Local path planning for unmanned surface vehicle with improved artificial potential field method

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Abstract. Aiming at the drawbacks of traditional artificial potential field method in local path planning for USV (unmanned surface vehicle), an improved artificial potential field method is proposed. By improving the gravitational potential field model and restraining the distant gravitational potential field, the problem of USV colliding with obstacles is solved. In the repulsion field model, the influence factors such as relative position and relative velocity are introduced to reduce the repulsion potential field intensity of the obstacle near the target, so as to solve the problem of goal nonreachable with obstacle nearby. The regulation mechanism of random perturbation potential energy is introduced to solve the problem that it is difficult to move at local minimum points. The rationality and superiority of the proposed improved artificial potential field method are verified by simulation and comparison experiments.

1. Introduction

During the voyage of USV (unmanned surface vehicle), there may be dynamic floating obstacles on the sea surface or static obstacles that cannot be shown in the electronic chart, which makes the ship unable to follow the expected path. In order to avoid the risk of collision between USV and obstacles, a path that can timely update the existing navigation route to achieve local obstacle avoidance is planned, which has important theoretical research value for the application of USV in the ocean. At present, the local path planning algorithms mainly include velocity obstacles algorithm [1-2], dynamic window method [3], artificial potential field method [4-6]. Artificial potential field method is widely used in dynamic navigation change planning and local obstacle avoidance due to its advantages of simple structure and quick response. Mabrouk proposed the extended artificial potential field method to solve the problem of dynamic programming [7]. Wu regarded the obstacle as an ellipse and constructed an artificial potential field to explore the obstacle avoidance of mobile robots [8]. Abdalla proposed a path planning method combining improved artificial potential energy method with fuzzy logic [9-10]. Aiming at the drawbacks of traditional artificial potential field method in local path planning of USV, this paper improves the gravitational potential field and the repulsive potential field respectively, and increases the regulation mechanism of random disturbance potential energy, so as to achieve effective local obstacle avoidance effect.
2. The traditional artificial potential field method

2.1. Artificial potential field model
In the virtual artificial potential field, the target position will attract the USV, and the gravity is positively correlated with the distance between the USV and the target position \([11-14]\). The farther the USV is from the target, the greater the gravity will be. The obstacle will generate repulsive force on the USV, and the magnitude of the repulsive force is negatively correlated with the distance between the USV and the target position. The closer the USV is to the obstacle, the greater the repulsive force it will receive. The total potential field superposed by the two potential fields encountered by the unmanned vessel on the sea surface can be expressed as:

\[
U(X) = U_\text{att}(X) + U_\text{rep}(X)
\]

Where, \(X\) is the position coordinates of the current state of the USV; \(U(X)\) is the total potential field; \(U_\text{att}(X)\) is the gravitational potential field generated by the target position; \(U_\text{rep}(X)\) is the total repulsive potential field generated by several dynamic obstacles.

The gravitational potential field function is defined as:

\[
U_\text{att}(X) = \frac{1}{2} k_a \rho^2(X, X_g)
\]

Where, \(k_a\) is the gain coefficient of the gravitational potential field; \(X_g\) is the position coordinates of the target point; \(\rho(X, X_g)\) is the distance between the USV's current position and the target position.

The repulsion potential field function is defined as follows:

\[
U_\text{rep}(X) = \begin{cases} 
\frac{1}{2} k_r \left[ \frac{1}{\rho(X,X_o)} - \frac{1}{\rho_o} \right]^2, & \rho(X,X_o) \leq \rho_o \\
0, & \rho(X,X_o) > \rho_o
\end{cases}
\]

Where, \(k_r\) is the gain coefficient of the repulsion potential field; \(\rho_o\) is the maximum distance affected by the obstacle; \(X_o\) is the position coordinates of the obstacle; \(\rho(X,X_o)\) is the distance between the unmanned vessel's current position and the obstacle.

