A Research on Intelligent Obstacle Avoidance for Unmanned Surface Vehicles

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***Abstract*—In order to solve the problem of intelligent obstacle avoidance when an unmanned surface vehicle navigates autonomously in a complex marine environment, the obstacle avoidance is divided into stationary obstacle avoidance and dynamic obstacle avoidance. Based on the ant colony algorithm, the local path planning of the simplified model of the unmanned surface vehicles is carried out to achieve the static collision avoidance. And in accordance with the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), a dynamic obstacle model is established and calculated to obtain the changes of the speed and course of the unmanned surface vehicles under different encounters. It is shown through the simulations that the proposed approach considering multiple factors can achieve the automatic collision avoidance.**

***Index Terms*—unmanned surface vehicle; ant colony algorithm; Intelligent Obstacle Avoidance**

I. Introduction

Unmanned Surface Vehicles (USVs) are the new type of autonomous marine vessles that can execute multiple tasks such as maritime operations, sea area monitoring and marine environment monitoring. USVs are characterized by high speed, high security and multi-functional integration. In recent years, unmanned surface vehicles have been widely used especially in industry and the military.

The intelligent obstacle avoidance of the USVs is one of the key technologies in the marine vessles intelligent research. Following decades of research and development, the intelligent obstacle avoidance of the USVs has made long-term progress. ZHUANG Guiyuan at al. [1] realized the global path planning for USVs based on improved Dijkstra algorithm, where reducing the planning time and improving the planning precision. Campbell at et al. [2] studied the path planning of unmanned ships based on the COLREGS.WU Bo at al. [3] provided a dynamic obstacle avoidance method for USVs based on the speed obstacle principle, which can achieve the obstacle avoidance safely and smoothly. A dynamic collision avoidance method of USVs was realized based on speed adjustment method that can generate the suitable guidance angle and velocity [4].

The above methods have certain references for realizing the intelligent obstacle avoidance of USVs, but there are still lots of things worthy of in-depth discussion and improvement. For example, in order to realize the autonomous obstacle avoidance, it is necessary to continuously update the environmental information, so that make the calculation amount larger. If establishing a simple obstacle avoidance model and algorithm, the calculation process of the changes of the speed and course of the USVs will be greatly simplified, and the timeliness of intelligent collision avoidance will be improved.

II. Model of Unmanned Surface Vehicles

In the collision avoidance process of USVs, the main influencing factors are speed, heading, location, etc., so it cannot be considered as a particle. In order to ensure the safety of navigation, when the unmanned surface vehicle passes through the obstacle, not only the hull cannot touch the obstacle, but also leaving a certain safety distance from the obstacle. Therefore, we set the sail safety range of USVs according to the Goodwin ship model modified by the British scholar Davis. Normally, the center of gravity of the unmanned boat is used as the center of the circle, and the length overall is used as the radius. The covered area is the safe navigation range and the simplified model of the unmanned boat.

During the navigation of the unmanned boats, the stationary obstacles encountered can often be abstractly referred to as irregular polygons. Taking into account the uncertainty and randomness in the navigational process, several irregular polygons can be randomly generated as the static obstacles. Connecting the vertices of each static obstacle to the start and end points of the unmanned boat and finding the midpoint of each link line, thereby forming a mesh model for initial path planning.

III. Research on stationary obstacle avoidance

A. Path planning based on ant colony algorithm

Initial path planning based on Dijkstra algorithm. Firstly, the starting point S, the midpoint V_i of the link line and the terminal T are connected. And these lines are regarded as a series of feasible tracks. Then find the shortest path $S->p_1->p_2->...->p_i->T$ by Dijkstra algorithm. The track node P_i is the intersection point between the shortest track and the midpoint V_i of the link line.

