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UNCREWED BOAT PATH PLANNING ALGORITHM BASED ON EVOLUTIONARY POTENTIAL FIELD MODEL IN DENSE OBSTACLE ENVIRONMENT

WEI ZHENG* AND XIN HUANG †

Abstract. In the trajectory planning of crewless ships, the artificial potential field method is commonly used. The results obtained using the classic potential field model for path design are not optimal and cannot fully meet the trajectory design requirements of uncrewed ships. This paper uses the evolutionary potential field model for trajectory planning. The evaluation formula of the potential path is combined with the differential evolution algorithm to evaluate and optimize the potential. A quadratic optimization smoothing algorithm is designed to limit the maximum turning angle of the uncrewed ship. Simulation experiments show that this method is effective and reliable.

Key words: Uncrewed boat; Path planning; Potential modeling; Differential evolution algorithm; Track optimization; Maximum turning angle limit

1. Introduction. The intelligent system of underwater uncrewed ships (UV) consists of motion control, sensors and communication. Among them, the path planning subsystem under the motion control system is the core for the autonomous navigation of uncrewed boats. Finding a new and effective trajectory optimization method is essential in this field.

A commonly used method in trajectory optimization is the artificial potential field method. This method has the characteristics of a simple model, fast calculation speed and smooth path. This method is currently the most widely used underwater uncrewed ship trajectory analysis method. However, the potential model itself has limitations. In practice, further improvement is often needed. Literature [1] uses various escape methods based on the existing potential method to study the problem that uncrewed ships are prone to falling into local minima during movement. In literature [2], the path obtained by integrating the potential field method with the grid model is safe and short but not smooth enough. Literature [3] proposed a tangent potential field method that can solve the local flutter problem of the path. However, the above methods are all based on the classic potential field theory. Because the optimality of the trajectory and rationality are not considered, the trajectory is only optimal from a certain angle. Since the maneuverability of uncrewed ships is not fully utilized, it cannot sufficiently meet the actual needs of uncrewed ships. There has been a lot of theoretical and practical work on the trajectory planning problem of uncrewed ships. Literature [4] proposes a new multi-target aircraft path planning method for the multi-target aircraft path problem. A path hazard evaluation method based on wind, waves and navigability is proposed, but the impact of other vessels and obstacles on path hazards is not considered.

Existing research results [5] have solved the problem of ship path re-planning in complex ocean environments by establishing a conflict hazard model between dynamic obstacles and ships based on the modified rate obstacle method. However, this algorithm only targets a single ship and ignores the influence of stationary obstacles on the course. Literature [6] uses a route planning method that combines A* with the dynamic window method to optimize road length and turning point problems. However, when making local map selection, the dynamic obstacles in the entire environment must first be judged before they can be adjusted, so real-time performance is lacking. Literature [7] presents a fast path optimization algorithm based on Fuzzy greedy. This algorithm can effectively control the growth direction and distribution density of various parts of trees in the

*1. School of Computer Science and Technology, Nanyang Normal University, Nanyang, Henan 473061, China; 2. Henan Engineering Research Center of Service and Guarantee for Intelligent Emergency, Nanyang, Henan 473061, China (Corresponding author, 15538757501@163.com)
†School of Computer Science and Technology, Nanyang Normal University, Nanyang, Henan 473061, China

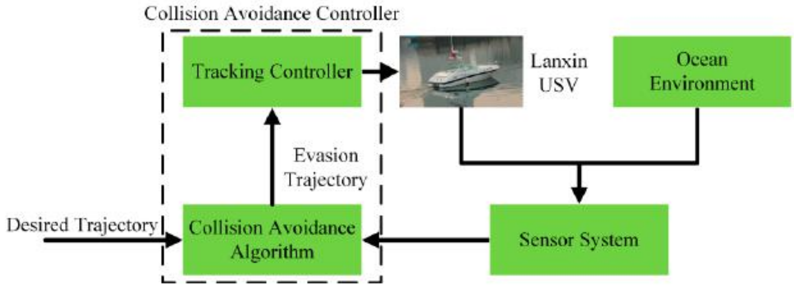

Fig. 2.1: Path collision avoidance coefficient.

configuration space, thereby avoiding various forms of stationary obstacles. However, this method requires high computing power and cannot avoid moving obstacles. Literature [8] uses an improved compressed sensing (CS) algorithm for trajectory planning. It adds a competitive filtering function to optimize the compressed sensing algorithm. Under stationary conditions, this algorithm can solve the local extreme value problem in the motion trajectory. However, due to the poor convergence of the algorithm, collisions in the motion trajectory cannot be effectively avoided. Through research on current uncrewed ship collision avoidance technology, few people can simultaneously conduct real-time collision avoidance against dynamic and static obstacles and static obstacles and discuss how to avoid collision when the two types of obstacles are approaching.

