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PATH PLANNING OF THE WAVE GLIDER BASED ON IMPROVED ACOPF

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Abstract. *The wave glider (WG) is a kind of glider which drove by wave energy and complex ocean environment. A kind of improved ant colony optimization with potential field (ACOPF) is proposed in this paper, which is used to realize path planning of WG. Firstly, the algorithm introduces artificial potential field (APF) force into heuristic information of ant colony optimization (ACO). Then the main environmental factors that affect WG speed should be considered. Thirdly, the update strategy of pheromone during iteration is improved by means of punishing the worst local path and rewarding the best local path. The experimental results show that the improved ACOPF not only applies for different marine environments, but also searches the optimal path by synthesizing distance, time, and obstacles avoidance according to the characteristics of WG.*
Keywords: Wave glider, Path planning, Ocean environment, Improved ACOPF

1. **Introduction.** The wave glider (WG) is the autonomous marine environmental monitoring platform, which has epoch-making significance in the field of international marine environmental technology [1]. In 2005, the first autonomous movement platform driven by marine environmental energy was invented by Roger Hine and Joseph D. Rizzi [2]. Four WGs of Liquid Robotics successfully completed the voyage from San Francisco to Hawaii in 2011 [3]. However, the speed of WG is completely influenced by the changeable ocean environmental factors. So it is necessary to design useful path planning algorithm in view of the characteristics of WG and ocean circulation.

The ACO is a relatively mature intelligent optimization algorithm proposed by Marco Dorigo in 1991 [4]. According to the change of external environment, it can make dynamic response, but it has many disadvantages, such as slow convergence speed, and easily trapped into the local optimal solution [5-7]. There are usually some factors influencing the sailing path of WG, such as wave, subsurface water current and obstacles, which need to be incorporated into the path planning algorithm. Based on these considerations above, we choose improved ACOPF to plan the route of WG.

2. **Wave Glider and Environment Modeling.** The WG is composed of 4 to 7 m flexible cable, float and glider, as shown in Figure 1. It absorbs energy from heaving motion of waves at a rate to convert into driving force, uses solar energy system to power all electrical equipment, transfers instructions and data via satellite and base station, and realizes long-range, long-time and large-scale ocean environmental monitoring, which has become the foundational platform of ocean surveillance network and the preferred monitoring tool under extreme ocean environment [8].

FIGURE 1. The wave glider

P. Ngo et al. used environment variables as inputs and gave the linear regression equation to predict WG speed as follows [9].

$$y_{sog} = 0.1623x_{wht} + 0.0086x_{wpp} + 0.0001x_{wdir} + 0.0124x_{wnd} - 0.0557x_{adcp} - 0.2660x_{hfr} \quad (1)$$

In the expressions, y_{sog} is the predicted WG speed; x_{wht} denotes the significant wave height; the wave peak period is marked by x_{wpp}; x_{wdir} is the wave direction offset; x_{wnd} represents the projected wind speed; x_{adcp} denotes the projected water surface current; and x_{hfr} is the projected subsurface water current.

Simplify the expression above only considering the major influencing factors of WG speed.

$$y_{sog} \approx 0.1623x_{wht} - 0.2260x_{hfr} \quad (2)$$

The WG can be considered as a particle in the two-dimensional plane space and assume that: 1) The WG moves in two-dimensional limited space, and has eight kinds of directions; 2) In view of the external size of WG, properly extend the boundary of obstacles; 3) According to the motion model of WG, simplify the ocean environment by ignore the factors which have little influence on WG speed.

Select the grid method to discretize the continuous surrounding of WG because of its convenience and efficiency in processing two-dimensional data [10,11]. In order to improve the efficiency of algorithm, express the grid model by means of serial number and two-dimensional rectangular coordinates. For example, show a path from start to finish point without collision by one-dimensional array, and when the path need be estimated, convert the serial number to two-dimension coordinate through Formula (3).

$$\begin{cases} x = a * (\mathrm{mod}(s/M) - 0.5) \\ y = a * (ceil(s/M) - 0.5) \end{cases} \quad (3)$$

where a denotes the edge length of grid; M is the grid number in a line; mod() is used to take the remainder; $ceil()$ expresses the rounding operation toward positive direction, s is the serial number of grid; and (x, y) is the two-dimension coordinate of grid.

