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A Hybrid Path Planning Algorithm for Unmanned Surface Vehicles in Complex Environment With Dynamic Obstacles

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ABSTRACT Unmanned surface vesssel (USV) has been widely applied due to its advantages in the military reconnaissance and resources exploration. Path planning is one of the critical issues for USV applications, which usually includes global and local path planning methods. However, individual global path planning algorithms may not be easy to detect the dynamic obstacles in the environment, and individual local path planning algorithms may not always guarantee the existence of the feasible solution for the complex environment. Therefore, a hybrid algorithm which effectively combines global and local path planning is proposed in this paper to overcome these drawbacks. The A* algorithm is used in the global path planning to generate a global path for USV to reach the target point. The dynamic window algorithm (DWA) is used in the local path planning to avoid the dynamic obstacles and track the global path by following the local target point which is the intersection of the global and local path planning. The weight coefficient considering sea state is added in the objective function of DWA, where the security of USV can be guaranteed by reducing the weight of velocity and increasing the weight of distance when the sea state level becomes high. Thus, USV can get a global optimal path and reach the target point in complex environment with dynamic obstacles and ocean currents via the proposed hybrid algorithm, and the comparative simulation is carried out to verify the effectiveness and advantage of the proposed method.

INDEX TERMS Hybrid path planning, dynamic window algorithm, unmanned surface vehicles, A* algorithm.

I. INTRODUCTION

With the development of advanced robotics and automation, unmanned surface vehicles(USVs) have been taken more attentions as a kind of important mobile robots in recent years [1]–[9]. USVs are able to complete a variety of tasks, such as ocean sampling, rescue, environmental monitoring, military reconnaissance, etc [10]–[12]. And to accomplish these tasks, it is important for USV to plan out a feasible path in uncertain environment. Therefore, path planning is an important issue for the USV application. There are many studies [13]–[20] in the area of path planning of USV, and most of the literature have focused on the planning under the static obstacles. However, the moving obstacles may also take great influence for the USV's motion. Neglecting mobility of obstacles may lead to a wrong planned path with potential collision.

The path planning of USV can be divided into two categories: One is local path planning and the other is global path planning. Many local path planning algorithms such as the dynamic window algorithm (DWA) [21] and the artificial potential field (APF) [22] have been developed, which plan USV's path based on the surrounding information collected by the sensors. Tang *et al*. [23] propose a local reactive obstacle avoidance approach based DWA for high-speed USV, but without considering the global map information,

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the USV cannot get a optimal path to the target point using this algorithm. These algorithms have short computation time and high real-time performance, but only considering the immediate environment. Therefore, individual local path planning algorithms may not always guarantee the exist of the feasible solution for the complex environment. And most of global path planning algorithms such as the probabilistic rapidly-exploring random trees (RRT) [24] are based on the grid search which is first proposed in form of Dijkstra algorithm [25]. The A* algorithm is another famous global path planning method, which can search the path towards the target point by adding a heuristic cost, reducing the blindness of the search, reducing the search scope, and speeding up the search speed. Song *et al*. [26] propose an improved A* algorithm with three path smoothers to improve the performance of the generated route and obtain a more continuous route, but dynamic obstacles are not considered in the algorithm, which may cause the USV to collide with dynamic obstacles. The A* algorithm combined with local bounded optimization is proposed in [27] for the path planning of USV in uncertain sea environment. International Regulations for Preventing Collisions at Sea(COLREGS) [28] was proposed by the International Maritime Organization(IMO) to prevent collision between ships in a marine environment. And the A* algorithm was also tried to comply with COLREGS for the way point navigation in an environment cluttered with static and moving obstacles [29]. Considering the dynamic constrains, Du *et al*. [30] propose a trajectory-cell based method to guarantee the final spliced path continuous for the motion planning of USV by determining the cost function of the A* algorithm, although the path obtained is continuous, it does not avoid dynamic obstacles which may cause the USV to collide with dynamic obstacles. Another new work [31] is found that the A* algorithm can be applied to the path planning of USV in sea environment with surface currents by modifying the heuristic function. Because the global algorithm is based on the available environmental information, USV could reach the end point without falling into local minima. However, due to the large amount of information in the environment, the global path planning algorithm usually needs a long computational time to plan the path. So it is difficult to meet the real-time requirement, and can not deal with the moving obstacle issue.