Differential evolution (DE) is a heuristic global optimization method that exploits population differences. This method is obtained by solving the Chebyshev polynomials in literature [9]. Compared with the classic evolution method, the DE method has the advantages of a simple model, fewer control parameters, and good robustness. In recent years, it has been used in areas such as optimization. This paper proposes an artificial potential energy field model based on differential evolution. The optimal properties of DE are added to the classic potential model. The evaluation formula of the geopotential channel is given, and the geopotential channel is modified using an evolutionary strategy. Then, a preliminary optimization of the geopotential trajectory was carried out. At the same time, the maximum turning angle of the uncrewed ship is included in the path planning as a limiting factor of its maneuverability. The smoothing method is used to realize the secondary optimization of the local track. Finally, simulation experiments were conducted under various circumstances to test the method's effectiveness.

2. Evolutionary potential field model for uncrewed ship path optimization.

2.1. Evaluation formula of a geopotential field path. Path optimization is to select the best path based on the path cost. The existing geopotential model lacks a mechanism for path evaluation, but this does not mean it is the best route. To this end, this paper establishes a channel evaluation formula based on the potential field method to compare and analyze various types of channels [10]. When planning the trajectory of an uncrewed ship, the collision avoidance, length, and smoothing coefficients should be comprehensively considered. The collision avoidance factor in the ship's trajectory is essential in ensuring the trajectory's safety. The motion performance of an uncrewed ship is affected by its length and smoothness. The collision avoidance factor is expressed by the sum of the distances between all access points in the area where the repulsive force acts and the corresponding obstacles (Figure 2.1 is cited in Appl. Sci. 2021, 11, 9741). It is the i obstacle in the environment. C_{inf} is the scope of action of the barrier. $O_j, \cdots, O_{j+m}$ refers to the route that falls within this obstacle exclusion circle.

The global avoidance factor of a path is

$$g_\alpha = \sum_{i}^{M} \sum_{j}^{j+m} c(W_i, O_j) \tag{2.1}$$

M is for all obstacles. m is the number of points on all routes that the obstacle passes under the repulsive effect. $c(W_i, O_j)$ represents the shortest distance between obstacle W_i and the j point G on route i. When

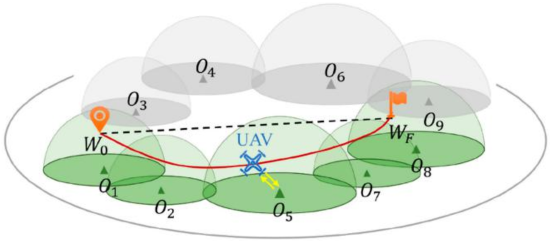

Fig. 2.2: Path Smoothing Factor.

H is larger, the distance between the entire route and the obstacle is more significant. The greater the ship's avoidance, the safer the route. The smoothness of the pathway is expressed by the sum of the spacing between all adjacent pathway points on the pathway (Figure 2.2 is cited in Electronics 2023, 12(11), 2358). O_i, O_{i+1}, O_{i+2} is three adjacent points. c is the length on the straight line from $O_i, O_{i+2}$to. From its structure, it can be seen that when the value of c is more significant, and the angle between the three points O_i, O_{i+1}, O_{i+2} is larger, the route becomes smoother in this area. The overall smoothness of the trajectory is

$$g_s = \sum_{i=1}^{N-2} c(O_i, O_{i+2}) \tag{2.2}$$

NAll access points. $c(O_i, O_{i+2})$is the length of the straight-line distance between $(O_i, O_{i+2})$and the path. As g_s increases, the change in curvature of the entire trajectory gradually decreases. There will be fewer unnecessary turns, making the operating system more efficient. The sum of the distances between adjacent path points approximates the path length. The length factor of this path is

$$g_1 = Ns \tag{2.3}$$

N is the total number of waypoints. s represents the traveling distance of the uncrewed boat. The results show that a smaller value of g_s results in a smaller total distance of the trajectory. Resources and time can be saved while completing this task while improving efficiency. A geopotential pathway efficiency evaluation formula was established based on the pathway as mentioned above efficiency factors.

$$g = \gamma g_\alpha + \delta g_s - \zeta g_1 \tag{2.4}$$

γ, δ, ζ represents the corresponding coefficient weight. It achieved a $\gamma + \delta + \zeta = 1$ grade. These three factors can be set according to their required weights in practical applications.