2.2. Drawbacks of artificial potential field method
The artificial potential field method is flexible, fast, real-time, smooth and safe. However, when artificial potential field method is applied to the path planning of the USV, there are still the following limitations:

- **Collision with obstacles at a distance**
  When the USV is far away from the target, the gravitational potential field it is subjected to will exert such a great gravity that the repulsive potential field generated by the nearby obstacles acting on the unmanned vessel can be ignored. Then, the risk of collision between the USV and the obstacles will be greatly increased.

- **Goal nonreachable with obstacle nearby (GNRON)**
  When there is a dynamic obstacle approaching the target, the repulsion potential field generated by it acting on the USV will be greater than the attraction exerted by the target, then the USV will not be able to reach the target point.

- **Local minimum problem**
  When the USV has not reached the target point but the resultant force is zero, it will fall into the local minimum point and stop moving.

3. Improved artificial potential field method

3.1. Improved gravitational potential field
The gravitational potential field function is composed of quadratic functions, which makes the variation of potential field intensity very sensitive at a distance, and the adjustment effect of potential field function coefficient is not obvious, which is also the fundamental reason for the collision with obstacles at a long distance in the Figure 1. Therefore, the distance threshold of gravitational potential field influence is added into the potential field model construction, beyond which logarithmic function will be used to replace quadratic function in the construction of gravitational potential field, to reduce the variation amplitude of potential field intensity. When the USV passes through the distance threshold affected by the gravitational potential field, it is affected by the intensity fluctuation of the gravitational potential field, so that the change of the gravitational potential energy of the USV becomes gentle and continuous in the Figure 2.

The improved gravitational potential field is as follows:

\[
U_{\text{att}}(X) = \begin{cases} 
\frac{1}{2} k_g \rho^2(X,X_g), & \rho(X,X_o) \leq \rho_g \\
 k_g \rho_g \log_{k_g} \left( \frac{\rho(X,X_g)}{\rho(X,X_o)} \right) + \eta \rho_g^2, & \rho(X,X_o) > \rho_g 
\end{cases}
\]  

(4)

Where, \( \rho_g \) is the distance threshold of potential field influence; \( k_g \) is the influence coefficient of potential field; \( \eta \) is the potential field regulation parameter.

We define a maximum safe distance \( d_o \) for obstacles, which means that the USV is hard to get into the range. If an obstacle moves near the target so that the target is within this range, the USV will fail to reach the target in the Figure 3. We need to take measures to reduce \( d_o \) while ensuring USV security.

In the repulsive potential field function, the distance \( \rho(X,X_g) \) between the USV and the target is introduced as the influence factor. When the USV approaches the target point, the repulsive potential field will be weakened due to the constant decrease of \( \rho(X,X_g) \). When the USV is far away from the target point, \( \rho(X,X_g) \) will increase, which will further strengthen the repulsive potential field and help solve the long-distance collision problem in the Figure 4.
The improved repulsive potential field is:

\[ U_{\text{rep}}(X) = \begin{cases} \frac{1}{2} k_f \left[ \frac{1}{\rho(X,X_o)} - \frac{1}{\rho_o} \right] \left( \frac{\rho(X,X_g)}{\rho_o} \right)^2, & \rho(X,X_o) \leq \rho_o \\ 0, & \rho(X,X_o) > \rho_o \end{cases} \]

(5)

3.2. Improved repulsive potential field

The relative position and relative speed between the dynamic obstacle and the USV may cause unnecessary influence on the repulsion potential field. \( v_u \) and \( v_o \) respectively represent the moving speed of the USV and obstacle; \( l_{ug} \) is the original navigation path of the USV, with the same direction as \( v_u \); \( l_{uo} \) is the relative position of the unmanned vessel and the obstacle, and the direction is pointed from the unmanned vessel to the obstacle; \( v_{ou} \) and \( v_{og} \) are respectively the components of the obstacle’s motion speed \( v_o \), where \( v_{ou} \) represents the motion speed of the obstacle relative to the USV; \( \alpha \), \( \beta \) and \( \theta \) respectively represent angles, indicating that clockwise is the positive direction, marked as shown in the figure in Figure 5.

