Research on Arbitrary Formation Control of Multiple Robots in Obstacle Environment

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Abstract: To overcome the multi-robots form arbitrary formation in obstacle environment, we propose a control algorithm that combines target allocation algorithm and obstacle avoidance strategy. Firstly, we express the distance between the position of robots and target points by distance information matrix, thus ensure each robot find the corresponding target point. The key idea of the algorithm is to avoid robots from detours and reduce the possibility of collisions between robots. Secondly, the obstacle avoidance is achieved by improving the artificial potential field method integrated with the strategy of moving along the periphery of obstacles. Finally, a simulation environment is established by pygame modules. Simulation results show that the proposed method is feasible and effective.

1. Introduction
With the research and development of robotics technology, multi-robot formation technology has been applied in many fields. For example, in the industrial field, Transport objects by using multi-robot coordination technology [1]; in the military field, multi-robots are involved in coordinated operations and reconnaissance on unknown areas [2]; Yamaguchi [3] proposed a method that multi-robot round up intruders by an arc formation and so on. At present, in the existing literature, there are not many researches on how to form target formation in the context of obstacles, including: Han Xuedong [4] and Hong Bing-rong [5] use formation vector control algorithm to realize multi-robot formation; Zhang Cui-cui [6] proposed a formation control algorithm based on behavior decomposition to achieve multi-robot formation; Yamaguchi [7] proposed a construct control vector method based on local information to form an arc formation and so on.

In fact, the key problem of multi-robots form arbitrary formation in obstacle environment is divided into two points. Firstly, assign the target points to each robot reasonably; secondly, each robot reaches the target point smoothly. To overcome the above mentioned problems, this paper proposes a target point allocation algorithm, combined with the improved artificial potential field method and the strategy of moving along the periphery of obstacles. Through final simulation experiment, it is demonstrated that the proposed method shows satisfactory moving trajectory even in a complex environment.

2. The Target Point Allocation Algorithm
Formation means that a multi-robot system from a disordered state to a designated formation. In general, the robot team mode is divided into static team and dynamic team. This part mainly discusses the static teaming method, we propose a target point allocation algorithm, and the purpose is to make the formation more reasonable and rapid.

The specific steps of the target point allocation algorithm are as follows:
1) Create all robot and target collections \( R = \{R_1, R_2, R_3, \ldots, R_n\} \); \( T = \{T_1, T_2, T_3, \ldots, T_n\} \);

2) Create distance information matrix, the matrix element \( d_{ij} \) represents the distance between the robot \( R_i \) and the target point \( T_j \);

\[
D_{ij} = \begin{bmatrix}
T_1 & T_2 & \ldots & T_n \\
R_1 & d_{11} & d_{12} & \ldots & d_{1n} \\
R_2 & d_{21} & d_{22} & \ldots & d_{2n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
R_n & d_{n1} & d_{n2} & \ldots & d_{nn}
\end{bmatrix}
\]  

(1)

3) Analyze the matrix, find the minimum value of each row and assign a value of 1, the rest of the value of this row is assigned 0;

4) If an element \( (d_{ij}) \) of a row in the matrix is equal to 1, and the rest elements of the column are equal to 0, then the target point \( T_j \) corresponding to the element is assigned to the \( R_i \); If a row element is equal to 1 and there are also some other elements equal to 1 in this column, it means that the target point is the minimum distance of multiple robots, we according to the minimum distance maximum value allocation principle, therefore, the target point \( T_j \) is assigned to the robot \( Ri \) that is farthest from it. Then remove the assigned robots and target points from the matrix;

5) Repeat 2)-5) until all robots find their own target points in the formation.

3. Robot Obstacle Avoidance

In an unknown environment, the robot may encounter different types of obstacles, so it must have obstacle avoidance capabilities. Traditional obstacle avoidance control methods include artificial potential field method, visible image method, and grid method and so on. Artificial potential field method is widely used because of its simple algorithm. However, the traditional artificial potential field method has certain flaws [8]. For example, when the robot approaches a target point or obstacle, gravitation and repulsion may be balanced, as a result, the robot may oscillate near the target point or obstacle attachments.

3.1 The Traditional Artificial Potential Field Method

In the traditional artificial potential field method [9], the repulsive force is applied under the condition that the distance between the robot and the obstacle is smaller than the maximum radius \( \rho_0 \) of the obstacle, ie: \( \rho < \rho_0 \). The value of \( \rho_0 \) is important. If the value is too big, the obstacle will be corrected too early for the robot path; if the value is too small, the robot path may be modified too late, causing the robot is tramping around the obstacle or colliding with the obstacle.

Let \( k \) is the positive proportional gain coefficient, \( X \) is the position of the robot, \( X_g \) is the position of the goal and the \( \rho(X,X_g) \) is the distance between the robot and the target, so the gravitational potential field \( U_g \) at the robot is defined as:

\[
U_g = \frac{1}{2} k \rho^2 (X, X_g)
\]

(2)

And the gravitational force \( F_g \) at robot is defined as:

\[
F_g = k \rho (X, X_g)
\]

(3)

Let \( X_{obs}(i=1,2,\ldots,n) \) is the position of the \( i \)th obstacle, \( \rho(X, X_{obsi}) \) is the distance between the robot and the \( X_{obsi} \), \( \eta \) is the positive proportional gain coefficient, the repulsive potential field is defined as:

\[
U_{rep} = \begin{cases} 
\eta \left( \frac{1}{\rho(X, X_{obsi})} - \frac{1}{\rho_0} \right)^2, & \rho(X, X_{obsi}) < \rho_0 \\
0, & \rho(X, X_{obsi}) \geq \rho_0 
\end{cases}
\]