There are two ways to obtain environmental information within a certain range: one way is through the built-in sensors; the other way is by the satellite system. The ocean environmental model for WG is built shown in Figure 2, in which the shades of background represent the change of wave, the static obstacles and ocean current are also considered.

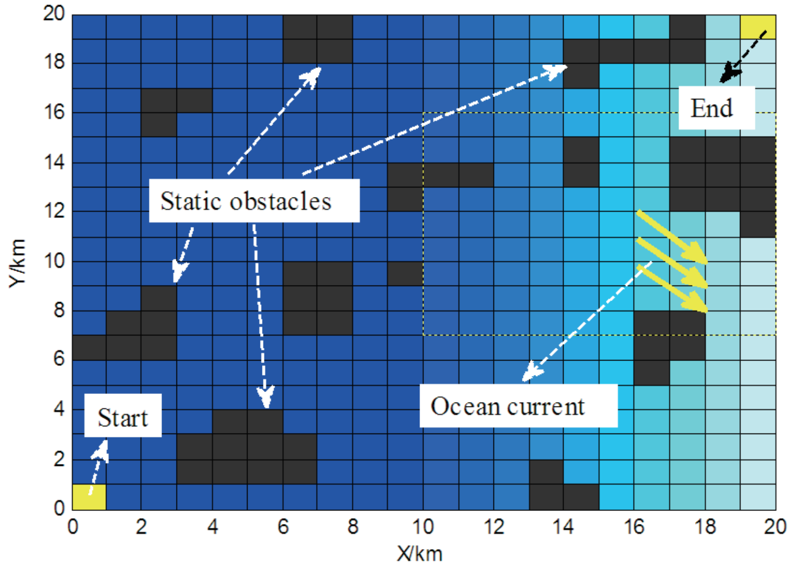

FIGURE 2. The ocean environmental model

3. Improved Ant Colony Optimization with Potential Field.

3.1. Theory of ant colony optimization with potential field. The ant colony optimization (ACO) is an evolutionary algorithm simulating the foraging behavior of ant colonies. In the foraging process, the ant leaves behind a volatile secretion called pheromone on the path, which not only disappears gradually with the passage of time, but has an inverse relationship with distance. The subsequent ant chooses which way to take according to the pheromone concentration. After iterative search, all ants can get the shortest path from the nest to food source [12-14].

The ant_k is used to express the k-th ($k = 1, 2, \ldots, K$) moving ant between grid. The pheromone will be adjusted by the following equations:

$$\tau_{ij}(t+1) = (1-\rho) * \tau_{ij}(t) + \rho * \Delta\tau_{ij}(t) \tag{4}$$

$$\Delta\tau_{ij}(t) = \sum_{k=1}^{m} \Delta\tau_{ij}^{k}(t) \tag{5}$$

$$\Delta\tau_{ij}^{k}(t) = \begin{cases} Q/L_k, & (s_i \to s_j) \in Path(ant_k) \\ 0, & (s_i \to s_j) \notin Path(ant_k) \end{cases} \tag{6}$$

where $\rho \in [0, 1]$ is the decaying-degree of pheromone, $\Delta\tau_{ij}(t)$ is the total pheromone increment of path $(s_i \to s_j)$ in the t-th iteration, $\Delta\tau_{ij}^{k}(t)$ is the pheromone increment which the ant_k leaves behind on path $(s_i \to s_j)$, Q is the pheromone intensity which is a given constant, and L_k expresses the total distance of the ant_k going through.

ACO can be combined with the artificial potential field, which can dynamically avoid obstacles and rapidly reach to the destination [15-18]. When the ant is located in grid s_j, the resultant force $F(s_j)$ is given by the following equations:

$$F(s_j) = F_{att}(s_j) + F_{rep}(s_j) \tag{7}$$

$$\begin{cases} F_{att}(s_j) = \xi \left[L_g(s_j, s_{des}) + \frac{1}{L_g(s_j, s_{des})} \right] \\ F_{rep}(s_j) = \begin{cases} \frac{\mu}{L_n^2(s_j, s_{obs})} \left[\frac{1}{L_n(s_j, s_{obs})} - \frac{1}{L_0} \right], & L_n(s_j, s_{obs}) \le L_0 \\ 0, & L_n(s_j, s_{obs}) > L_0 \end{cases} \end{cases} \tag{8}$$

Here $F_{att}(s_j)$ and $F_{rep}(s_j)$ respectively denote the attraction and repulsion on grid s_j, ξ is the attraction gain, $L_g(s_j, s_{des})$ expresses the distance between the current grid and target, μ is the repulsion gain, $L_n(s_j, s_{obs})$ represents the distance between the current grid and obstacles, and L_0 is the effective radius of repulsive field.

