Equilibrium-breaking Artificial Potential Field for Path Planning of Mobile Robot by Randomly Generating Proximal Repulsion Sources

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Abstract. Artificial potential field (APF) is a very attractive method for the path planning of mobile robots, borrowing ideas from physics in the from of introducing attraction and repulsion between robots and their targets /environments. However, APF suffers from the issue of local minimum due to the equilibrium between attraction and repulsion. In this paper, a novel equilibrium-breaking APF is proposed to drive the robot to break away from deadlock caused by the equilibrium. The new APF will detect the equilibrium and randomly generate virtual repulsive sources near any local minimum according to a Gaussian model. The repulsive force changes the resultant potential field and gets rid of the local minimum point. This method can achieve effective path planning for a mobile robot in an unknown environment. Experimental simulations validated the validity and feasibility of the APF-based path planning method.

Keywords: Path planning; Artificial potential field; Unknown environment; Proximal repulsion source

1. INTRODUCTION

Path planning is the key to the development of mobile robots and the prerequisite for the progress of robot technology. The basic requirement of path planning is to reach the target point and complete the task on the premise of avoiding obstacles. This can be understood as finding a collision free path from the starting position to the target position and being able to complete the task [1]. The requirements for path planning change depending on the different environments.

With the increase of the requirements to complete the task, the complexity of the environment is constantly improving, so the study of algorithm is also ongoing. The performance of the algorithm is not only reflected in whether it can complete the task, but also in robustness, complexity, correctness, and the demand for environmental information.

For the path planning problem, through the efforts of researchers, some recognized path planning algorithms are proposed, such as Dijkstra algorithm, A* algorithm, simulated annealing algorithm, ant colony optimization and classical genetic algorithm and so on. Among them, the artificial potential field is widely recognized and used, which is a classical algorithm using physics concepts [2]. The artificial potential field is widely applied to the problem that the number of obstacles is large and the obstacle avoidance requires high real-time performance because of its simple calculation and good real-time performance [3]. Its basic idea is to design a potential field, in which the target points generate "attractive force" to the mobile robot and the obstacles generate "repulsive force" to the mobile robot. Finally, the motion of the mobile robot is controlled by seeking resultant force to complete the path planning. This method was proposed by Khatib at the end of the 20th century and has the advantages of simple operation, clear reasoning, fast response speed, good real-time performance and smooth path [4]. However, the traditional artificial potential field has some limitations, that is, when the robot is in the force field, it is easy to cause the problems of equilibrium point and unreachable target point. Researchers are also making continuous improvements, such as combine artificial potential field with A* algorithm [5,6], artificial potential field with ant colony algorithm [7,8], artificial potential field with simulated annealing algorithm [9], virtual target point method [10], dynamic window algorithm [11], change the force field function [12], etc.

The improved method proposed in this paper is aimed at the situation that the environment is unknowable. However, the artificial potential field method can still be realized by recognizing local information. In the unknown environment, the path planning of the robot is prone to meet the situation of local minimum value, so when it occurs, a proximal repulsive source is generated in the fixed range with the robot as the center of the circle and R as the radius. What is more, the proximal repulsive source and the obstacle have the same repulsive force, but when the distance between the robot and the repulsive source source exceeds the range, the proximal repulsive source disappears without any effect and has no influence on the following path planning. By generating the proximal repulsive sources randomly, the robot can avoid the deadlock phenomenon and complete the path planning under unknown conditions. This improved method has important research significance and contribution to the path planning of unknown environment.

2. TRADITIONAL ARTIFICIAL POTENTIAL FIELD METHOD

2.1. Basic Principles

The traditional artificial potential field method is a path planning algorithm which places a robot in a potential field, in which the target point produces a "attractive potential field" and the obstacle produces a "repulsive potential field". For the robot, the direction of the robot's next motion planning is determined by the change of potential field.

