal of development. And the safety of spacecraft navigation in space requires the development of a path planning system. Although there have been many kinds of methods for path planning at this stage, all of them have their strengths and specialize in planning directions, but they also have defects. Based on this, this study improves the traditional artificial potential field method, by adjusting its repulsive field calculation and combining it with the RRT algorithm. The improved method can avoid the local minimum problem of the traditional artificial potential field and generate paths to meet the requirements of spacecraft. The effectiveness of the algorithm is verified by simulation experimental results.

Keywords: artificial potential field, RRT, repulsive potential field.

1. Introduction

The world is in a state of rapid innovation, with people increasingly keen to explore the unknown, and space has become a unique arena. The first artificial satellite was launched from the Soviet Baikonur Cosmodrome and entered orbit around the Earth in 1957, sending man-made objects into space for the first time. In the 1970s, Soviet cosmonaut Yuri Gagarin became the first human in space when he orbited the Earth in the manned Vostok 1 spacecraft. By the 1990s, this period saw Apollo 11, Challenger, the Hubble Telescope, and the Pathfinder missions, which had successes and failures, but confirmed a constant stream of people trying to explore space. Detection technology has developed rapidly into the 21st century. From basic astronomical telescopic observations to iterations of spacecraft and artificial satellites, and towards spectral analysis and cosmic ray analysis, the technologies involved have been constantly advancing. In future exploration, spacecraft will need to reach further and deeper into space to complete a specific task, so it will be challenging to ensure the safety and accuracy of path planning through automatic navigation systems during exploration.

In the current status of path planning research, autonomous navigation is one of the conditions whether the target can complete the mission in the specified environment, and a relatively important and easy way to complete the mission[1]. The core problem is how to solve the target to reach the endpoint in a stable, safe, and fast way. From the current research, the research directions are divided into two main categories: global path planning and local path planning. Among them, global path planning can quickly get the overall optimal route, while local route planning can better focus on the route analysis of the local environment, which can be used to cope with path planning in an unknown environment[2].

The A* algorithm and PRM are most commonly used to solve problems in global path planning, where improvements to both algorithms have been effective. Current research indicates that the distance between the goal and the endpoint can be presented as an exponential function, while the gradient descent method is used to smooth the path, thus reducing the repetition rate of nodes in the search. Another research combined the A* algorithm and DWA algorithm to perform dynamic obstacle avoidance and obtain the best path by iteratively updating the local target points obtained by the A* algorithm, but this method is computationally intensive and slow to update[3]. the D* algorithm, as an improved version of the A* algorithm, is relatively more efficient in the form of reverse computation. The PRM algorithm, a path planning approach based on a heuristic node improvement strategy, is a good answer to the challenge of building an efficient path graph in a high-dimensional environment. The PRM algorithm and the RRT algorithm are both sampling-based algorithms. The PRM, introduced by M.H. Overmars et al. in the 1990s, reflects the connectivity of a path by sampling in the constructed space, performing collision detection on the sampled points, and deciding if neighboring sampled points may be connected. This approach has the benefit of being generalizable to other settings since its complexity is mostly determined by how difficult it is to locate pathways and has little to do with the size of the entire planning scene and the dimension of the constructive space. But the efficiency of PRM is relatively low when the obstacles are too dense, and the spacecraft may encounter asteroid swarms or meteorite belts during its voyage, which the PRM algorithm could not cope with perfectly[4]. RRT is an algorithm with small complexity and a high degree of freedom, which finds an optimal route from the starting point to the endpoint by expanding the nodes in any space. The artificial potential field method was first proposed by khatib et al. in 1986. The APF algorithm assumes that the carrier is always in a virtual force field where all surrounding objects exert repulsive forces on it and only the target point provides the gravitational force, by calculating the combined force at this moment and performing local path planning according to the direction of the combined force[5]. The DWA method samples many sets of velocities in velocity space, simulates their trajectories over a while, and then rates each trajectory using an evaluation function to determine which is best. The DWA algorithm can achieve real-time obstacle avoidance, which is a reference value for the safety of the spacecraft in the unknown universe environment and brings a certain guarantee.