Though the combined method of global and local path planning has been applied in robots [32], [33], few related works have been studied in USV, especially when considering the integrated influence of dynamic obstacles and sea state. Thus, this paper proposes a hybrid path planning algorithm by combining the advantages of global and local path planning in complex environment of consideration of dynamic obstacles and sea state level. The A* algorithm is used in the global path planning subsystem, and a global path is generated for USV to reach the target point. The novel interaction between global and local path planning is proposed, where the local target point is generated by the global path and real-time environment information is used as the target point for the later local path planning. DWA is subsequently used in the local path planning for real-time obstacle avoidance and tracking the global path, and the objective function of DWA is modified by adding the coefficients of sea state level, when the sea state is poor, the weight of speed is reduced and the weight of distance is increased. Based on the global path planner to reach the target point and the local path planner to avoid dynamic obstacles, the good path planning of USV in complex environment with dynamic obstacles and ocean currents can be achieved. The comparative simulation with other existing planning method is carried out, the results show the effectiveness of the proposed algorithm.

FIGURE 1. The USV configuration.

The rest of this paper is organized as follows. Section II describes the overview of the hybrid path planning algorithm of USV. Section III introduces the global path planning subsystem and Section IV presents the local path planning subsystem. Section V implements the simulation and the comparative results demonstrate the effectiveness and superiority of our algorithm. Section VI concludes the whole work in this paper.

II. HYBRID PATH PLANNING OF USV

A. USV CONFIGURATION

To validate the proposed algorithm, practical experiments can be conducted with USV as shown in Fig.1. The driving system is controlled by two brushless dc electric motor (BLDC) motors. An single-board computer is equipped on USV. To measure the motion and position of the USV, the inertial measurement sensor and GPS antenna/receiver are furnished on USV.

A radar mounted on USV transmits a detection signal (laser beam) to the dynamic obstacle, and then compares the received signal (target echo) reflected from the dynamic obstacle with the transmitted signal. The control host obtains radar information through data exchange unit. After information processing, the path planning system can obtain information about dynamic obstacles, such as obstacle distance, azimuth, altitude, speed, attitude, and even shape, which can accurately identify the dynamic obstacles.

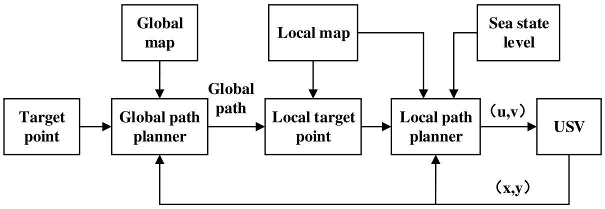

FIGURE 2. The system of hybrid path planning algorithm.

B. THE SYSTEM OF HYBRID PATH PLANNING ALGORITHM

The global path planning algorithm is used to plan a path of USV in large scale global map which takes a lot of computing time. Therefore, it is difficult to plan the path of USV in real time by using only global planning algorithm. Moreover, dynamic obstacles are not taken into account in large scale global map, which puts the USV in danger of colliding with obstacles. The local path planning algorithm is used to plan the local path of USV in the local map which includes environment information around the USV. Therefore, because global map information is not taken into account, it is dangerous for the USV to be trapped in a local minima by using only local path planning algorithm. Moreover, from the global perspective, the path only planned by the local planning algorithm is not the optimal value, which extends the path of the USV and consumes more energy.