In the virtual potential field, the closer the robot is to the obstacle, the greater the repulsive force will be generated, so as to avoid collision. Generally, in the setting, if the distance between the robot and the obstacle exceeds a certain value, the repulsive force is judged to be 0. Because the obstacle beyond a certain range cannot pose a threat to the robot, it will also go beyond the recognition range of the robot. Therefore, the repulsive potential field function of the robot:

$$U_{rep}(q) = \begin{cases} \frac{1}{2} K_r \left(\frac{1}{\rho(q, q_{obs})} - \frac{1}{\rho_0}\right)^2 \\ 0 \end{cases} \quad (1)$$

$$if \begin{cases} \rho(q, q_{obs}) \le \rho_0 \\ \rho(q, q_{obs}) > \rho_0 \end{cases}$$

U_{rep} is the repulsive potential field function, K_r is the direct proportional gain parameter of the repulsive potential field, $\rho(q,q_{obs})$is the distance between the robot and the obstacle, ρ_0 is the identification range of obstacles, when the distance between the obstacle and the robot exceeds the range, the obstacle does not generate repulsion.

The repulsive force function is the negative gradient of the repulsive force potential field function, and the repulsive force function is obtained as follows:

$$F_{rep}(q) = \begin{cases} K_r\left(\frac{1}{\rho(q,q_{obs})} - \frac{1}{\rho_0}\right)\frac{1}{\rho^2(q,q_{obs})}\frac{q-q_0}{\rho(q,q_{obs})} \\ 0 \end{cases} \quad (2)$$

$$if \begin{cases} \rho(q,q_{obs}) \le \rho_0 \\ \rho(q,q_{obs}) > \rho_0 \end{cases}$$

F_{rep} is the repulsive force received by the robot, q is the current position of the robot, and q_0 is the position of the obstacle.

In the virtual potential field, the robot is attracted to the target point. The greater the distance between the target point and the robot, the greater the attractive force will be. The smaller the distance is, the less the attractive force will be generated until the target point is reached [13]. When the potential energy drops to zero, it means that the target is reached [14]. In the traditional artificial potential field, distance is not limited. The attractive potential field function is as follows:

$$U_{att}(q) = \frac{1}{2} K_a \rho^2 (q, q_{goal}) \quad (3)$$

U_{att} is the attractive potential field function, K_a is the proportional gain coefficient of the attractive potential field, and $\rho(q,q_{goal})$ is the distance between the robot and the target point.

The attractive force function is the negative gradient of the attractive force potential field function, and the attractive force function is obtained as follows:

$$F_{att}(q) = -K_a \rho(q, q_{goal}) \quad (4)$$

In order to prevent the larger attractive force generated when the distance between the robot and the target point is too far, the simple improvement is made after the research. When the distance between the robot and the target point exceeds a certain range, the attractive force is fixed. The attractive potential field function is as follows:

$$F_{att}(q) = \begin{cases} -K_a \rho(q, q_{goal}) & \rho(q, q_{goal}) \le D \\ Q & \rho(q, q_{goal}) > D \end{cases} \quad (5)$$

D is a range parameter. When the distance between the robot and the target point exceeds D, the maximum attractive force is constant Q, which is a parameter set artificially to prevent the system from collapsing due to excessive attractive force.

Therefore, the repulsive force and attractive force drive the robot to the next step, and each calculation is planning for the next step according to the environment, so it has a strong real-time performance and a fast response speed. The total potential field function is as follows:

$$U(q) = U_{att} + U_{rep} \quad (6)$$

The resultant force on the robot is:

$$F(q) = F_{att} + F_{rep} \quad (7)$$

It can be seen from the above that the force field function received by the robot in the potential field is a differentiable function, and then a feasible path is planned according to the descent gradient of the potential field, in which the gradient function of the potential field is the force function.

2.2. Problem Analysis

The problem of equilibrium point is a problem existing in the principle of artificial potential field, and it is also the focus of current research. As for the equilibrium point in an unknown environment, it is more difficult to solve because of the particularity of environment.