In contrast, research in this paper focuses on the traditional artificial potential field for the local minima problem, improves its attractional and repulsive functions and combines them with the RRT algorithm to meet the path planning needs of spacecraft.

2. Traditional method

2.1. Artificial potential field method

Dr. Oussama Khatib introduced the artificial potential field approach in 1985 as a virtual force path design technique. The basic idea is to calculate the combined force on the moving target by making the endpoint exert " attractional force" on the moving target and the obstacles exert "repulsive force" on the moving target in a certain range of environment, and to control the movement of the target by this artificially constructed gravitational field. By controlling the movement of the target through this artificially constructed gravitational field, this method can plan the best route to the endpoint[6].

In the artificial potential field method, the spacecraft q is treated as a mass affected by the artificial potential field, which is attracted to the target by the endpoint Q and repelled by the local environmental boundary and the obstacle O to move away from the obstacle area.

When the spacecraft q moves to a certain point, the potential field U(q) at its position can be expressed as the sum of the attractional force of the endpoint Q and the repulsive force of the obstacle O, and the potential field is constructed as follows:

$$U(q) = U_{att}(q) + U_{rep}(q) \tag{1}$$

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The direction of the attractional potential field $U_{att}(q)$ generated by the endpoint Q to the spacecraft q is directed towards the endpoint.

The direction of the repulsive potential field $U_{rep}(q)$ generated by the obstacle O to the spacecraft q is directed away from the obstacle.

In the artificial potential field, the spacecraft will be subjected to forces from the endpoint and all the obstacle potential fields in the local area. In the case that the forces satisfy the parallelogram law, the combined forces will drive the spacecraft to move, and under the action of these two forces, it will move in the direction of the fastest decreasing gradient of the combined potential field toward the endpoint.

2.1.1. Attractional potential field function model

The attraction of the endpoint to the spacecraft creates the attractional potential field, which has the effect of directing the spacecraft towards the direction of the endpoint. The distance between the spaceship and the endpoint mostly determines the strength of the attractional force; the bigger the distance, the stronger the attractional potential field; conversely, the smaller the attractional potential field. When the spacecraft reaches the endpoint, the target distance is zero, the attractional potential field is zero, and the spacecraft stops moving[7].

The function of the Attractional potential field is constructed as follows:

$$U_{att}=\frac{1}{2}K_{att}{P_0}^m \tag{2}$$

In this function:

K_{att} is attractional potential field positive series coefficient.

P_0 is Straight line distance between spacecraft and the target point position.

m is attractional potential field factor.

Next, defining the negative function of the attractional function F_{att} to represent the attractional force in the direction of the fastest change in the attractional potential field, which can represent here as the derivative of the function of the attractional potential field F_{att} concerning for to the distance between the spacecraft and the endpoint.

$$F_{att}(P0)=-\nabla U_{att}(P0)=-K_{att}P0 \tag{3}$$

2.1.2. Repulsive potential field function model

The size of the repulsive force is mostly influenced by the distance between the spacecraft and each barrier. The repelling force increases when there is a greater separation between the spaceship and the obstructions, and decreases when there is a greater separation. The repulsive potential field will vanish and there will be no repulsive force if the distance between the spaceship and the obstruction is beyond the range of the potential field's effect.

Based on the above theory, construct the repulsive potential field function:

$$U_{rep}(P_g)=\begin{cases}\frac{1}{2}K_{rep}\left(\frac{1}{P_g}-\frac{1}{\rho}\right)^2,\ P_g\leqslant\rho\\ 0,\ P_g>\rho\end{cases} \tag{4}$$

$$F_{rep}(P_g)=\begin{cases}K_{rep}\left(\frac{1}{P_g}-\frac{1}{\rho}\right)\frac{1}{{P_g}^2},\ P_g\leqslant\rho\\ 0,\ P_g>\rho\end{cases} \tag{5}$$

In this function:

ρ is the maximum radius of an obstacle that exerts a force on the spacecraft.

P_g is distance between the obstacle and the spacecraft.

K_{rep} is Positive scale factor of the repulsive potential field.