![Figure 5. Dynamic obstacles without threats](image)

![Figure 6. Dynamic obstacles with threats](image)

When the dynamic obstacle moves towards the direction of the USV, the change of relative position between the USV and the dynamic obstacle is considered to avoid collision. When the dynamic obstacle moves within the threat area of USV, the repulsion potential field model needs to be improved according to the change of their relative positions in Figure 6.

The repulsion field function is improved as follows:

\[ U_{\text{rep}}(X) = \begin{cases} \frac{1}{2} k_f \left[ \frac{1}{\rho(X,X_o)} - \frac{1}{\rho_o} \right] \left( \frac{\rho(X,X_g)}{\rho_o} \right)^2, & \rho(X,X_o) \leq \rho_u \\ 0, & \rho(X,X_o) > \rho_u \end{cases} \]

(6)

Where, \( k_f \) is the adjustable influence coefficient.

3.3. Path planning for solving local minimum problem

When the USV moves to the position of local minimum point, this is the potential energy around is higher than that at this point, thus making the USV trapped in the local minimum point "unable to move". We can add a random disturbance potential energy to the potential field to fill up the sag of potential energy at this local minimum point, so as to get rid of the equilibrium state of USV here. The disturbance potential energy is defined as follows:
\[ \Delta U = k_{\text{dis}} \rho (X_u, X_g)^2 \]  

Where, \( \Delta U \) represents the added disturbance potential energy and its direction is pointed from the USV to the target position; \( k_{\text{dis}} \) is the random coefficient of the adjustable disturbance potential energy.

### 4. Simulation and Discussion

The traditional and improved artificial potential field method were simulated by MATLAB under the same conditions, and then the simulation results were compared, so as to verify whether the improved algorithm could solve the drawbacks of the traditional artificial potential field method.

The green dot startPoint in the figure represents the starting position coordinates of the USV that starts to adjust the path planning. Path_tro, a series of small blue squares, represents the path adjusted based on the traditional artificial potential field method. The purplish red dot endpoint represents the location area of the target point; Small yellow dot \( O_i (i = 1, 2, ..., 11) \) scattered on the way represent the position of the dynamic obstacle when the USV passes near it. From figure 5.7 the path planning of the simulation results, obviously can be found when USV \( O_{10} \) and \( O_{11} \) two obstacles, because of the gravitational potential field and repulsion potential field around together, makes the USV in the near coordinates the potential energy of the local minima problem and target problem, so that no one ship sinked into the force equilibrium condition could not go on.

Under the same condition, the improved artificial potential field method is simulated again, and the results are shown in Figure 8. It is not difficult to find that adding random disturbance as potential energy \( \Delta U \) can make USV out of to the equilibrium state. Therefore, the improved path_imp left a continuous addressable track in the local scope near the two obstacles \( O_{10} \) and \( O_{11} \), and thus solved the problem of unreachable target. Considering the problem of remote obstacle avoidance and energy consumption, the repulsion potential field of the improved algorithm at the obstacle \( O_1 \) is also enhanced, and the path_imp trajectory near the obstacle \( O_6, O_7 \) and \( O_8 \) tends to be smooth, which is also reflected in the simulation results.

### 5. Conclusions

An improved artificial potential field method is proposed in this paper. The gravitational potential field function is improved, so that the weight of the gravitational potential field at a long distance is limited to some extent, and the safety of USV protected by the repulsive potential field from obstacles at a long distance is improved. For the problem of GNRON, the repulsion potential field function is improved to reduce its influence when obstacles move near the target. Aiming at the local minimum problem, the regulation mechanism of random disturbance potential energy is introduced. The
simulation experiments of the traditional artificial potential field method and the improved artificial potential field method are carried out, and the simulation results of both algorithms further verify the rationality and superiority of the proposed improved artificial potential field method.

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