The reason why the equilibrium point appears is that when the robot is in a balanced position, it will reach the local minimum value instead of reaching the target point. However, there is no planning for the next movement of the robot, which makes the robot stop moving. As shown in Figure 1, when the resultant force of F_{rep1} and F_{rep2} balances with F_{att}, the robot cannot reach the target point [15]. In other words, for the robot, the virtual potential field is invalid and has no effect.

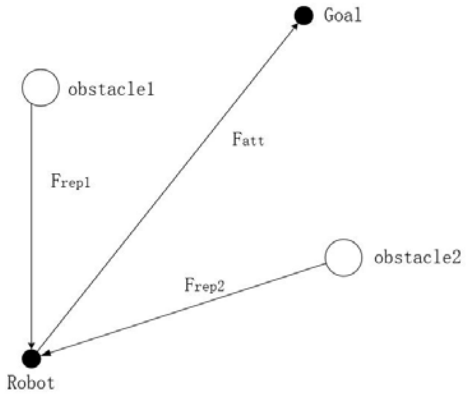

Fig. 1 Equilibrium position

3. THE SYEPS OF THE IMPROVED ALGORITHM

Based on the artificial potential field, an improved scheme is proposed in this paper, which can be applied to path planning in the unknown environment and solve the local minimum problem. The specific steps of the algorithm are as follows:

3.1. The Introduction of the Improved Algorithm

In this paper, the equilibrium point of artificial potential field is solved, and the artificial potential field is improved considering the unknown environment. When a robot moves from the current point to the target point, its environment is in an unknown state, which makes it difficult for traditional path planning algorithms to build an accurate mathematical model for the obstacle avoidance process of a mobile robot. The artificial potential field can accomplish the path planning with the local information obtained at the current position.

3. 1. 1. The preparatory work

Firstly, detailed information collection is carried out according to the environment where the task is to be completed to prepare for the simulation experiment. Robot does not have global information, so it is unable to build potential field model for the global environment. The experimenter places the robot at the starting point and mesh the current recognized environment, including the location of the target point. In the process, the information in each grid is marked as 1 when there are obstacles in the grid, and 0 when there are no obstacles in the grid.

Then, according to the repulsive potential field formula and attractive potential field formula, each marked grid is processed. In the established entire grid diagram, the distance between zero elements and non-zero elements is calculated to obtain the repulsive potential field, and the attractive potential field of each grid position and target point is obtained through local information. Then we add the two to get the current total potential field, and perform negative gradient operation on the potential field, which is the basis of path planning. Each time the position is moved, the identified range will be expanded. The identified environment will be meshed and calculate the potential field again. This step is complete.

3. 1. 2. Motion planning

The path planning in the unknown environment is based on the above meshed map and potential field calculation. By solving the negative gradient of the total potential field obtained each time, the gradient information under the current information is obtained. The gradient is used to induce the robot to move.

The loop condition is defined as the distance between the robot and the target point, which is determined according to the actual conditions. When the iteration meets the condition, the path planning is completed. During the iterations, the robot starts to move, and the next moving point of the robot is determined by taking the integer to the negative infinity direction according to the current coordinate point. And then using the coordinates after the integer to locate in the transverse and longitudinal gradient, so as to determine the magnitude of the gradient under this point. Then we can calculate the modulus according to this gradient to get the x and y coordinates of the next point, so as to obtain the respective step length.

This method can set the step length and plan the path in the meshed map, so as to avoid the situation of penetrating the obstacle directly.

3. 1. 3. Solve the equilibrium problem

When the local minimum value occurs, a virtual proximal repulsive source is randomly generated around the robot. And the robot is the center of the circle, R is the adjacent range of the circle. The proximal repulsive source can also have the same influence with other obstacles and lead to gradient change. The probability of the proximal repulsive source is generated randomly with Gaussian distribution as model. Suppose the line between the robot and the obstacle nearest to the robot is L, the circle with the robot as the center R as the radius is O, and the point where L intersects with O that is far away from the obstacle is A, then A is the point with the maximum probability. And this point is set as 0°, then the Gaussian model is built to both sides ±180° with the angle as the variable. This method can avoid generating a repulsive force in the same direction of the nearest obstacle's repulsive force and cause the collision problem.