In computer science and operations research, the ant colony optimization algorithm (ACO) is a probabilistic technique for solving computational problems which can be reduced to finding good paths through graphs. Artificial Ants stand for multi-agent methods inspired by the behavior of real ants. The ant K (k=1, 2, ... M) determines the next visiting city according to the pheromone concentration on the connection paths between each city. And set up $P_{ij}^{k}(t)$ to express the probability that the ant K is transferred from city I to city J at time t,and the formula is as follows:

$$\rho_{i,j}^{k}=\begin{cases}\frac{[\tau_{i,j}(t)]^{\alpha}*[\eta_{i,j}(t)]^{\beta}}{\sum\limits_{s\in allow_k}[\tau_{i,s}(t)]^{\alpha}*[\eta_{i,s}(t)]^{\beta}} & s\in allow_k\\ 0 & s\notin allow_k\end{cases}$$

Where $\eta_{i,j}(t)={}^{1}\!/_{d_{i,j}}$, and it indicates the degree of expectation of the ants moving from city I to city J. $allow_k$ are a set of cities to which the ant k is to visit. α is the pheromone importance factor. β is the importance factor of heuristic function.

When the ant is looking for the shortest path, the pheromone will be released, and the pheromone on the connection path between the cities will be gradually disappeared. The parameter indicates the degree of volatilization of the pheromone. After all ants have visited all cities, the concentration of pheromone on the connection path between cities needs to be updated in real time:

$$\begin{cases}\tau_{i,j}(t+1)=(1-\mathrm{P})\,\tau_{i,j}(t)+\Delta\tau_{i,j}\\ \Delta\tau_{i,j}=\sum\limits_{k=1}^{n}\Delta\tau_{i,j}^{k}\end{cases}$$

Where $\Delta\tau_{ij}{}^{k}$ indicates the pheromone concentration released by the kth ant on the path between city i and city j; $\Delta\tau_{ij}$ denotes the sum of pheromone concentrations released by all ants in the connection path between city i and city j.

B. Simulation analysis of stationary obstacle avoidance

Using Matlab software to test the feasibility of the collision avoidance strategy based on ant colony algorithm. The parameters are set as: pheromone calculation parameter $\beta=2$, population number m=10, cycle number N_c=500, pheromone selection threshold μ_0=0.8, and pheromone update parameter p=[0.1 0.0003]. The initial track according to the Dijkstra algorithm is shown in Fig. 1, which is $S->v_8->v_7->v_6->v_{12}->v_{13}->v_{11}->T$. The final optimization track based on the ant colony algorithm is shown in Fig. 2.

Through simulation experiments, the data of the number of iterations and the total path length are recorded in Table 1. It is clear to see from the TABLE 1 that the total length of the initial path obtained by the Dijkstra algorithm is 223.66km. When the number of iterations is 163, the optimal value is obtained, that is, the shortest path is 173.82km.

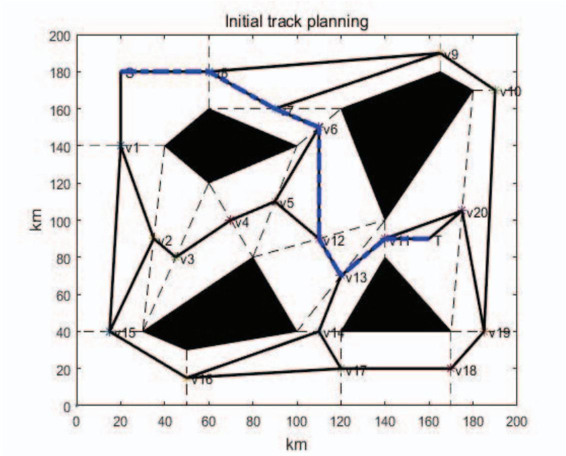


Fig. 1: The initial track

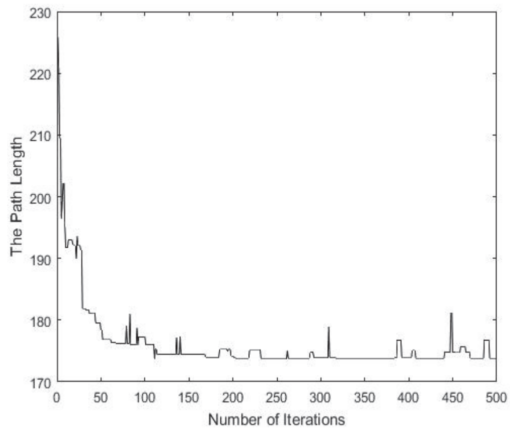


Fig. 2: Convergence trend of fitness value

IV. Research on dynamic obstacle avoidance

A. Dynamic obstacle avoidance behavior calculation

When USVs operate in complex marine environments, Cameras, Automatic Radar Plotting Aids (ARPAs), compasses and Global Positioning System (GPS) devices are widely employed for environment perception and obstacle detection

