A New Adaptive Artificial Potential Field and Rolling Window Method for Mobile Robot Path Planning

Yalong Zhang[1], Zhenghua Liu[1], Le Chang[1]

1. School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191
E-mail: zyl1503@buaa.edu.cn

Abstract: The artificial potential field (APF) method is a classical path planning algorithm for mobile robots. Although the artificial potential field method is simple, it still has some defects, which limit the scope of its application. In this paper, we propose an adaptive repulsive potential function to solve the problem, goals nonreachable with obstacles nearby (GNRON). Then, the adaptive artificial potential field (AAPF) combined with the rolling window method is used to solve the local-minima problem and can be used for the path planning in dynamic environment.

Key Words: Adaptive Repulsive Potential Function, GNRON, Rolling Window, Local-minima

1 Introduction

Path planning is the key technology of robot navigation and obstacle avoidance. Path planning of mobile robot is to find a collision free trajectory form the starting point to the target point, which can be divided into global path planning and local path planning. Global path planning is based on the information of the robot's work environment is known. Local path planning is suitable for applications where the mobile robot's work environment is unknown or partially known. At present, the commonly used path planning algorithms in robotics are A* heuristic search algorithm, state lattice algorithm, Rapidly-exploring Random Tree (RRT) and artificial potential field algorithm [1]. In addition, there are some artificial intelligent path planning technology, such as, the path planning algorithm based on genetic algorithm (GA), particle swarm optimization algorithm (PSO), and artificial neural network (ANN) [2]. APF is a real-time local path planning method proposed by Uussama Khatib in 1986, and was applied to the collision avoidance of manipulators [3]. The artificial potential field consists of the attractive potential field around target point and the repulsive potential field around the obstacles. The attractive potential field generates the gravitational force to move the robot towards the target. The repulsive potential field produces the repulsive force to move the robot away from the obstacles. Eventually the robot will move in the direction of the resultant of attraction and repulsion

Although the APF has a simple mathematical expression and is easy to use and efficient, there are also some inherent problems: 1) trap situations due to local minima; 2) no passage between closely spaced obstacles; 3) oscillations in the presence of obstacles; 4) oscillations in narrow [4] and 5) goals nonreachable with obstacles nearby (GNRON) [5]. Most previous studies always assumed that the obstacles was far from the goal point, Ge and Cui first described the GNRON problem and gave mathematical analysis of the problem. Then they proposed an improved repulsive potential function to solve GNRON problem. The modified artificial potential field (MAPF) solves the GNRON problem, however, in some cases, the path is more likely to fall into the local minima and longer.

In this paper, we propose an improved adaptive repulsive potential function, which solves the GNRON problem. Compared with MAPF, our adaptive artificial potential field (AAPF) has a shorter path and is less likely to fall into the local minimum. Then, the AAPF is combined with the rolling window method, which solves the defect of the local minima and can be applied to the path planning in the dynamic environment.

This paper is structured as follows. Section 2 describes the traditional APF algorithm and the modified repulsive potential function. In section 3, we propose a new adaptive repulsive potential function. Section 4 shows the principle of the rolling window method, and section 5 lists the results of the simulation experiments in static and dynamic environment.

2 Artificial Potential Field Algorithm

Artificial potential field consists of attractive potential field and repulsive potential field, the attractive potential field drives the robot close to the target, and the repulsive potential field drives the robot away from the obstacles. The artificial potential field follows the principle of minimum energy. In the virtual potential field, the target is in the position where the potential

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energy is the smallest, and the direction of attractive force and repulsive force is the direction of potential energy reduction, so that the robot can reach the goal point.

2.1 Traditional Artificial Potential Field

In the traditional APF, the expression of the attractive potential function is

$$U_{att}(q) = \frac{1}{2}\eta\rho^2 \tag{1}$$

Where η is attractive potential gain coefficient, q is current position of robot, ρ is relative position between the robot and the goal. The corresponding attractive force function is

$$F_{rep}(q) = -\nabla U_{att}(q) = \eta\rho \tag{2}$$

The traditional repulsive potential field function can be represented as

$$U_{rep}(q) = \begin{cases} \frac{1}{2}k\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)^2, \rho \le \rho_0 \\ 0 \qquad\qquad\qquad, \rho > \rho_0 \end{cases} \tag{3}$$