The effect of this virtual proximal repulsive source is to make the robot get rid of the local minimum and leave the equilibrium position.

3.2. The Basic Flow of the Improved Artificial Potential Field

The improved artificial potential field method is still completed on the basis of the potential field. The basic operation process of the improved algorithm is as follows:

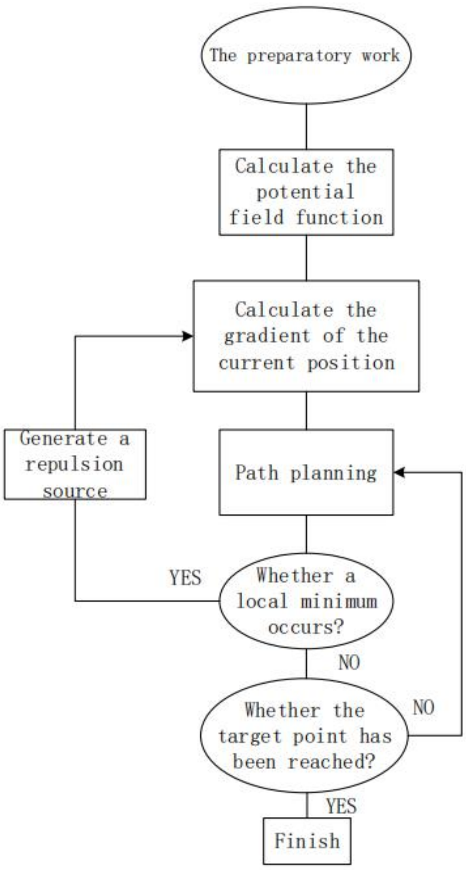

Fig. 2 The flow chart

3.3. The Model of Improved Artificial Potential

The model of improved artificial potential field is shown in Figure 3. The obstacle is a black dot, the target is a red dot, and the robot is a yellow dot. As shown in the figure, the robot is at an equilibrium position.

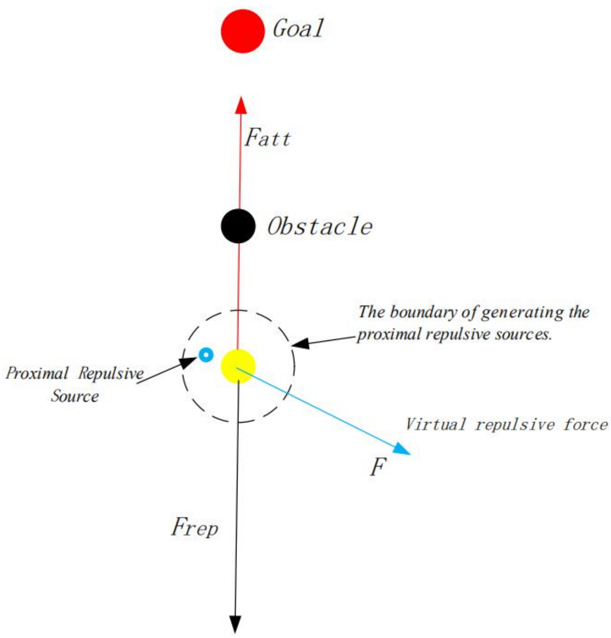

Fig. 3 Improved artificial potential field model

At this point, the repulsive force and the attractive force are of the same magnitude and opposite directions. So we need a proximal repulsive source to break the equilibrium point. The dotted line is the boundary of generating the proximal repulsive sources. A proximal repulsive source is generated in the range randomly, and a new repulsive force F is generated for the robot, which will make the robot move out of the equilibrium position.

4. THE EXPERIMENT PART

In order to solve the problem of local minimum value in path planning, the artificial potential field is improved and can be applied to path planning in an unknown environment.