2.1.3. Combined potential field model
The attractional force and various repulsive forces on the spacecraft are equalized to a combined force to produce the combination function of the effects brought on by the artificial potential field after the attractional potential field and the repulsive potential field have been determined[8].

The combined functions are as follows:

$$F_{tal}(P) = F_{att}(P) + F_{rep}(P) \tag{6}$$

$$U_{tal}(P) = U_{att}(P) + U_{rep}(P) \tag{7}$$

2.2. **RRT algorithm**
The RRT method is a stochastic technique that has minimal computational complexity and may be applied directly to limited planning of incomplete systems. The main goal is to fast extend a collection of tree-like trails to thoroughly investigate the entire area while waiting for a chance to locate a workable path[9]. Since the RRT algorithm plans not the optimal route, a part of the planning by applying the RRT algorithm can quickly choose the appropriate location to create virtual points and make optimization for solving the local minimum point problem.

2.2.1. The flow of RRT algorithm
Step 1: Random tree initialization. The starting point is used as the starting point of the search for random numbers, and only this starting point is included in the current random tree. Set the initial point X and the endpoint Y .

Step 2: Random search in the environment. A random sample is taken in space to obtain a sample point $X_{rand,}$ and the distance between the sample point and all the nodes in the collection of nodes U that have been generated is calculated to obtain the nearest point X_{near} to the sample point X_{rand}, and a straight line is generated from the X_{near} to sample point X_{rand} in a fixed step. The point and the branch formed by the growth process are recorded in the random tree.

Step 3: Collate the sampling results. If no obstacle is encountered in the process, the new node X_{new} substitute X_{rand} and the paths with the new nodes X_{new} are counted in the collection U ; if an obstacle is encountered in the process, the sampling is resampled.

Step 4: Find the endpoint Y. Repeat step 2 and step 3 of the above cycle until the distance between the point on the random tree and the endpoint is within the set range, then add the endpoint to the random tree and plan a route without collision obstacles.

3. Improved method
The research in this paper first uses the RRT algorithm to write a program that can make a judgment on whether it is caught in a local minimum problem, and then improves the repulsive function so that it can generate a virtual force to help the spacecraft out of the problem when it is confirmed that the spacecraft is at a local minimum. Next is the step-by-step procedure of the improved method[10].

The ensemble function of the artificial potential field is known to be:

$$F_{tal}(P) = F_{att}(P) + F_{rep}(P) \tag{8}$$

When a local minimum is reached:

$$F_{tal}(P) = F_{att}(P) + F_{rep}(P) = 0 \tag{9}$$

At this time, the spacecraft cannot move without being pulled by external forces. To solve this problem, the study will optimize the artificial potential field method by improving the repulsive potential field.

The root cause of the local minimum, i.e., the combined force of the attractional and repulsive forces is exactly zero, and the solution to this problem is that if the combined force is greater than zero, moving to another position and recalculating the combined force:

$$F_{tal}(P) = F_{att}(P) + F_{rep}(P) > 0 \tag{10}$$

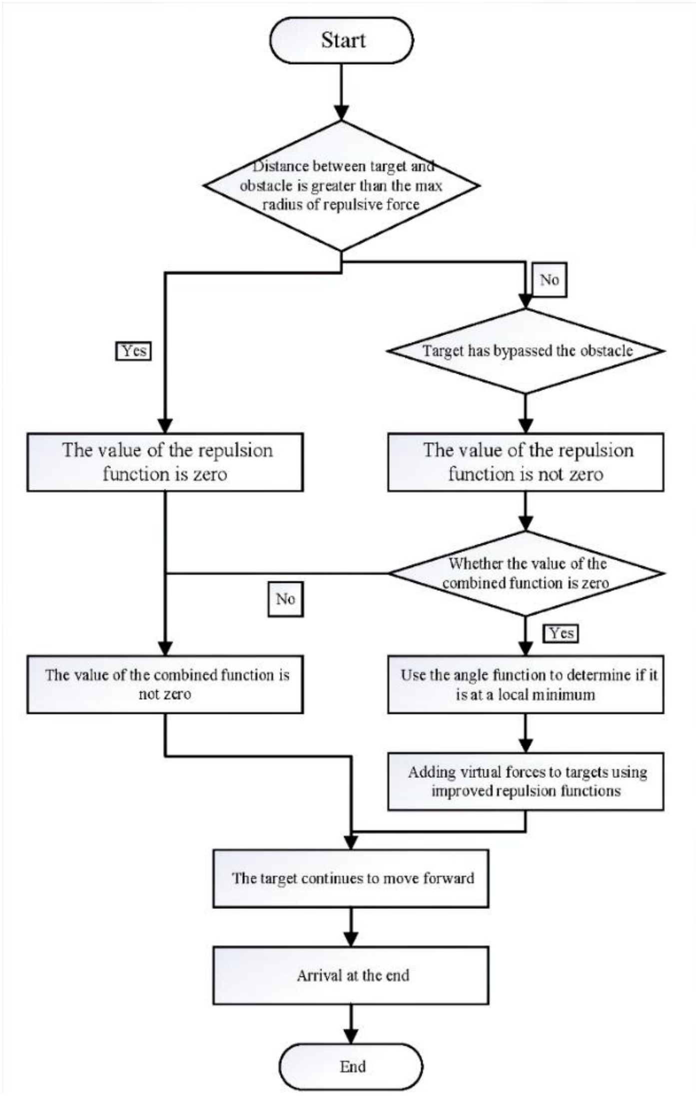


Figure 1. The flow of improved artificial potential field.

Here, the RRT algorithm is chosen to create a virtual point at a suitable location in the global environment, and to ensure the uniqueness of the attractional force generated at the endpoint without affecting the experiment, the virtual point is made to form a repulsive force on the spacecraft, so that the combined force is greater than zero, thus controlling its movement away from the local minimum.

The model of the RRT algorithm is still chosen to be constructed in Matlab, and to optimize it for the artificial potential field method, the first step is to determine whether the spaceship enters the local minimum problem. Overall structure is shown on figure 1.

Step 1: The angle function Angle is used to determine whether the spacecraft is at the local minimum.

$$angle_{att}(j) = angle \tag{11}$$

$$F_{att} = sqrt({F_{attx}}^2 + {F_{atty}}^2) \tag{12}$$

$$F_{rep} = sqrt({F_{repx}}^2 + {F_{repy}}^2) \tag{13}$$

$$\begin{cases} \text{abs}\left(\frac{F_{att} - F_{rep}}{F_{att}}\right) < 0.5 \\ \cos\left(angle_{att}(j) - angle_{rep}(j)\right) < -0.9 \end{cases} \tag{14}$$

Step 2: If the spacecraft is at the local minimum, the current position is taken as the initial point X of the random tree, and the random sampling is started in space, with the cosine of the difference between the attractional force and the repulsive force less than -0.9 as the sampling range, and the route suitable for creating the virtual point is obtained.

Step 3: Finally, the attractional and repulsive modules in the artificial potential field method model are called and the repulsive potential field is improved by adding the repulsive force generated by the virtual point to the original repulsive potential field function and recalculating the potential field.

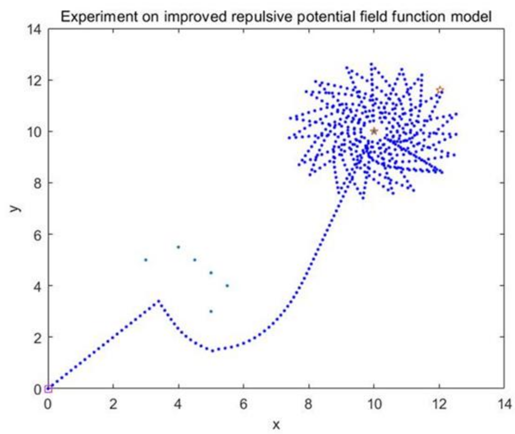


Figure 2. Experiment on improved repulsive potential field function model.