TABLE I: Data of the number of iterations and the total path length

Number	Iteration	Length(KM)	number	Iteration	Length(KM)
1	1	223.66	6	100	173.99
2	5	200.64	7	130	174.44
3	15	190.59	8	163	173.82
4	40	181.05	9	200	173.99
5	70	174.44	10	300	173.82

on most USVs to get the information such as the shape, speed and position of the dynamic obstacle to establish the dynamic obstacle model which is shown in Fig.3. The relevant motion parameters of the USV are calculated to predict its future velocity and position and to design the suitable collision avoidance strategy. The coordinates of the USV are (x_0, y_0)

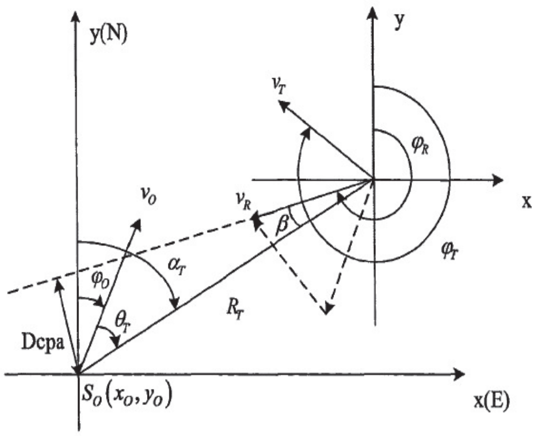


Fig. 3: dynamic obstacle model

whose heading is φ_0 and speed is v_0; the coordinates of the obstacles detected by the ship are (x_T, y_T) whose heading is φ_T and speed is v_T. The velocitys of the USV and obstacles are decomposed in the direction of x and y to obtain v_{x_0}, v_{y_0}, v_{x_T}, v_{y_T}. The relative movement speed of the obstacle and the unmanned boat is v_R. The position of the obstacle relative to the unmanned boat is described as:

$$\alpha_T = \arctan \frac{x_T - x_0}{y_T - y_0}$$

The distance R_T between the unmanned surface vehicle and the obstacle is:

$$\alpha_T = \arctan \frac{x_T - x_0}{y_T - y_0}$$

Collision risk assessment is vital before an USV makes any obstacle avoidance decisions. The risk assessment is mainly determined by the closest point of approach (DCPA), the time to the closest point of approach (TCPA), vessel size and the preset safety distance, which together reflect collision possibility and the degree of collision risk. The lower the DCPA, the greater danger of collision; the lower the TCPA, the more urgent it is to take obstacle avoidance action. If the DCPA is less than a preset threshold distance in future time, the USV is in danger of collision with other vessel(s).

$$DCPA = R_T * \sin(\varphi_R - \alpha_T - \pi)$$

$$TCPA = \frac{R_T * \cos(\varphi_R - \alpha_T - \pi)}{v_R}$$

The ship collision risk is not a certain value, it is floating, and the randomness is strong. Therefore, the fuzzy mathematics method can be selected to obtain the collision risk. When obstacles collide with an unmanned surface vehicle, dangerous membership functions u_{DCPA_i} , u_{TCPA_i} , $u_{R_{Ti}}$, $u_{\theta_{Ti}}$, u_{K_i} are established for each obstacle respectively, and the collision risk expression of each obstacle is:

$$f_i\left(u_{DCPA_i}, u_{TCPA_i}, u_{R_{Ti}}, u_{\theta_{Ti}}, u_{K_\mathrm{i}}\right) = \alpha_{DCPA} * u_{DCPA_i} + \alpha_{TCPA} * u_{TCPA_i} + \alpha_{T_i} * u_{R_{Ti}} + \alpha_{\theta_T} * u_{\theta_{Ti}} + \alpha_K * u_{K_\mathrm{i}}$$