θ_j is the angle between the direction of resultant force $F(s_j)$ and alternative path $(s_i \to s_j)$, then:

$$\eta_{ij} = \frac{e^{\cos\theta_{art}(s_j)}}{L(s_j, s_{des})} \tag{9}$$

As shown in this expression, ensure the correctness of moving direction and reduce inferior solutions due to random search by adding potential field force. The improved heuristic information searches the optimal solution with greater probability, which can effectively reduce the occurrence of premature phenomenon.

3.2. **Improvement method of ACOPF.** In consideration of the complexity of ocean environment and the characteristics of WG, the effect of various factors on the path planning should be comprehensively considered. It is imperative to further improve ACOPF for avoiding obstacles, shortening the path length and increasing the WG speed.

The major factors of impacting the WG speed have significant wave height and subsurface water current. For purpose of increasing the WG speed and shortening the time of travel, incorporate the data of these two factors into the heuristic information of ACOPF.

$$\eta_{ij} = \left(e^{\cos\theta_{art}(s_j)}\right)^{\varsigma} * \left(\frac{1}{L(s_j, s_{des})}\right)^{\sigma} * \left(e^{(a*\sin(X_{wht}(s_j))+b*X_{hfr}(s_j)*\cos(\theta_{hfr}(s_j)))}\right)^{\omega} \tag{10}$$

where $X_{wht}(s_j)$ denotes the significant wave height on grid s_j; $X_{hfr}(s_j)$ expresses the size of subsurface water current; $\theta_{hfr}(s_j)$ is the angle between the direction of subsurface water current on grid s_j and alternative path $(s_i \to s_j)$; a and b respectively denote the influence coefficients of $X_{wht}(s_j)$ and $X_{hfr}(s_j)$ which are confirmed by the kinetic model of WG; ς, σ and ω, whose ranges are from 0.5 to 1.5, are used to adjust the weights of potential field force, basic heuristic information and environmental factors.

Adopt elite strategy in each iteration for strengthening the global search ability and improving the efficiency of algorithm. The optimized update policy is shown below.

$$\tau_{ij}(t+1) = (1-\rho) * \tau_{ij}(t) + \rho * (\Delta\tau_{ij}(t) + \Delta\tau_{ij}^{best}(t) - \Delta\tau_{ij}^{worst}(t)) \tag{11}$$

$$\Delta\tau_{ij}^{best}(t) = \begin{cases} Q/L_{best}, & (s_i \to s_j) \in Path(ant_{best}) \\ 0, & (s_i \to s_j) \notin Path(ant_{best}) \end{cases} \tag{12}$$

$$\Delta\tau_{ij}^{worst}(t) = \begin{cases} Q/L_{worst}, & (s_i \to s_j) \in Path(ant_{worst}) \\ 0, & (s_i \to s_j) \notin Path(ant_{worst}) \end{cases} \tag{13}$$

In the expressions, $\Delta\tau_{ij}^{best}(t)$ and $\Delta\tau_{ij}^{worst}(t)$ respectively denote the additional pheromones to reward the best local path and to punish the worst local path in the t-th iteration; L_{best} and L_{worst} represent the shortest and the longest paths, respectively.

In conclusion, select the improved ACOPF to plan the WG route. The process is shown as follows.

(1) Initialize the parameters of marine environment: the matrix of significant wave height X_{wht}, the matrix of subsurface water current size X_{hfr}, the direction of subsurface water current θ_{hfr}', and the influence coefficient of environmental factors a and b;
Initialize the parameters of ACO: the total number of iterations T, the current number of iterations $t = 1$, the size of ant colony K, the current number of ants $k = 1$, the matrix of original pheromone concentration τ_0, the weight of pheromone concentration α, the weight of heuristic information β, the decaying-degree of pheromone ρ, and the pheromone intensity Q;
Initialize the parameters of APF: the attraction gain ξ, the repulsion gain μ, and the effective radius of repulsive field L_0.