As the figure 2 shown, it is worth noting that when the spacecraft approaches the endpoint, it moves repeatedly around the perimeter without reaching the endpoint. By analyzing and examining the code, the RRT algorithm is used only to find the location of the virtual point created, and in the subsequent run away from the local minimum, it conflicts with the original artificial potential field method function because it plans the path to the endpoint at the same time. Here replacing the coordinates of the endpoint in the RRT algorithm with a point that is approximately the same as the endpoint and the values of x and y coordinates are greater than the values of the endpoint. After the spacecraft reaches the endpoint, the artificial potential field method and the RRT algorithm are stopped and the mission objective is accomplished.

4. Simulation experiment

4.1. The experiment of traditional method

Step 1: Preload the environmental parameters before the test. The parameters to be used in the study consist of the locations of planets, meteorites, space junk, and other space obstacles as well as their sizes, which can be detected in real-time by fitting detection radar on the spacecraft, but due to the limitations of the current technology and considering the unknown nature of the environment in the universe, the spaceship cannot guarantee that it can get the centre coordinates of planets and other obstacles from the detection radar, so the edge data of the detected obstacles are usually loaded as the centre coordinates. The attractional potential field created at the terminus and the repulsive potential field created by the obstacles are established as the paper's centre coordinates here for the experiment's convenience. Setting them in this way, it helps to simplify the experiment and thus to perform the test better.

Step 2: After setting the parameters of the environment, it also preload the spaceship with various parameters, such as volume, velocity, etc. In the experiment, the spaceship should be set as a point, considering the varying designs of spaceships at this stage and the unforeseeable future development, as well as simplifying the experimental process. In this paper, our study decompose the repulsive potential field, which is generated by a vector repulsive force in the real environment.

Step 3: Next, using Matlab to conduct the test, setting the coordinates of the starting point of the spacecraft as (0,0), and the coordinates of the ending point as (20,20). To simulate the space environment, the gap between the volume of the planets and the spaceship, and the interference of many obstacles, by setting the attractional potential field positive scale factor K_{att} to 10 and the repulsive potential field positive scale factor to 1000. Finally, To ensure the stability of the experiment and because that the spaceship is not infinite energy, so set the total moveable step capacity of the spaceship to 10000 and the step length of each advance to 0.01. The safe distance between the spacecraft and the obstacle is set to 1 because, in the actual exploration, the planets and the obstacles have volume.

Step 4: Build the angle calculation function module:

$$[\cos, \sin] = compute\_\mathrm{Angle}(\mathrm{a}, \mathrm{b}) \tag{15}$$

Step 5: Build the gravitational potential field function module:

$$[f_{attx},\ f_{atty}] = compute\_\mathrm{Attacrt}(\mathrm{x},\ \mathrm{y},\ \mathrm{x}_Q,\ y_Q, K_{att}) \tag{16}$$

Step 6: Build the repulsive potential field function module:

$$[f_{repx},\ f_{repy}] = compute\_\mathrm{Repulso}(\mathrm{x},\ \mathrm{y},\ \mathrm{x}_O,\ y_O, K_{rep}) \tag{17}$$

Step 7: Build the model environment: The study chooses the two-dimensional coordinate axes as the top view of the simulated universe. And set the spacecraft, the starting point, the endpoint, and the obstacles cannot be generated outside of the coordinate plane. At the same time, to ensure the rigor of the experiment, and use the Randperm function to restrict the obstacles not to be generated at the starting point and the endpoint.

Step 8: Set the number of obstacles to 20 for the experiment.

Step 9: Call the angle calculation function, attractional potential field function, and repulsive potential field function to plan the path of the spacecraft.

4.2. The experiment of improved method

To ensure the accuracy of the experiment, the improved repulsive potential field is conducted as a separate experiment, a local minimum environment is re-established with Matlab, the starting point of the spaceship is set as (0,0), the ending point is set as (10,10), and a star-shaped marker is used to indicate the position of the spaceship out of the local minimum and the last stopping position. The results are shown in figure 3.