2.2. Trajectory smoothing based on maximum turning angle. Conventional robots can calculate the potential field force in the potential field through the potential field equation to determine the forward direction of each step of the robot and thus determine the entire path. The trajectory planning problem of uncrewed ships is very different from that of ordinary robots. Given the exceptional environment in which uncrewed ships travel in the ocean and the limitations of their maneuverability, it is often challenging to meet the requirements of engineering applications by only using potential-based methods for route design. This limitation must be considered when determining an uncrewed ship's actual trajectory. The maximum rudder angle is a significant parameter to measure the navigation performance of uncrewed ships [11]. The maximum swing distance is defined on the planned route. Assume that the current track point O_i and track point $\overrightarrow{O_i O_{i+1}}$ are given. The maximum steering angle of the uncrewed ship is κ . The step length is s. Then, the point O_{i+2} of the following straight line can only be limited to the 2κ arcuate AB with the angle DD (Figure 2.3 is cited in Scientific Reports, 2022, 12(1): 13997).

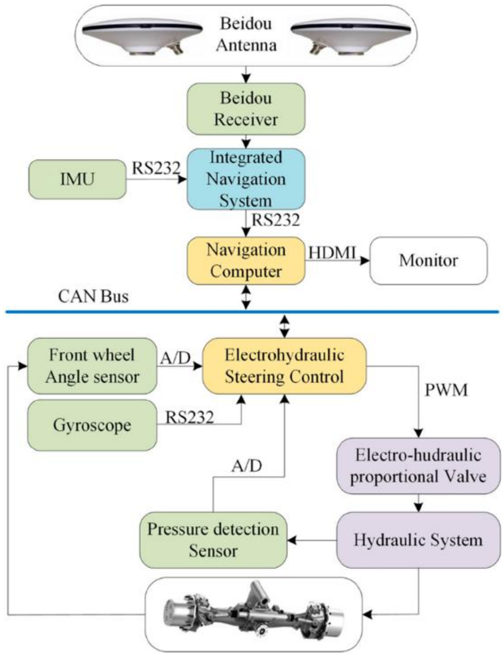

Fig. 2.3: The maximum turning angle of the uncrewed ship in the adjacent stairs.

It can be seen from Figure 2.3 that the maximum turning angle between the two steps is expressed as follows

$$\kappa = 2acr\tan\left(\frac{s}{D}\right) \tag{2.5}$$

Use the potential field method to set the path step size s. The minimum rotation radius D can be obtained through the rotation test of the uncrewed ship. The trajectory generated based on the evolved geopotential model has dramatically improved regarding collision avoidance coefficient, smoothness and trajectory length. However, the potential field method has limitations and cannot simultaneously meet the maximum rudder angle limit. This may result in excessive trajectory angles and unnecessary arcs. It cannot ensure the planned trajectory is reasonable and feasible [12]. This article gives a quadratic optimization method based on the maximum turning angle - the smoothing method. The three routes from the starting point to the end take three adjacent routes O_i, O_{i+1} and O_{i+2} respectively. The angle φ formed by these three points was judged to determine whether it could meet the requirements of the maximum control angle. If the angle κ is larger than the maximum turning angle, the point O_{i+1} passed halfway will be removed. At the same time, the route is updated until all points on the route comply with the maximum turning angle limit (Figure 2.4 is cited in Electronics 2023, 12(11), 2358).

2.3. Improved artificial potential field method. Khatib proposed the artificial potential field method in 1986. The artificial potential field method was used to plan the robot's trajectory.

Its core idea is to regard people's sensory space as virtual power. Obstacles or dangerous areas repel robots. The target point exerts a gravitational force on the robot, and the closer it is to the obstacle, the greater the repulsive force is, and the closer it is to the target point, the greater the gravitational force is. Their combined force then moves the robot towards the target. Establish gravitational and repulsive fields in artificial potential fields. Simplify robots and obstacles into dots to facilitate analysis [13]. The robotic arm and obstacles are converted into dots to facilitate calculation. This paper proposes a modified artificial potential field method to overcome the local minimum problem that is prone to occur in the classic artificial potential function method.

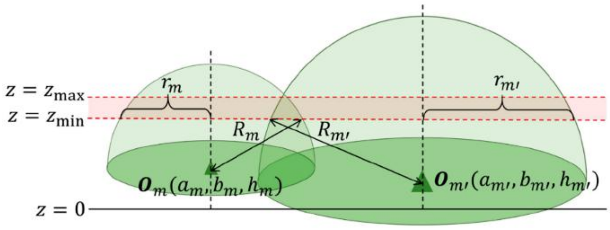

Fig. 2.4: Track smoothing method under maximum turning angle.