In order to solve the problem of avoiding dynamic obstacles and planning the optimal path, the hybrid path planning algorithm of USV is proposed, which includes a local path planner and a global path planner, and the architecture of the hybrid path planning algorithm is shown in Fig.2. The global map is obtained by gridding the satellite map. A* algorithm is used in global path planner to generate a global path for USV in global map. Subsequently, a local target is generated from a global path and a local map updated in real time with radar data of the USV. Moreover, DWA is used in local path planner to plan a optimal trajectory avoiding static and dynamic obstacles in local map updated in real map and following the local target. And the function of DWA is modified by adding the coefficients of sea state level, the weight of speed is reduced and the weight of distance is increased when sea state level is greater. The optimal velocity which is the corresponding velocity of the optimal trajectory is selected to drive the USV.

C. INTERSECTION OF GLOBAL PATH PLANNER AND LOCAL PATH PLANNER

The key of the hybrid path planner of the USV is the intersection of global path planner and local path planner which is shown in Fig.3. Firstly, the global map is gridded by the satellite map, and the local map is generated by the radar of USV to detect the environmental information. Subsequently, the global planner generates a global path of USV in the global map. The local target is the intersection of the global path and the edge of local map whose size is determined by the sea conditions and the detection range of radar. When the waves are higher and the sea breeze is bigger, the local map

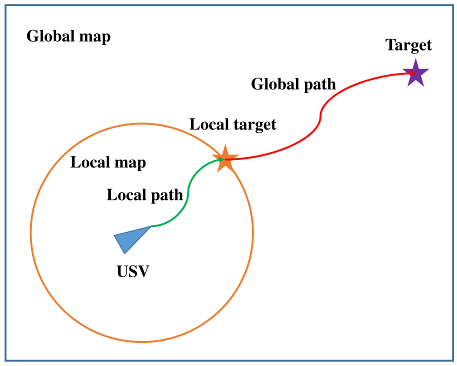

FIGURE 3. The intersection of global path planner and local path planner.

FIGURE 4. The map of Qiandao Lake.

should be larger to improve the algorithm's ability to avoid obstacles. Moreover, the local path planner generates the local path of USV to follow the local target and avoid obstacles in local map. The local path planner and the global planner are combined by using the local target. The global planner plans the path to reach the target point over long periods of time, and the local planner avoids dynamic and static obstacles by updating trajectory in real time. In this way, the USV gets a global optimal path and achieves excellent performance of dynamic obstacle avoidance.

III. THE GLOBAL PATH PLANNER

A. ENVIRONMENTAL MAPPING

Environment information is required to plan the path from the start point to the target point for USV. Therefore, the global map that contains environmental information is one of the key elements of path planning [34]. Qiandao Lake is a man-made lake with numerous small islands and is a excellent area for path planning of USV, as is shown in Fig.4. The approach to generate a global map is to rasterize satellite map of the USV's navigation area. The resolution of the global map is determined by the size of USV. Thus, the USV is treated as a particle in the global map, regardless of its volume. As is shown in Fig.5, the global map converts world space into binary array, and the value of the grid is zero means that the area represented by this grid is an obstacle while the value of the grid is one means the USV can sail in the area represented by this grid. The gridded map contains environmental information in the navigation area of the USV. Therefore, it can be utilized as the global map for the path planning of USV.

FIGURE 5. The grid map of Qiandao Lake.

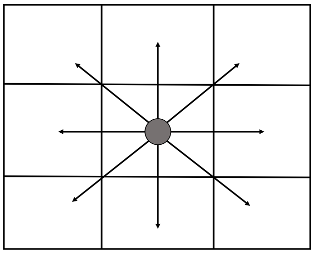

FIGURE 6. Schematic of 8-connectivity of A*.

Due to its good applicability, it can be easily applied to the path planning algorithm and conveniently stored in computers.