Where the weights of α_{DCPA}, α_{TCPA}, α_{T_i}, α_{θ_T}, α_K are the weights corresponding to obstacles respectively, and the value ranges from [0,1] to 1. The membership function of DCPA is the u_{DCPA_i}:

$$\begin{cases} 1 & |DCPA_i| \le d_1 \\ \frac{1}{2} - \frac{1}{2}\sin\left[\frac{\pi}{d_2 - d_1}\left(|DCPA_i| - \frac{d_1 + d_2}{2}\right)\right] & d_1 < |DCPA_i| \le d_2 \\ 0 & d_2 < |DCPA_i| \end{cases}$$

And the membership function of TCPA is the u_{TCPA_i}:

$$\begin{cases} 1 & |TCPA_i| \le t_1 \\ \left(\frac{t_2 - |TCPA_i|}{t_2 - t_1}\right) & t_1 < |TCPA_i| \le t_2 \\ 0 & t_2 < |TCPA_i| \end{cases}$$

Where t_1 and t_2 refer to the shortest and longest time to avoid collision in an emergency situation.

And the membership functions of θ_T and K are $u_{\theta_{Ti}}$ and u_{k_i}:

$$u_{\theta_{Ti}} = \frac{1}{2}\left[\cos(\theta_{Ti} - 19°) - \frac{5}{17} + \sqrt{\frac{440}{289} + \cos^2(\theta_{Ti} - 19°)}\right]$$

$$u_{k_i} = \frac{1}{1 + \frac{w}{K_i\sqrt{K_i{}^2 + 1 + 2K_i \sin C}}}$$

B. Dynamic collision avoidance strategy

By changing the heading of the USVs to achieve the purpose of dynamic collision avoidance. And what is the most important is to find out the number of the steering angle ΔC. Based on the dynamic obstacle model, it can be concluded that:

$$\sin\beta = \frac{DCPA}{R_T}$$

$$\beta = \arctan \frac{\sin(\Delta C + \theta_T) - \sin\theta_T - \beta\sqrt{K^2 - \sin^2\theta_T}}{\cos(\Delta C + \theta_T) + \beta\sin(\Delta C + \theta_T)}$$

Where β refers to the relative motion angle; K refers to the speed ratio of obstacles to USV; ΔC refers to the steering angle. In the case of known β, we can get the ΔC by Newton iteration.

$$\Delta C_{n+1} = \Delta C_n + \frac{\sin(\Delta C_n + \theta_T) - \sin\theta_T - \beta * \sqrt{K^2 - \sin^2\theta_T}}{\cos(\Delta C_n + \theta_T) + \beta\sin(\Delta C_n + \theta_T)}$$

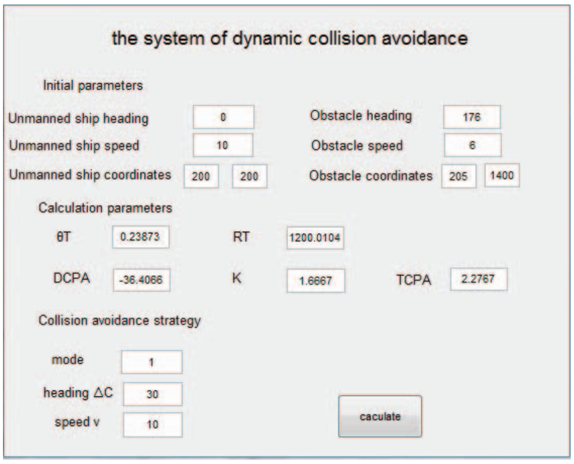
In some emergency situations, it is necessary to change the speed and heading of the unmanned ship at the same time to achieve collision avoidance. By taking a weighted approach to determining the amount of changes in course and speed of the unmanned vehicle. ΔC_1 and V_1 are described as:

$$\Delta C_1 = \Delta C - (1-u)^2 * \Delta C$$

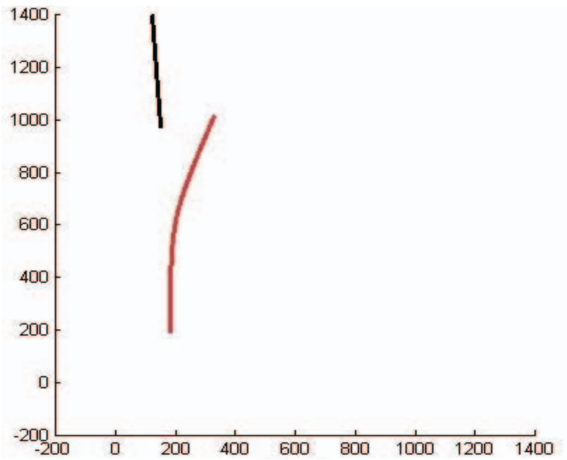
$$v_1 = (1-u) * v_0$$

C. Simulation analysis of dynamic obstacle avoidance

In system (1), when the obstacle avoidance situation is the head-on situation. Suppose the initial states of the USV and dynamic obstacle are the heading , speed and coordinates of the USV are 0°, 10 m/s and (0,0) and the heading , speed and coordinates of the obstacle are 178°, 6 m/s and (5,1200). The collision avoidance simulations are shown in Fig.4 (a) and (b).



(a)



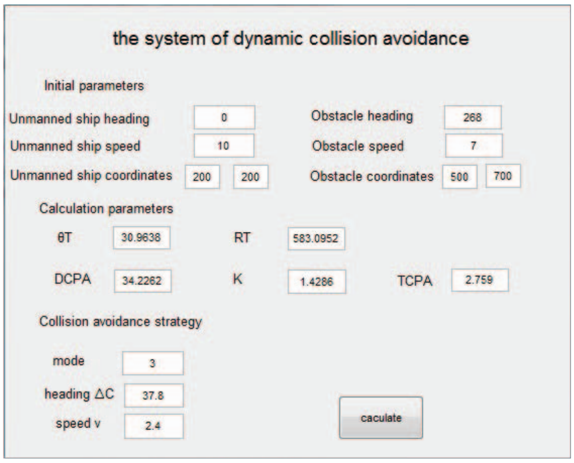
(b)

Fig. 4: (a)Parameter calculation for system(1);(b)Navigational trajectories for system(1).

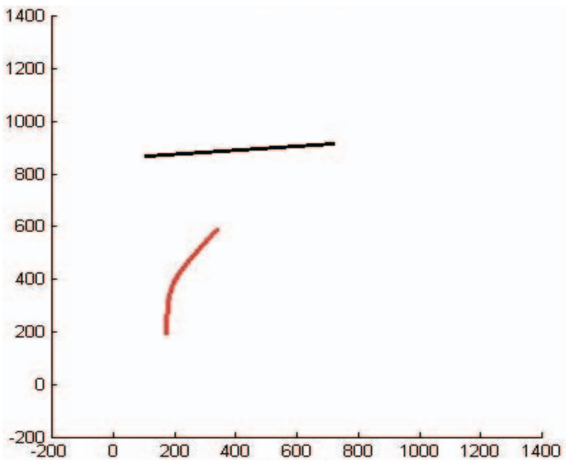
In Fig.4 (b), The black curve represents the track of obstacles, and the red curve represents the track of the USV.

When the USV met the front of the dynamic obstacles, we can get the calculation results of each motion parameter like the relative position of 0.2387°, the distance between each other of 1200m, the DCPA of -20.7066, the speed ratio of 1.6667 and the TCPA of 1.2943. At this obstacle situation, the USV can adopt a steering avoidance strategy. Turning to 30° can achieve the obstacle avoidance safely.