(2) Discretize the marine environment data of WG through the grid method to build four different environment models. In addition, set the starting grid s_{str}, the objective grid s_{obj} and the grids of obstacles.
(3) Put K ants back on s_{str} and initialize the tabu table and path table.
(4) Determine the selectable grids of ant_k $(k = 1, 2, \ldots, K)$ according to the tabu table. Compute the improved heuristic information η_{ij} of each selectable grid.
(5) Caculate transfer probability $p_{ij}^k(t)$. Select the next grid by roulette method based on $p_{ij}^k(t)$ and then record this positional information in the tabu table.
(6) Judge whether the ant_k reaches s_{obj}. If not, return to the step (4). Otherwise, record this foraging route and path length in the path table and execute the next step.
(7) Judge whether k is less than or equal to K. If not, set $k = k + 1$ and then return to the step (4) until meet the judging condition.
(8) On the basis of the path table, choose the best local path and the worst local path. Update the pheromone concentration of each path.
(9) Judge whether the terminal condition $(t = T)$ is met. If not, set $t = t + 1$ and then return to the step (3). Otherwise, export the optimal feasible path of WG.

4. **Simulation and Analysis.** In order to validate the performance of the improved ACOPF, the experiment takes MATLAB R2014a as the programming platform to plan the WG path in four kinds of common marine environments. After experimenting repeatedly, set the starting grid $s_{str} = 0$, the objective grid $s_{obj} = 400$, the total number of iterations $T = 60$, the size of ant colony $K = 30$, the decaying-degree of pheromone $\rho = 0.85$, the pheromone intensity $Q = 6$, the influence coefficient $a = 0.3$ and $b = 0.7$, etc.

1) Apply the improved ACOPF to plan the WG path in the first marine environmental conditions, where the wave remains unchanged, and the subsurface water current is non-existent. In the first marine environment, the WG speed has no change. As it can be seen from the Figure 3, there are two optimal paths with same length under the influence of this algorithm.

2) Seek the best path by the proposed algorithm in the second state of marine environment. There is no environmental change in the region $\{(x, y)\,|0 \le x \le 10, 0 < y \le 20\}$.

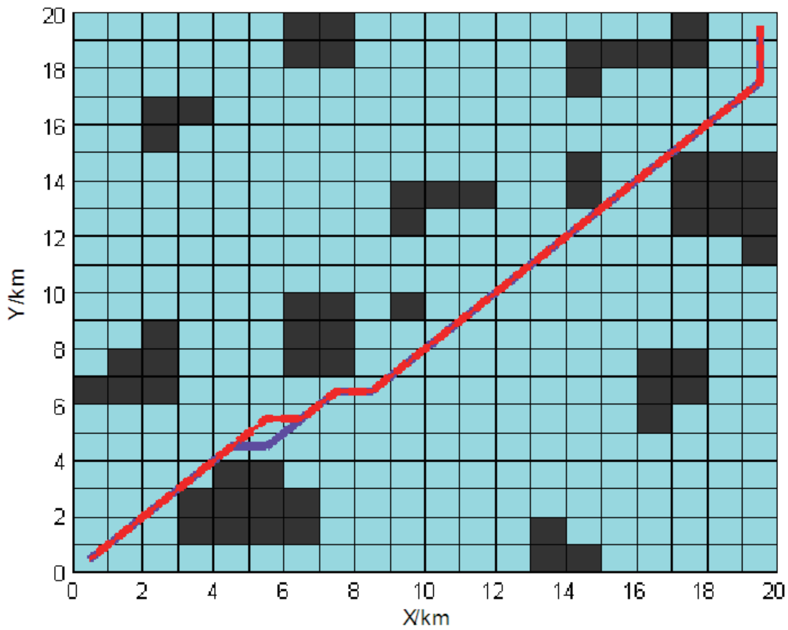

FIGURE 3. The optimal path of WG (Fixed wave height, No ocean current)