Where k is repulsive potential gain coefficient, q is current position of robot, ρ is the minimum distance between the robot and the obstacle, ρ_0 is a constant which limits the range of the repulsive potential field. When the distance between the robot and the obstacle is greater than ρ_0, the robot will not be affected by the repulsive force. The expression of repulsive force function is

$$\begin{aligned} F_{rep}(q) &= -\nabla U_{rep}(q) \\ &= \begin{cases} k\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)\frac{1}{\rho^2}\frac{\partial\rho}{\partial q}, \rho \le \rho_0 \\ 0 \qquad\qquad\qquad\qquad, \rho > \rho_0 \end{cases} \end{aligned} \tag{4}$$

The robot will be along the direction of the combined force of attraction and repulsion, avoiding the obstacles and moving to the target. The resultant force can be expressed as

$$F_{total} = F_{att} + F_{rep} \tag{5}$$

2.2 Modified Repulsive Force Field Function

Ge and Cui first presented the GNRON defect of APF, and analyzed its causes [5]. When the target is close to the obstacles, the distance between the robot and obstacles and the distance from the robot to the goal point are very small, which makes the attractive force caused by target less than the repulsive force caused by obstacles, so the robot cannot reach the goal point, and oscillates around the target. To solve this problem, they proposed a modified repulsive force field function

$$U_{rep}(q) = \begin{cases} \frac{1}{2}k\left(\frac{1}{\rho_b} - \frac{1}{\rho_0}\right)^2 \rho_g^n, \rho_b \le \rho_0 \\ 0 \qquad\qquad\qquad\qquad, \rho_b > \rho_0 \end{cases} \tag{6}$$

Where k, q, ρ_0 are the same as that used in conventional repulsive force field function. ρ_b is the minimum distance between the robot and the obstacle, ρ_g is the relative distance from robot to the target. The modified repulsion force consists of two components and is given by

$$\begin{aligned} F_{rep}(q) &= -\nabla U_{rep}(q) \\ &= \begin{cases} F_{rep1}\,\mathrm{n}_{OR} + F_{rep2}\,\mathrm{n}_{RG}, \rho_b \le \rho_0 \\ 0 \qquad\qquad\qquad\qquad, \rho_b > \rho_0 \end{cases} \end{aligned} \tag{7}$$

Where

$$F_{rep1} = k\left(\frac{1}{\rho_b} - \frac{1}{\rho_0}\right)\frac{\rho_g^n}{\rho_b^2} \tag{8}$$

$$F_{rep2} = \frac{n}{2}k\left(\frac{1}{\rho_b} - \frac{1}{\rho_0}\right)^2 \rho_g^{n-1} \tag{9}$$

$\mathrm{n}_{OR} = \nabla\rho_b$, $\mathrm{n}_{RG} = -\nabla\rho_g$, $\mathrm{n} > 0$. So the total force is

$$\begin{aligned} F_{total} &= F_{att} + F_{rep} \\ &= F_{att}\,\mathrm{n}_{RG} + F_{rep1}\,\mathrm{n}_{OR} + F_{rep2}\,\mathrm{n}_{RG} \end{aligned} \tag{10}$$

Using the improved repulsive force field function, when the robot is close to the target, the repulsive force is weakened. The closer to the goal point, the smaller the repulsion force is, so that the robot can reach the target. However, the modified repulsive field function has some drawbacks: 1) the repulsive force becomes larger in the region away from the target, and it is easier to fall into the local minimum; 2) as the repulsive force becomes larger, the planned path becomes longer. As shown in Figure 1, the path planned by MAPF is easier trap into local minima.

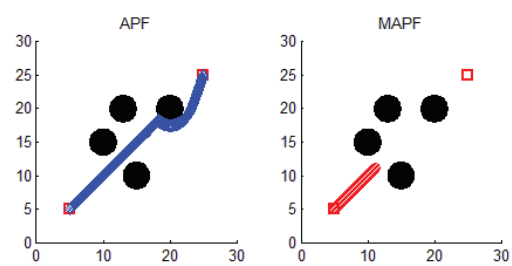

Figure 1 MAPF gets into local minima

3 Adaptive Repulsive Force Field Function

In order to solve some defects of the improved repulsive force field function, we propose a new adaptive repulsive force field function:

$$U_{rep}(q)=\begin{cases}\frac{1}{2}k\left(\frac{1}{\rho_b}-\frac{1}{\rho_0}\right)\frac{\rho_g^n}{1+\rho_g^n}, & \rho_b\le\rho_0\\ 0 & ,\rho_b>\rho_0\end{cases} \quad (11)$$

Where n > 0, when the robot is far away from the target, $\rho_g^n \gg 1$, so $\rho_g^n/\left(1+\rho_g^n\right)\approx 1$, at this time, the repulsive potential field function is equal to the repulsive potential field function in the traditional APF. The formula (11) can be regarded as equivalent to the formula (3). In the region far from the target, the path planned by AAPF is shorter than the path planned by MAPF and not easy to fall into the local minima. When the robot is close to the target, $\rho_g^n \ll 1$, so $\rho_g^n/\left(1+\rho_g^n\right)\approx \rho_g^n$, the repulsive potential function is approximately equal to the modified repulsive potential field function. The formula (11) can be regarded as equivalent to the formula (6). In the vicinity of the target, even if there are obstacles, the robot can reach the goal point.