B. GLOBAL PATH PLANNING ALGORITHM

A* algorithm is one of popular heuristic search algorithms, which is widely used in the field of path planning. Due to the maturity of A* algorithm and the good search path effect, the global path planner of the hybrid algorithm adopt A* algorithm for the global path planning of USV. Considering the kinematic performance of USV, it is difficult for USV to turn 90 degree on the sea. Therefore, we adopt 8-connectivity A* algorithm, as is shown in Fig.6, and the turns of path planned by A* algorithm are 45 degree, which makes it easier for AUV to turn and track its path.

Each grid of global map is evaluated by $f(n)$, which represents the estimated distance between the start point and the target point, and $f(n)$ is defined as:

$$f(n) = g(n) + h(n) \tag{1}$$

where, $g(n)$ is the length of the path that USV has traveled form the start point to the current grid, and $h(n)$ is the heuristic value which estimates the distance from the current gird to the target point. In this paper, the Euclidean distance from the current gird to the target point is adopted by $h(n)$. All eight grids connected to the current grid are evaluated by $f(n)$, and the one with the lowest value of $f(n)$ will be selected as the extension point of the global path. It is worth noting that the value of $g(n)$ of the grid with obstacles in global map is set to the maximum value, so the path of USV planned by the A* algorithm can avoid obstacles. Thus, the USV along this path will not collide with obstacles in the global map. In this way, the USV gets a global path from the starting point to the target point, which will be used to generate local target points to guide the USV to the target point.

IV. THE LOCAL PATH PLANNER

A. SEARCH SPACE OF VELOCITIES

The local path planner is a part of the hybrid path planner, and it is used to generate the local path for USV to follow the local target point and avoid dynamic obstacles. DWA is a local path planning algorithm based on trajectory prediction which has real-time performance and is suitable for obstacle avoidance. Therefore, DWA is enrolled as the local path planning algorithm for hybrid path planner, where the weight coefficients considering sea state level are designed in the objective function of DWA to enhance the sailing performance of USV under the external disturbances (e.g. wind, waves, current). DWA is to search for an optimal velocity in the set of feasible velocity pairs(u,r), which consist of the surge speed u and the yaw rate r, and the set of feasible velocity pairs are discretized from the velocity space which is obtained based on the surge speed u and yaw rate r limits of the USV. The optimal velocity calculated by DWA is used as the reference speed for the controller of USV. For every feasible velocity pairs, the local path of the USV is generated using kinematics model of USV. Each velocity is evaluated by the objective function, and the velocity with the highest score is the optimal velocity and input into the USV controller as reference speed.

It is necessary to obtain the velocity space before using the DWA. Therefore, an intersection of three sets are used to generate the velocity space. The dynamic window V_d consists of velocities the USV can reach in one time period. The feasible region of velocity V_s consists of feasible velocities considering limitation of USV motion and the set of safe velocities V_f consists of velocities, at which the USV follows a predicted trajectory and can stop before collide with obstacles.

Allowing the USV to accelerate over a time t, the dynamic window V_d is defined as

$$\begin{aligned} V_d = \{(u, r) \in R \times R \\ | u \in \left[u^* + \dot{u}_{\min} \cdot t, u^* + \dot{u}_{\max} \cdot t\right] \\ \wedge r \in \left[r^* + \dot{r}_{\min} \cdot t, r^* + \dot{r}_{\max} \cdot t\right]\} \end{aligned} \tag{2}$$

The feasible region of velocity V_s is defined as

$$V_s = \{(u, r) \in \times | u \in [u_{\min}, u_{\max}] \wedge r \in [r_{\min}, r_{\max}]\} \tag{3}$$

The set of safe velocities V_f is defined as

$$V_f = \left\{(u, r) \in R \times R | u \leq \sqrt{2x_o |\dot{u}_{\min}|} \wedge |r| \leq k\right\} \tag{4}$$

where

$$k = \begin{cases} \sqrt{2x_0 |\dot{r}_{\max}|}, & r < 0 \\ \sqrt{2x_0 |\dot{r}_{\min}|}, & r \geq 0 \end{cases} \tag{5}$$