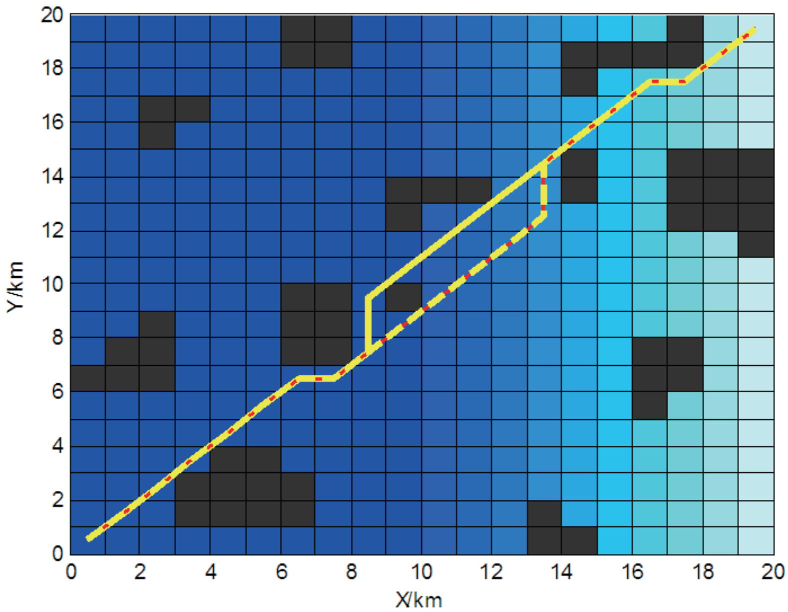

FIGURE 4. The optimal path of WG (Variable wave height, No ocean current)

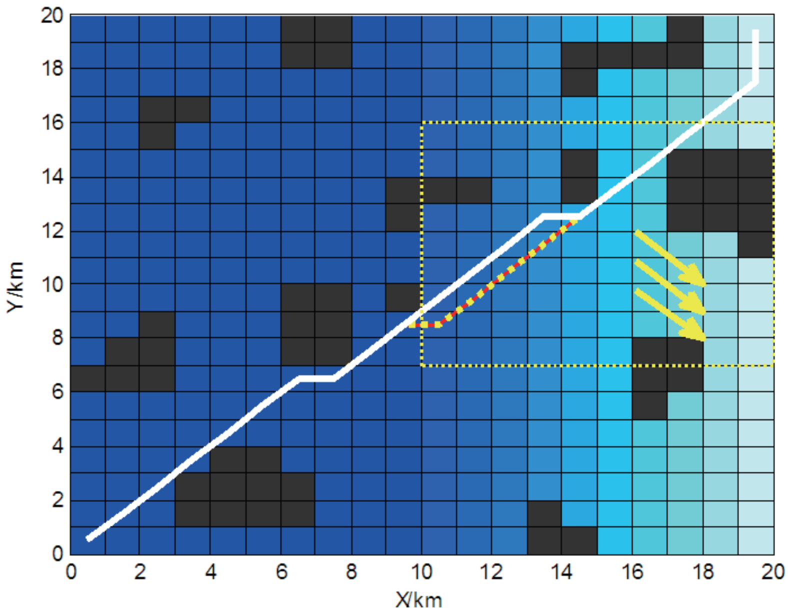

FIGURE 5. The optimal path of WG (Variable wave height, Fixed ocean current)

In the area $\{(x, y) \,|10 < x \leq 20, 0 \leq y \leq 20\}$, the size of significant wave height decreases with the increase of x coordinate and the other environmental factors remain the same. It is clear in the simulation results that this algorithm makes the WG move to the objective grid along the locations of larger wave energy, as it can be seen from Figure 4.

3) Use the improved ACOPF to plan the route of WG in the third marine environmental conditions. In the region $\{(x, y) \,|0 \leq x \leq 10, 0 \leq y \leq 20\}$, the environmental factors remain constant. The size of significant wave height decreases with the increase of x coordinate in the area $\{(x, y) \,|10 \leq x \leq 20, 0 \leq y \leq 20\}$. And the southeast-oriented subsurface water current exists in the district $\{(x, y) \,|10 < x \leq 20, 8 \leq y \leq 16\}$, where the WG speed is mainly affected by subsurface water current, secondly by wave. It can be

seen from Figure 5 that the algorithm can still plan an optimal path in the more complicated situation.

5. **Conclusion.** The wave glider is a sort of autonomous mobile platform with many functions, which has many advantages over the other monitoring platforms. With the purpose of voiding obstacles, enhancing the WG speed and achieving the large-scale underway measurement, the improved ACOPF is proposed in this paper based on the features of WG. This algorithm not merely overcomes the deficiency of the traditional ant colony algorithm, but also makes improvements in view of the power source of WG, which has higher research value and huge market application foreground. However, except the wave and subsurface water current, there are other environmental factors of influence on the WG speed. So it is necessary to incorporate other factors into the path planning algorithm in the future research.

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