In system (2), when the obstacle avoidance situation is the head-on situation, the initial states of the unmanned boat and obstacle are assumed to be: the USV's heading is 0°, the speed is 10m/s, and the coordinate is (0,0); the obstacle's heading is 268° with a speed of 7m/s and a coordinate of (500,700). The collision avoidance simulation is shown in Fig.5 (a) and (b). In Fig.5(b), The black curve represents the track of obstacles,



(a)



(b)

Fig. 5: (a)Parameter calculation for system (2); (b) Navigational trajectories for system(2).

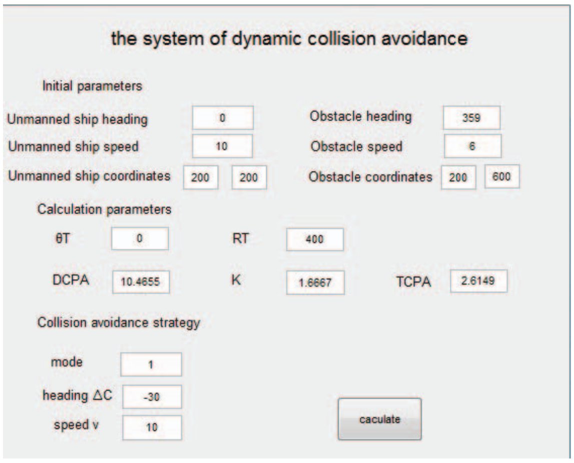
and the red curve represents the track of the USV.

When the USV and the dynamic obstacle crossed each other, we can get the calculation results of each motion parameter like the relative position of 35.54°, the distance between each other of 860m, the DCPA of -18.1485, the speed ratio of 1.4286, and the TCPA of 1.463. At this obstacle situation, turning to 37.6° and reducing the speed of the USV to 2.4 m/s can make it safe from the obstacle.

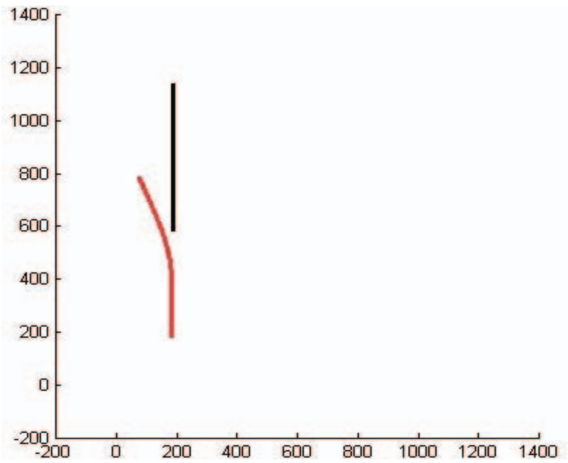
In system (3),when the obstacle avoidance situation is the overtaking situation, the initial states of the unmanned boat and obstacle are assumed to be: the USV's heading is 0°, the speed is 10m/s, and the coordinate is (0,0); the obstacle's heading is 359° with a speed of 6m/s and a coordinate of (0,400). The collision avoidance simulation is shown in Fig.5 (a) and (b).

In Fig.6 (b), The black curve represents the track of obstacles, and the red curve represents the track of the USV.

When the USV and the dynamic obstacle are overtaken, we can get the calculation results of each motion parameter like the relative orientation of 0°, the distance between each other of 400m, the DCPA of 10.4655, the speed ratio of 1.6667, and the TCPA of 2.6149. At this situation, Turning to -30° can make the USV safe from the obstacle.



(a)



(b)

Fig. 6: (a)Parameter calculation for system (3); (b) Navigational trajectories for system (3).

V. Conclusion

In this work, we have introduced an intelligent obstacle avoidance strategy for unmanned surface vehicles that classifying collision avoidance into static obstacle avoidance and dynamic obstacle avoidance.

In this paper, static obstacle avoidance is achieved by path planning for USVs and by establishing a dynamic obstacle model and changing the course and speed of the USV to realize dynamic collision avoidance. In the simulation, the two collision avoidance strategies were verified. The results demonstrate that this strategy can indeed guide USVs in realizing safe navigation in the presence of both static and dynamic obstacles. Further work includes studying the collision avoidance of multiple obstacles based on electronic charts. And the strategy needs validation in real marine environments.

VI. Acknowledgment

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