Finally, the search space of velocities V is defined by the intersection of three sets

$$V = V_d \cap V_s \cap V_f \tag{6}$$

B. PREDICTED TRAJECTORY OF USV

After DWA gets the search space of velocities V, the set of feasible velocity pairs are discretized from the search space of velocities V. In order to get the optimal velocity in the set of feasible velocity pairs, it is necessary to predict the local path of USV at each velocity in a certain period of time T, and the kinematics model of USV is vital for predicting the local path of USV. The formula of kinematics model of USV is as follows:

$$\eta_k = A \cdot \eta_{k-1} + B \cdot \upsilon_{k-1} \tag{7}$$

where η_k, η_{k-1} are the postures consist of the position (x,y) of the USV in global map and the heading angle ψ of the USV. The matrix A and B are the motion transformation matrixes. υ_{k-1} is the velocities consist of the surge speed u and the yaw rate r of the USV. The postures η_k, η_k are defined as:

$$\eta_k = \begin{bmatrix} x_k & y_k & \psi_k \end{bmatrix}^T \tag{8}$$

$$\eta_{k-1} = \begin{bmatrix} x_{k-1} & y_{k-1} & \psi_{k-1} \end{bmatrix}^T \tag{9}$$

The matrix A and B are defined as:

$$A = I_{3\times3} \tag{10}$$

$$B = \begin{bmatrix} t\cdot\cos\varphi & t\cdot\sin\varphi & 0 & 1 & 0 \\ 0 & 0 & \Delta t & 0 & 1 \end{bmatrix}^T \tag{11}$$

where t is a unit of motion time and φ is the heading angle of the USV. The velocities of the USV are defined as:

$$\upsilon_{k-1} = \begin{bmatrix} u_{k-1} & r_{k-1} \end{bmatrix}^T \tag{12}$$

With the kinematics model of USV, it is easy to predict the local path of USV in the predicted time $T = n \cdot t$, under each velocity in the search space of velocities. The blue circle represents the position of USV, and the green paths represent the local path predicted by DWA in a certain period of time under each velocity in the search space of velocities, as is shown in Fig.11.

C. OBJECTIVE FUNCTION OF DWA

After the multiple groups of predicted local paths of USV are obtained, these local paths are evaluated by objective function to select the optimal local path. Subsequently, the optimal velocity which is the corresponding velocity of the optimal local path is selected as the reference velocity of USV. In this way, the USV can follow the local target point and avoid dynamic obstacles. In the end, a short and safe path to the target point is obtained.

To enhance the sailing performance of USV with the external disturbances (e.g. wind, waves, current), the weight coefficients considering sea state level are added to the objective function of DWA. Then, the objective function that evaluate the local path can be defined as:

$$\begin{aligned} \max_{(u,r)} \; & G(u,r) = \alpha \cdot n\_head(u,r) + k_1 \cdot \beta \cdot n\_dist(u,r) \\ & + k_2 \cdot \gamma \cdot n\_vel(u,r) \\ s.t. \; & (u,r) \in V \end{aligned} \tag{13}$$

where the variables α,β,γ are the initial weight of functions, k_1,k_2 are the weight coefficients, which are defined as follow:

$$k_1 = 1 + \rho \cdot F \tag{14}$$

$$k_2 = 1 - \eta \cdot F \tag{15}$$

where F is the sea state level which can be measured by anemometer, $\rho, \eta \in (0, 1)$ are the adjustable parameters in weight coefficients.