The optimization and improvement of artificial potential field in an unknown environment cannot detect whether there is an obstacle in the path, so the robot can only move through the gradient of potential field function. The problem of local minimum value in the path process is mainly solved by increasing the repulsive source. When the robot falls into the equilibrium point, the repulsive force source will be generated randomly in the adjacent range with the robot as the center and R as the radius. And the effect of the repulsive force source on the robot is the same as the obstacle. The newly generated repulsive force makes the robot move out of the equilibrium position. When the distance between the robot and the virtual repulsive source exceeds the adjacent range, the repulsive source disappears to avoid secondary interference to the path planning of the robot.

The path planning problem of the algorithm proposed in this paper is mainly carried out in the unknown environment where the general algorithm fails and the obstacle avoidance and the equilibrium point problem are solved.

4.1. The Experimental Apparatus

In order to prove the effectiveness and practicability of the improved algorithm, we all use: Intel(R)Core(TM)i5-10210U CPU@1.60GHz 2.11GHz. The simulation software is MATLAB R2017b.

In the experiment, we first apply the traditional artificial potential field to some typical environments, and then carry out the experiment with the improved artificial potential field method in the same environment. Finally, the conclusion was reached by comparing the simulation results.

In order to ensure that the robot can complete the obstacle avoidance task in practical application, the obstacle is expanded into a graph with regular shape in the experiment, and the robot is set to be expanded into a circle. In the same group of experiments, the same environment was adopted, including the obstacle target points and other information. Three different groups of experiments will be carried out to prove the superiority of the algorithm.

4.2. The Simulation Results

In the three groups of experiments, different typical environments are tested respectively. Experimental environments are difficult to be realized with traditional artificial potential field method. In the following experiments, the range of the robot's repulsive source is 2-3.

4. 2. 1. Experiment 1

In this experiment, the unknown environment is a three-point line of robot, obstacle and target point. Before the robot recognizes the obstacle, it will only move toward the target point. However, during the movement, it will find the obstacle, and then the equilibrium point will appear at a certain moment, as shown in Figure 4. In order to solve this problem, a random repulsive source will be generated around the robot to generate disturbing force on the robot, so that the robot will get rid of the equilibrium point and reach the target point, as shown in Figure 5.

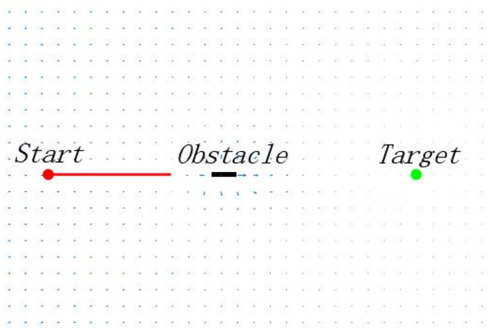

Fig. 4 Equilibrium point in experiment 1

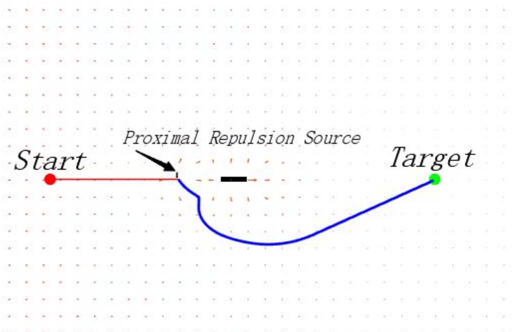

Fig. 5 Improved algorithm in experiment 1

By comparing the experimental results of this group, Some conclusions can be drawn. We can see that repulsive force is generated when the robot recognizes the obstacle. We learn that the repulsive force and the attractive force are opposite, and the formula shows that the repulsive force is increasing and the attractive force is decreasing, so there is an equilibrium point at the position shown in the figure. An equilibrium point appears at the location shown in the figure. By adding the proximal repulsive source around the robot, the robot can successfully complete the path planning.