In the adaptive repulsive field function, the repulsive force is also composed of two components

$$F_{rep}(q)=-\nabla U_{rep}(q)=\begin{cases}F_{rep1}\,\mathrm{n}_{OR}+F_{rep2}\,\mathrm{n}_{RG}, & \rho_b\le\rho_0\\ 0 & ,\rho_b>\rho_0\end{cases} \quad (12)$$

Where

$$F_{rep1}=k\left(\frac{1}{\rho_b}-\frac{1}{\rho_0}\right)\frac{\rho_g^n}{\rho_b^2\left(1+\rho_g^n\right)} \quad (13)$$

$$F_{rep2}=\frac{n}{2}k\left(\frac{1}{\rho_b}-\frac{1}{\rho_0}\right)^2\frac{\rho_g^{n-1}}{\left(1+\rho_g^n\right)^2} \quad (14)$$

4 Rolling Window Method

4.1 Local Window Path Planning

We use the method of rolling window to decompose the global path planning problem into the problem of finding local targets in local window. Specify a local sub-target for the robot in each rolling window. After reaching the local sub-target, the planning window is regenerated with the local sub-goal point as the center, and rolling forward in turn.

Before each search in the rolling window, not only to determine the environmental information in the local window, but also to select the sub-goal of the current window. To select a local window sub-target, it must be combined with the global goal [6]. The global target is known and the location of the local sub-target is on the boundary of the planning window, so the distance between the boundary of the planning window and the global target can be regarded as the heuristic function

$$H(n)=\sqrt{\left[x(n)-x_g\right]^2+\left[y(n)-y_g\right]^2} \quad (15)$$

$$\begin{cases}x(n)=x_r+r\cos\left(\frac{2\pi n}{m}\right)\\ y(n)=y_r+r\sin\left(\frac{2\pi n}{m}\right)\end{cases} \quad (16)$$

Where (x_r, y_r) represents the position of the previous sub-target and the center position of the next window, (x_g, y_g) indicates the position of the global target, r is the radius of the local window, m means that m points are equally spaced on the circumference of the window, n represents the selected nth point. When taking the point i, the window intersects with the obstacle, then take $H(i)=\infty$. When $H(n)$ to take the minimum value, the corresponding point is the new sub-target.

Rolling window combined with AAPF, not only can be applied to the path planning of dynamic environment, and can solve the problem of local minima. When the local window contains obstacles, the radius of the local window is very small, which can be considered as sub-target in the vicinity of obstacles. When the repulsive force is calculated by using the adaptive repulsion force field function, the repulsive force of the robot is relatively small, so it won't fall into local minimum point. Therefore, the local path planning in the window can be regarded as the path planning when the target is near the obstacle. As depicted in Figure 2, when the new adaptive repulsive field function is used in the local window, although the repulsion is weakened when the robot is very close to the target, it can effectively avoid the robot getting into the local minima.

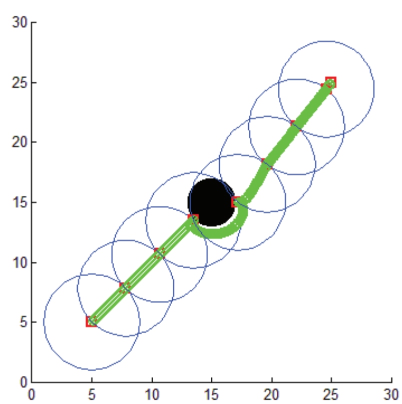

Figure 2 Rolling window gets out local minima

4.2 Path Smoothing

As is shown in the figure 2, the planned path is not a smooth curve, therefore, the implementation of post-processing is necessary to get a relatively smooth trajectory.