The function $n\_head\ (u, r)$ is used to evaluate the angle difference between the local target and the heading of USV when the USV reaches the end of predicted local path at the current sampling velocity. The function $n\_dist\ (u, r)$ represents the distance between the nearest obstacle and the current local path of USV. The function $n\_vel\ (u, r)$ is used to evaluate the velocity of USV.

$$n\_head(i) = \frac{head(i)}{\sum_{i=1}^{n} head(i)} \tag{16}$$

$$head(i) = 180 - \theta \tag{17}$$

$$n\_vel(i) = \frac{v(i)}{\sum_{i=1}^{n} v(i)} \tag{18}$$

$$n\_dist(i) = \frac{dist(i)}{\sum_{i=1}^{n} dist(i)} \tag{19}$$

where n is all the local paths and i is the current local path to be evaluated. $dist\ (i)$ is the Euclidean distance from the end of local path to the nearest obstacle. $v\ (i)$ is the corresponding velocity of the local path. As is shown in Fig.11, θ is the angle between the heading of the USV in the predicted position and the local target point, and θ is defined as follow:

$$\theta = \psi - \frac{180^o \cdot \arctan\left(\frac{y_l - y}{x_l - x}\right)}{\pi} \tag{20}$$

where (x_l,y_l,) is the position of local target point in the global map. (x,y) is the predicted position of USV in the global map. ψ is the heading angle of USV.

The meaning of the objective function is that, the USV avoids obstacles and travels towards the local target at a faster speed in the process of local path planning. When sea state is poor, k_1 will increase and k_2 will decrease, so the weight of distance in the objective function will increase, and the weight of velocity will decrease. USV will sail with slower speed and greater safe distance as the level of sea state greater.

V. SIMULATION

A. SIMULATION SETUP

In this section, the proposed hybrid planner is discussed and analysed in the complex environment with the consideration of dynamic obstacles and sea state level. The comparative simulation is implemented in the Matlab environment and performed on a PC with Inter i5 quad core CPU and 12GB RAM. To verify the effectiveness of the proposed algorithm to achieve the good combination of path planning and dynamic obstacle avoidance, four path planning algorithms are implemented for the fair comparison, as shown below:

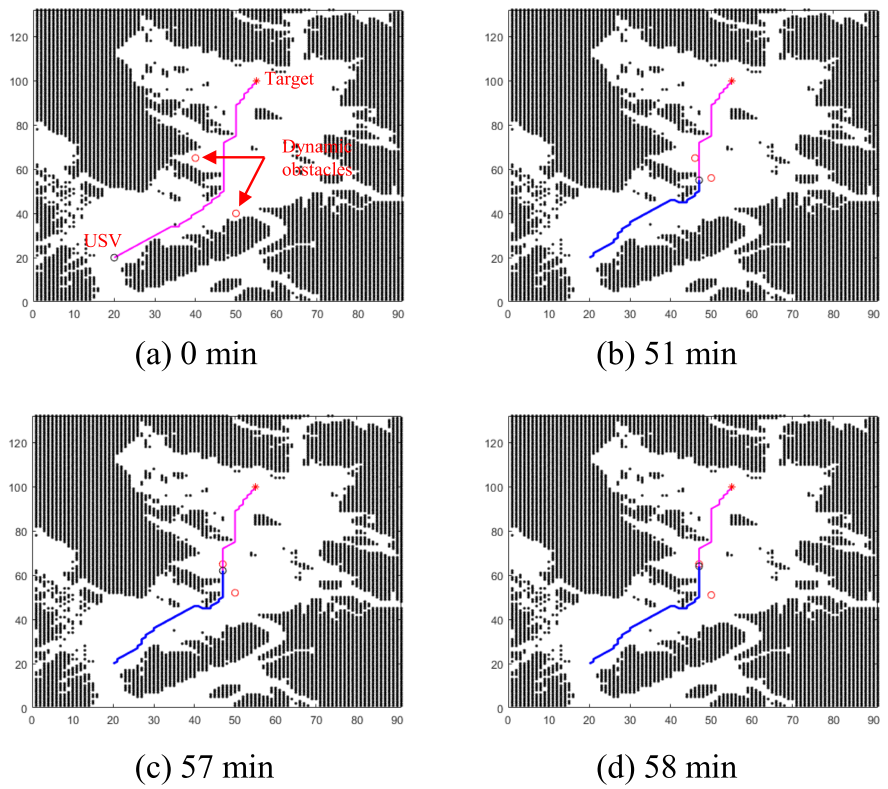

FIGURE 7. Planning results with A1-simulation.