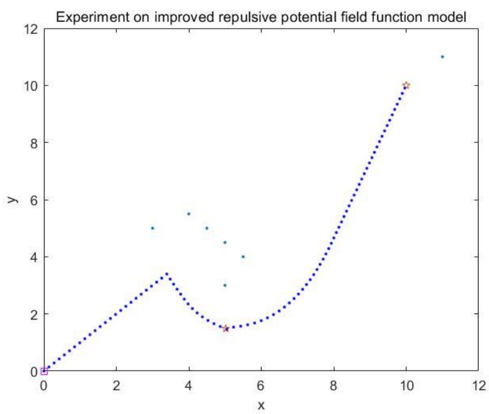


Figure 3. Experiment on improved repulsive potential field model.

The standard artificial potential field approach and the modified artificial potential field method suggested in this work are both validated using the aforementioned environment simulation.

5. Results

5.1. Results of traditional artificial potential field methods

After testing by the artificial potential field method, the following results were obtained:

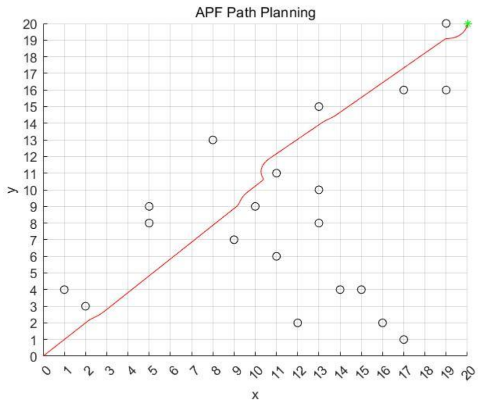


Figure 4. APF path planning of 20 obstacles.

Shown on figure 4, several experimental tests have found that when the number of obstacles is 20, the spacecraft can almost always reach the end, but there are cases where it does not reach the end in figure 5：

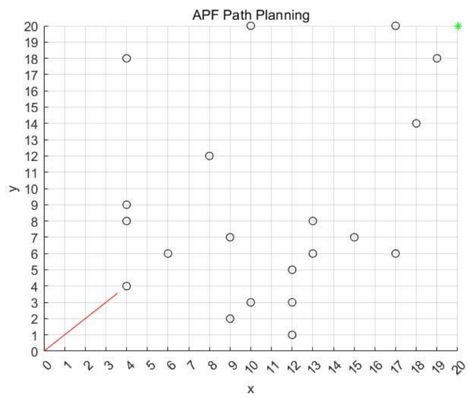
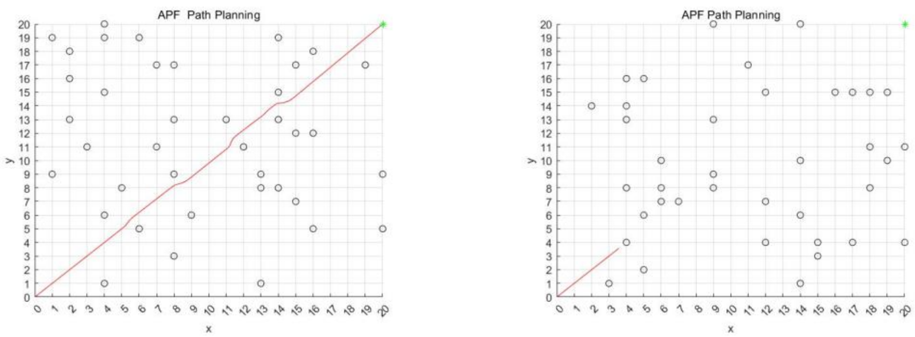


Figure 5. Failed APF path planning of 20 obstacles.

The number of obstacles was adjusted upward to 40, and the test was continued. Shown on figure (a) and figure (b) in figure 6, it was found that the experimental results were not much different from when the number of obstacles was 20, and the spaceship could reach the end, but there were very few cases where it could not.



(a) **(b)**

Figure 6. APF path planning of 40 obstacles. (a) Succeed APF path planning of 40 obstacles; (b) Failed APF path planning of 40 obstacles.

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Finally, the number of obstacles was adjusted upward to 80 for testing, and it was found that there was a relative increase in the number of cases where the spaceship could not reach the end in figure 7.