4. 2. 2. Experiment 2

The environment of this experiment is shown in Figure 6. The connection line between the robot and the target point is the vertical bisector of the wall, and the wall is symmetric around the middle gap. However, due to the unknown global environment, the robot cannot directly pass through the middle of wall and reach the target point.

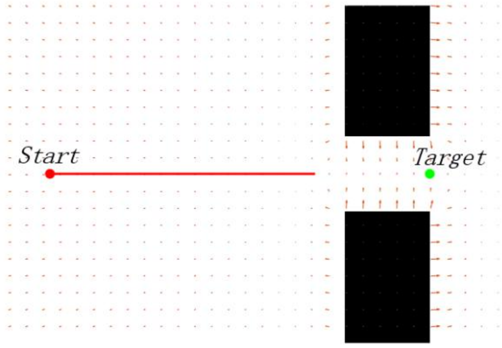

Fig. 6 Equilibrium point in experiment 2

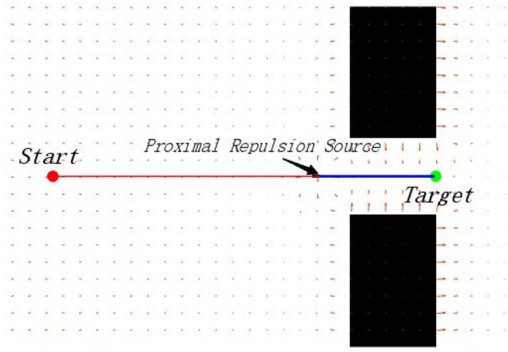

Fig. 7 Improved algorithm in experiment 2

The robot is placed at the starting point on the left, and path planning is started with the improved algorithm. As shown in Figure 6, at one point in the path, a local minimum occurs. The path planning of the environment is tested with the improved algorithm again. The simulation results are shown in Figure 7. The robot completes the path planning by increasing the repulsive force source successfully. Due to the randomness of the increase of the repulsive force source, the repulsive force source will exist in all positions. In this environment, the best point to generate the repulsive force source is on the left side near the robot. In this case, the robot can receive the repulsion continuously and reach the target point in a straight line. By comparing the simulation results, we can see the effect of the repulsive force source and the effectiveness of the improved algorithm.

In order to understand the cause of the equilibrium point and the effect of the improved algorithm more intuitively, the potential field diagram can be used for analysis. Figure 8 is the total potential field diagram without the repulsive force source. The robot moves from the starting position to the target point. The *Z* value in the figures represents the potential field value, and the robot moves along the negative gradient of the potential field value. We can see that there is a local minimum point E at the position where the robot stops, that is, the low-lying point in the potential force diagram. But it is not the location of the target point. Therefore, we need to generate a repulsive source to help the robot get rid of the position. The effect after adding the repulsive force source is shown in Figure 9. The repulsive source makes the potential field at the position of point E not a minimum, and the robot will continue to move along the negative gradient of the potential field.