TABLE 1. Parameter information of the USV.

Parameter	Value	Units
Maximum surge speed	3	m/s
Maximum yaw rate	120	°/s
Maximum accelerated speed	2	m/s^2
Surge speed resolution	0.2	m/s
Yaw rate resolution	1	$°/s^2$

A1: Global path planner using A* algorithm. A* algorithm is used by the global planner to plan a path of the USV in global map.

A2: Local path planner using DWA. DWA is used to by local path planner to generate path for USV to target point and avoid dynamic obstacles.

A3: A* approach with safety distance constraints(proposed in [31]).

A4: Hybrid path planning algorithm with global path planner using A* algorithm and local path planner using DWA. The parameters are specified as $\rho = \frac{1}{2}$, $\eta = \frac{1}{6}$, $\alpha = 0.05$, $\beta = 0.2$, $\gamma = 0.1$, $t = 1s$, $T = 15s$, $n = 15$.

In the simulation, the parameters of USV are shown in Table.1. Simulation is conducted in gridded map which is converted by the satellite map of Qiandao Lake. There are static islands and dynamic obstacles in the environment, which forms a dynamic environment as shown in Fig.12. The start point of the USV is selected as $S = [20, 20]$, and the target point of the USV is selected as $G = [66, 100]$. The sea state level is selected as $F = 1$.

In order to make comparisons on the proposed path planning algorithm with other algorithms in terms of the smoothness of path, the number of course changes of the path [26] is used to evaluate it, where the greater the number of course changes of the path, the more tortuous the path. Conversely, the path is smoother.

The following symbols and color codes in motion sequence diagram are applied: The land is represented by the black area and the surface of Qinadao lake is represented by the white area. The red $'*'$ markers are used to mark the target point for the USV, and the blue $'*'$ markers are used to mark the local target point for the USV. If the position of the USV and the target point are close enough, it means that the USV reaches target point and the task of path planning is finished. To verify the hybrid planner's ability to avoid dynamic obstacles, two dynamic obstacles are added in the simulation environment, and the red $'\circ'$ markers are used to mark the dynamic obstacles. One obstacle moves left and right, and the other obstacle moves up and down in a simulation environment. The black $'\circ'$ marker is used to mark the USV which is treated as a point, regardless of its volume, and the course of the USV is represented by the black arrow. The diagram includes three kinds of curve. The path planned by the global path planner is represented by the pink curve. The paths simulated by the local path planner are represented by the green curves. The path that the USV has traveled is represented by the blue curves.