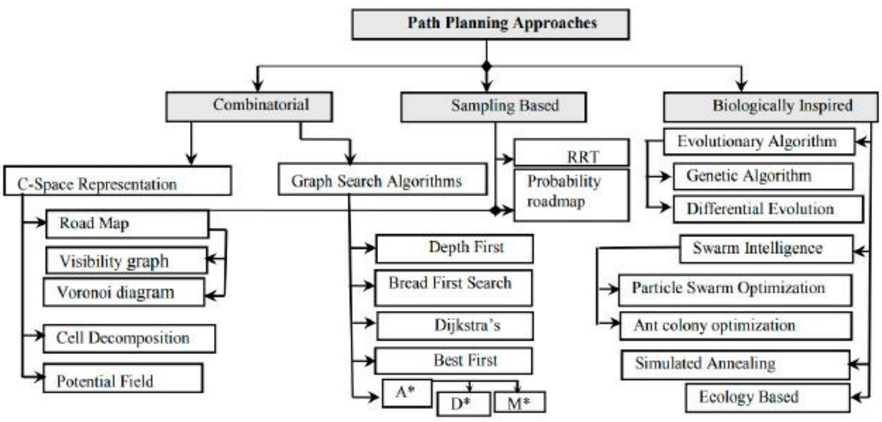

Fig. 2.5: Evolutionary potential field method for uncrewed ship trajectory planning.

The commonly used repulsive potential field is expressed as follows:

$$A_{rep}(w)\begin{cases}\frac{1}{2}\lambda_{rep}\left(\frac{1}{\omega w, w_{obs})}-\frac{1}{\omega_0}\right)^2\omega^n(w,w_{goal}) & \omega(w,w_{obs})\leq\omega_0\\ 0 & \omega(w,w_{obs})>\omega_0\end{cases}\tag{2.6}$$

$\omega w, w_{obs})$ represents the distance between the uncrewed ship and the obstacle. ω_0 represents the area of influence of the repulsive potential field. λ_{rep} is a proportional increase in force. n is the distance coefficient by which the distance to the target can be adjusted. n is 2. The repulsive force formula can be obtained by applying a negative gradient to the repulsive potential field in equation (2.7).

$$G_{rep}(w)=\begin{cases}\lambda_{rep}\left(\frac{1}{\omega w, w_{obs})}-\frac{1}{\omega_0}\right)\frac{\omega^n(w,w_{goal})}{\omega^2(w,w_{obs})} & \omega(w,w_{obs})\leq\omega_0\\ 0 & \omega(w,w_{obs})>\omega_0\end{cases}\tag{2.7}$$

This paper uses the heading selected when avoiding obstacles at the fastest speed to replace the artificial gravity potential, preliminarily changing rates, and replacing rate obstacles in artificial potential fields to ensure that the uncrewed ship leaves the threat area.

2.4. Algorithm flow chart. An uncrewed ship trajectory planning method is proposed. Based on the known environmental factors, the route evaluation formula of the potential field method is established to evaluate the route [14] comprehensively. The parameters in the potential field method were evolutionarily optimized using the DE algorithm, and the optimal trajectory under the potential field method was obtained. Considering the potential field model's limitations, secondary smoothing is performed on the local path points of the potential field path. This achieves the maximum turning angle requirement for uncrewed ships. The specific process of this algorithm is shown in Figure 2.5 (picture quoted from/Proceedings of the 11th National Technical Seminar on Uncrewed System Technology 2019: NUSYS'19. Springer Singapore, 2021: 99-111).