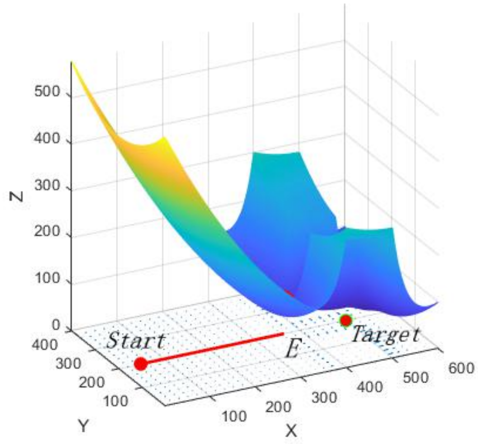

Fig. 8 The total potential field of equilibrium point in experiment 2

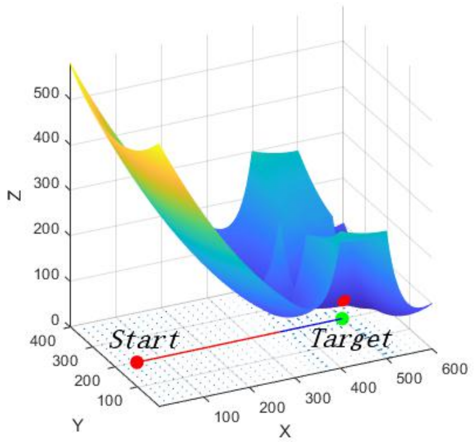

Fig. 9 The total potential field of improved algorithm in experiment 2

4.2.3. Experiment 3

This experiment is carried out in a complex environment which is also unknown. The experiment proves that the algorithm is feasible and effective in the unknown environment.

Experimental environment and the results are shown in Figures 10, 11 and 12. The robot starts from the top left. At point A, the equilibrium point appears, then the proximal repulsive source solves the equilibrium point problem. At point A, the equilibrium point occurs, and the proximal repulsive source is used to solve the equilibrium problem. Two proximal repulsive sources which are generated at different positions cause the following different paths, as shown in Figures 11 and 12. Although the paths are different, they can all arrive at the target point in the shorter paths.

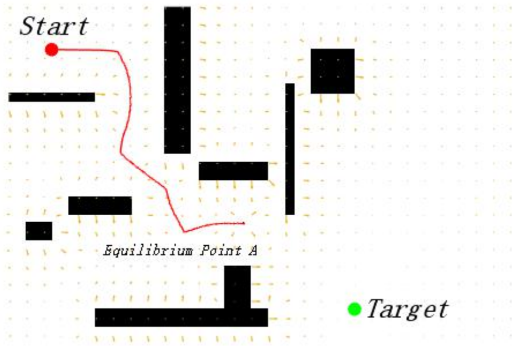

Fig. 10 Equilibrium point in experiment 3

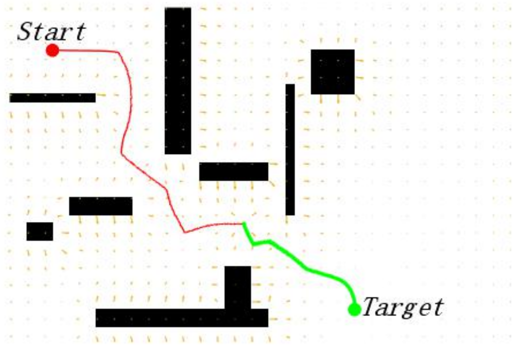

Fig. 11 Improved algorithm in experiment 3

(proximal repulsive source at the first position)

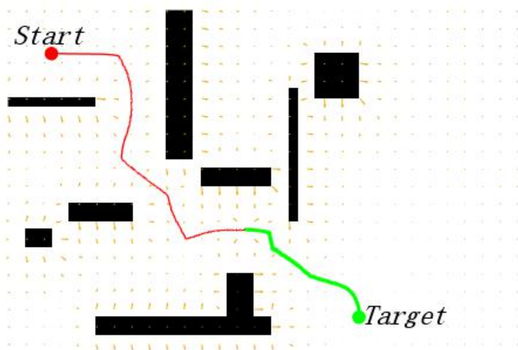

Fig. 12 Improved algorithm in experiment 3

(proximal repulsive source at the second position)

4.3. The Experimental Conclusion

Through the above three groups of experiments, we can conclude that it is effective to improve the artificial potential field in the unknown environment and solve the problem of equilibrium point by increasing the proximal repulsive sources. The improved algorithm can improve the performance of the artificial potential field method significantly and complete the path planning in the unknown environment.

5. CONCLUSION

In this paper, an improved method of artificial potential field is proposed to solve the problem of local minimum by increasing the proximal repulsive sources around the equilibrium point for the mobile robot in the unknown environment. Simulation experiments are carried out in some environments which are difficult to be realized by traditional artificial potential field. Finally the results show that the improved algorithm is feasible and effective, and the performance of artificial potential field is greatly improved.

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