(4)

And the gravitational force \( F_{rep} \) at robot is defined as:

\[
F_{rep} = \begin{cases} 
\frac{2\eta}{\rho(X, X_{obsi})} - \frac{1}{\rho_0}, & \rho(X, X_{obsi}) < \rho_0 \\
0, & \rho(X, X_{obsi}) \geq \rho_0 
\end{cases}
\]

(5)
3.2 The Improved Artificial Potential Field Method

In this paper, when the robot detects an obstacle in front of it and their distance is less than $b_0$, it triggers obstacle avoidance and introduces an improved repulsive force function. Due to the complexity of the surrounding obstacles, robots may be too close to obstacles, when the distance between the obstacle and the robot is less than $b_f$, as shown in Figure 1. In order to prevent the collision from occurring, the robot performs another strategy, i.e., moving along the periphery of the obstacle. The movement direction of the robot is determined according to the relative relationship between the robot and the target position. When the target position is on the left side of the robot, it moves to the left, and when the target position is on the right side of the robot, it moves to the right.

![Figure 1. Robot obstacle avoidance distance](image1)

As shown in Figure 2, let $R$ is the position of the robot, $\rho(R, T)$ is the distance between the robot and the target point, $K$ is the correction coefficient, and then the gravity function is $F_T$:

$$F_T(R) = K\rho(R, T)$$

(6)

We improved the repulsive force function, introduce the square of the distance between robot and target, so that when the robot approaches the obstacle, the repulsive force increases, ensure the robot moves out of the obstacle within the safety distance. Let $\rho(R, O)$ is the distance between the robot and the obstacle, $n$ is the repulsive force correction coefficient, $\rho_0$ is the maximum radius of the influence of the obstacle, $b_o$ is the maximum radius of the repulsive force function, and $b_f$ is the maximum radius of movement along the obstacle, then the repulsion function $F_o$ is:

$$F_o(R) = \begin{cases} n \ast \left( \frac{1}{\rho(R,o)} - \frac{1}{\rho_o} \right) \ast \rho^2(R,T), & b_o < \rho(R,o) < b_f \\ 0, & \rho(R,o) \geq b_f \end{cases}$$

(7)
So the robot works together under the action of gravity and repulsion:

\[ F(R) = F_T(R) + F_o(R) \]  

(8)

4. Simulation Experiment

The pygame module is used as a mapping tool for simulation verification. Take the upper left corner of the environment map as the origin of the coordinates, the horizontal direction is the X axis, the vertical direction is the Y axis to establish the coordinate system, and the obstacle is indicated in red, green points indicate the starting position of the robot, blue dots represent the target location, and the white line represents the robot movement trajectory.

4.1 Simulation of Obstacle Avoidance Algorithm

Create a map model with a size of 600*600 and a minimum movement unit of 5. Where \( K=0.8, n=0.9, b_i=10, b_o=20, \) the obstacle is 100*100 in size and coordinates is (250,250), the starting point coordinate is (200,400) and the end point coordinate is (280,100). The traditional artificial potential field method obstacle avoidance result is shown in Figure3 (a). The simulation result of combine the improved artificial potential field method and along the wall movement strategy is shown in Figure3 (b).

![Figure 3](attachment:image.png)

(a) The traditional artificial potential field method  (b) The Improved obstacle avoidance algorithm

Figure 3. Results of two obstacle avoidance algorithm

The simulation results show that according to the traditional artificial potential field method, when the target point and the obstacle and the robot are in a straight line, the robot cannot get out of the obstacle and reach the target point; but the improved algorithm can make the robot get out of the obstacle smoothly.

In order to verify the practical effectiveness of the improved obstacle avoidance algorithm, it is applied to a complex environment and the simulation result is shown in Figure4. The simulation results clearly show that in a complex interlaced obstacle environment, the robot can successfully pass through the obstacle area and reach the target position.
Figure 4. Improved Algorithm for Complex Environments

4.2 Simulation of Multiple Mobile Robot Formation
Establish a map model with a size of 800*600, set obstacle groups and discrete obstacles, and can set arbitrary formation. This article takes the “W” formation as an example, mainly consists of five target points, placed on the most obstacles above.

According to the target point allocation algorithm, after the first iteration, the target point of R2 is T2, the target point of R5 is T4, the new robot set is R={R1 R3 R4} and the target point set is R={T1 T3 T5}. Through the second iteration, the corresponding target points of R1, R3, and R4 are T1, T3, and T5, respectively, as shown in figure 5.

Figure 5. The environment map and “W” formation
In combination with the improvement of the artificial potential field method and the movement strategy along the periphery of obstacles, each robot moves along the trajectory toward the target point. The simulation results are shown in figure 6. From the results, we can see that the robot can continuously correct its own movement trajectory according to the target position and obstacle information, finally complete the formation, and prove that the algorithm can run in a complex environment, and the control algorithm is effective and feasible.

5. Conclusion
This paper decomposes the problem of multi-robot arbitrarily forming into two problems: the distribution of arbitrary formation targets and the successful arrival of multi-robots. Using the target point allocation algorithm, the robot may actually avoid the detour and energy waste, and then combined with the improvement of the artificial potential field method and the movement along the periphery of obstacles strategy; finally the robot can reach the target point smoothly. Simulation experiments show that the algorithm is effective.

6. References
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