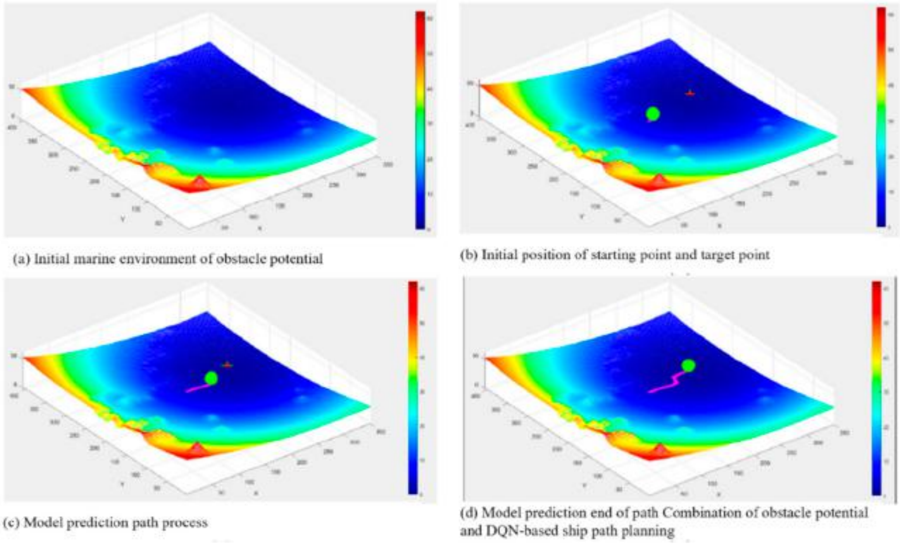

Fig. 2.6: Simulation situation of traditional artificial potential field method.

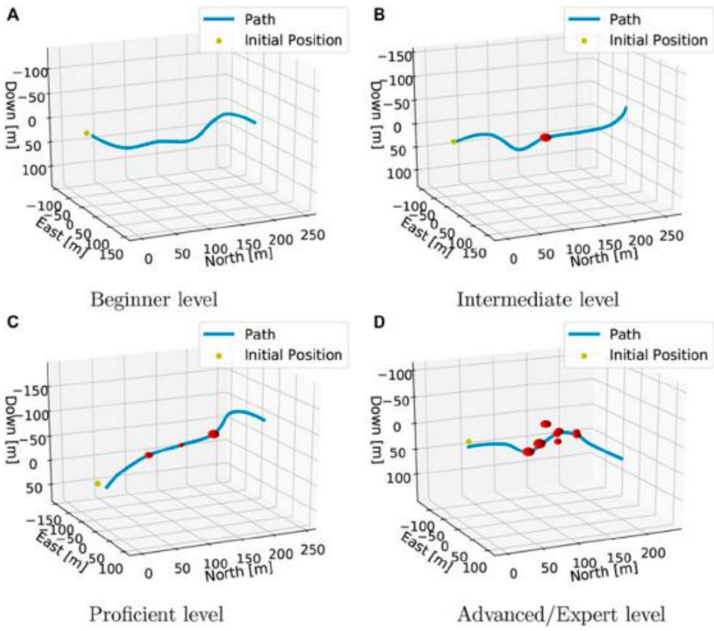

Fig. 2.7: Improved simulation results.

3. Simulation experiments and analysis. This paper tests the effectiveness of this method. According to the obstacle conditions encountered by the uncrewed ship in natural waters, regular obstacles are replaced with specific radius obstacles. And the setting is more realistic. The simulation results are shown in Figure 2.6 (picture quoted from Journal of Marine Science and Engineering, 2021, 9(2): 210.). As shown in Figure 2.6(a), the uncrewed ship is prone to collision when it is close to obstacles and far from the target point. This is because, in the classic "artificial potential" method, the strength of the gravitational potential increases exponentially with the increase in distance, causing collisions [15]. It can be seen from Figure 2.7 (a) that no

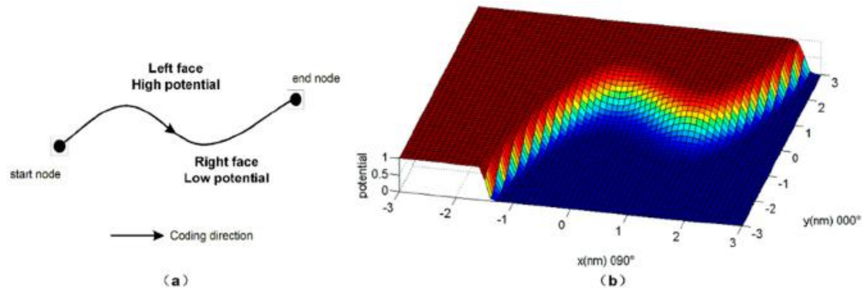

Fig. 3.1: Simulation situation before and after local minimum point situation improvement.

matter how far away the drone is from the target, as long as the gravitational potential field strength exceeds a certain distance, it will always be a specific value and safety accidents can be avoided.

From Figure 3.1, we can see that under the action of 0 net force, an uncrewed ship will stop at the minimum value of a certain point. The uncrewed ship was optimized using differential equations. Although there is still some oscillation, it finally leaves the target point.

4. Conclusion. The artificial potential field method is a local trajectory optimization method that is very suitable for uncrewed ships. However, this method has some flaws that make it problematic in practical applications. This paper proposes a gravitational potential field function and threshold and modifies them with the differential equation method. Finally, the obtained results were tested using the Matlab simulation program. The method proposed in this article can effectively improve the above problems. It can reach the target point safely, even in complex situations.

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