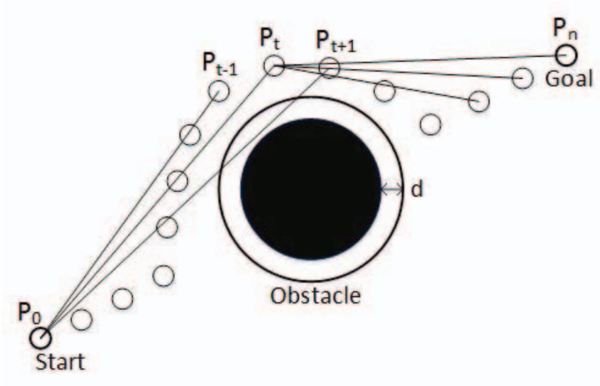

Figure 3 Path post processing

As depicted in Figure 3, the initial path consists of a series of path points, P_0 is the starting point of the path, P_n is the end of the path. In order to make the path smooth and as short as possible, take P_0 as the starting point to connect to other path points until the line intersects the obstacle, such as P_0P_{t+1}. Then take P_t as a turning point of the path and a new starting point, continue to connect with the following points until reaching the target point. d is the radius increment. The expansion of the obstacle radius, can avoid the collision between the robot and the obstacles. Finally, a smooth path is obtained by connecting the turning points and fitting the curve.

5 Simulation Results

In this section, we will present the results of simulation experiments performed in MATLAB R2014a. The simulation results are divided into two parts. In the first part, the comparison between AAPF and APF and MAPF is carried out. The second part shows the results of combining AAPF with rolling window. In the simulation experiments, the specification of robot's working space is 30 m × 30 m. The starting position is (5,5), and the target is (25,25). For APF, MAPF and AAPF, all the attractive potential gain coefficients η are equal to 1 and all repulsive potential gain coefficients are also equal to 1.

5.1 Results of APF, MAPF and AAPF

As shown in Figure 4 and Table 1, when the target is close to the obstacle, the path planned by APF cannot reach the goal point. Although both the paths found by MAPF and AAPF can reach the target, the path planned by AAPF is shorter.

5.2 Results of combining AAPF with rolling window

Firstly, we test the algorithm of combining AAPF and rolling window in static environment. As shown in Figure 5, we get a path that is not regular, but after the post-processing, the irregular path becomes a smooth path. Then, the experimental results in dynamic environment are revealed in Figure 6. The path can avoid the dynamic obstacles to reach the destination.

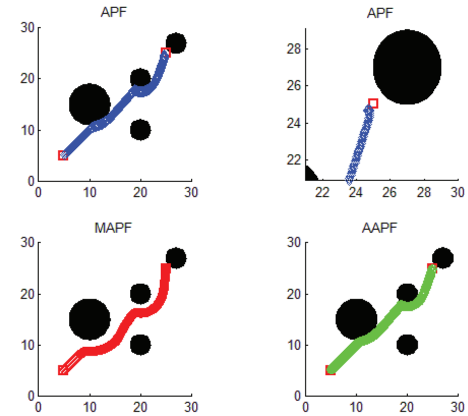

Figure 4 Comparison of AAPF and APF, MAPF

Table 1 Results of APF, MAPF and AAPF

APF	Nonreachable
MAPF	31.3m
AAPF	29.9m

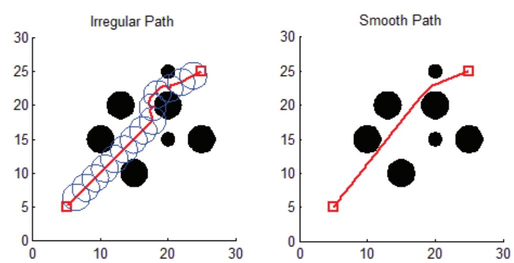

Figure 5 Rolling window path planning in static environment

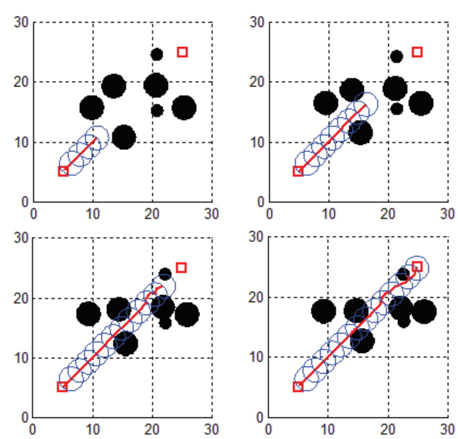

Figure 6 Rolling window path planning in dynamic environment

6 Conclusion

In this paper, we propose a new adaptive repulsive field function, which improves the artificial potential field. Compared with APF, AAPF solves the GNRON problem. Compared with MAPF, AAPF can plan a shorter path, which cannot easy trap into local minima. Then we propose a path planning method based on AAPF and rolling window. This method not only can effectively solve the problem of local minima, but also can be applied to the path planning in dynamic environment.

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