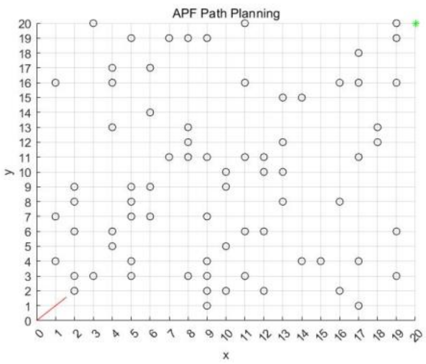
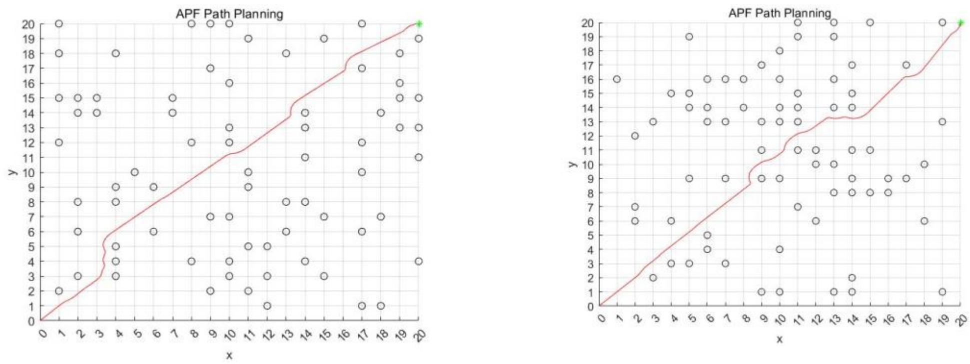


Figure 7. Failed APF path planning of 80 obstacles.

5.2. Test results of the improved method

Testing with an optimized artificial potential field method combining the RRT algorithm and improving the repulsive potential field function gives the following results.



(a) **(b)**

Figure 8. Optimized APF path planning of 80 obstacles. (a)(b) represent different conditions.

As shown in the figure 8, in the case of encountering a local minimum, the spacecraft can respond significantly and continue moving toward the target.

6. Discussion

From the above experimental results, it can be found that when the number of obstacles gradually increases, the target can easily fall into the local minima, and it is difficult to generate the path directly based on the traditional method, while the improved method can help the target to get out of the local minima and continue the path planning.

There are many directions of optimization for the artificial potential field method, but how to choose the least complexity and the most comprehensive optional route to solve the problem is the direction of optimization made in this paper. the RRT algorithm, as an algorithm that can continuously search for optional route planning in the global environment, is very suitable for comprehensive optimization, and at the same time, choosing to perform route planning only in the local range and terminating the RRT algorithm in time also circumvents its planning results. The problem of not being the optimal route.

The improvement of the repulsive potential field has the following advantages over the improvement of the gravitational potential field:

1. The repulsive force on the spacecraft can be generated from all sides, and adding a virtual point to generate the repulsive force has little effect on the global environment. In contrast, the gravitational

potential field can only be generated by the endpoint, and adding another virtual point to generate the gravitational force may affect the operation of the program.

2. The repulsive potential field can be decomposed during the calculation, which simplifies the complexity of the operation.

3, The virtual points for repulsive force are available in a wide range of locations, while the virtual points for gravitational force are limited by the endpoint location.

7. Conclusion

This study introduces the RRT algorithm while enhancing the repulsive potential field to handle the optimization problem of local minima for the automated navigation of spacecraft using the artificial potential field approach. The model can judge whether the target is at a local minimum, and if it is at a local minimum, it searches the surrounding environment and creates a virtual point that can exert a repulsive force to help the target get out of the problem and thus continue planning the path to the endpoint.

Experimental results show the optimized method established in this paper has low complexity and runs concisely and efficiently, and also solves the defects of the artificial market method. In practical applications, solutions can be provided for space exploration by spacecraft and artificial intelligence path planning for unmanned aerial vehicles and drones. Factors such as terrain and the volume of obstacles are the main problems affecting the method in practice. Future work attempts try to establish 3D coordinates to investigate the path planning of this optimized method in 3D space.

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