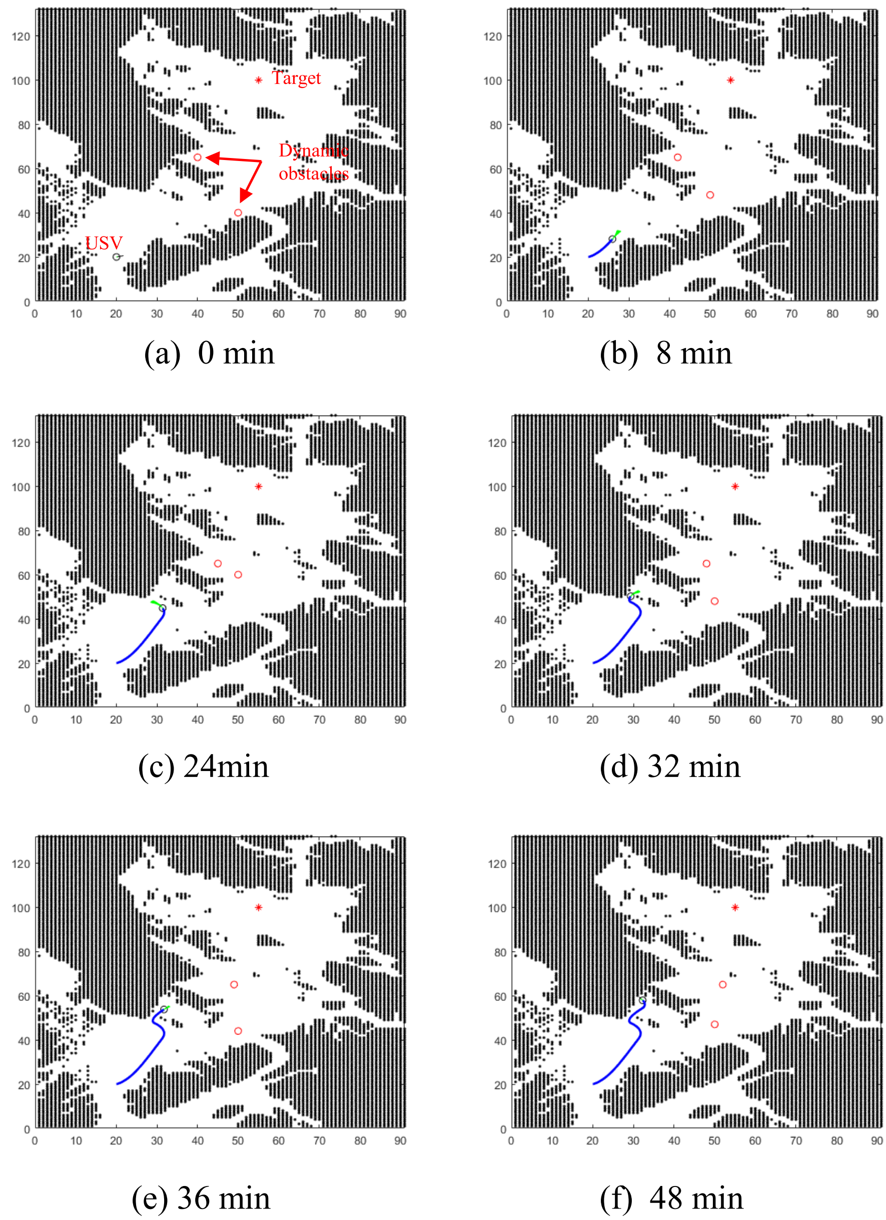

FIGURE 8. Planning results with A2-simulation.

B. SIMULATION RESULT

The simulation is carried out in the environment of Qiandao lake with some dynamic obstacles, and the simulation is designed to test the hybrid path planning algorithm in a realistic environment with the consideration of dynamic obstacles and sea state level.

With the global path planner designed of A1, USV can obtain a path form the start point to the target point. The results shown in Fig.7 show that USV can plan a path in the global map, but cannot avoid dynamic obstacles. Finally, the USV collide with a dynamic obstacle, as shown in Fig.7d.

With the local path planner designed of A2, USV can detect the obstacles around the USV and avoid them, as shown in Fig.8. However, without consideration of global map information, only obstacles around USV are detected and considered, which leads to the fact that the path planned by A2 is only a local one, and USV is easily trapped in local minimum point and cannot reach the target point along this path. As show in Fig.8f, the USV is trapped at local minimum point and cannot reach the target point.

With the path planning algorithm designed of A3, USV can obtain a path from the start point to the target point, which can be seen in Fig.9a-f. Although A3 can plan a path from start point to the target point, the path has too many turns to be applied to the actual navigation of USV.

With the hybrid path planner designed of A4, USV has the improved path planning performance when compared to A3. As shown in Fig.10a-b, the USV sails to the target point

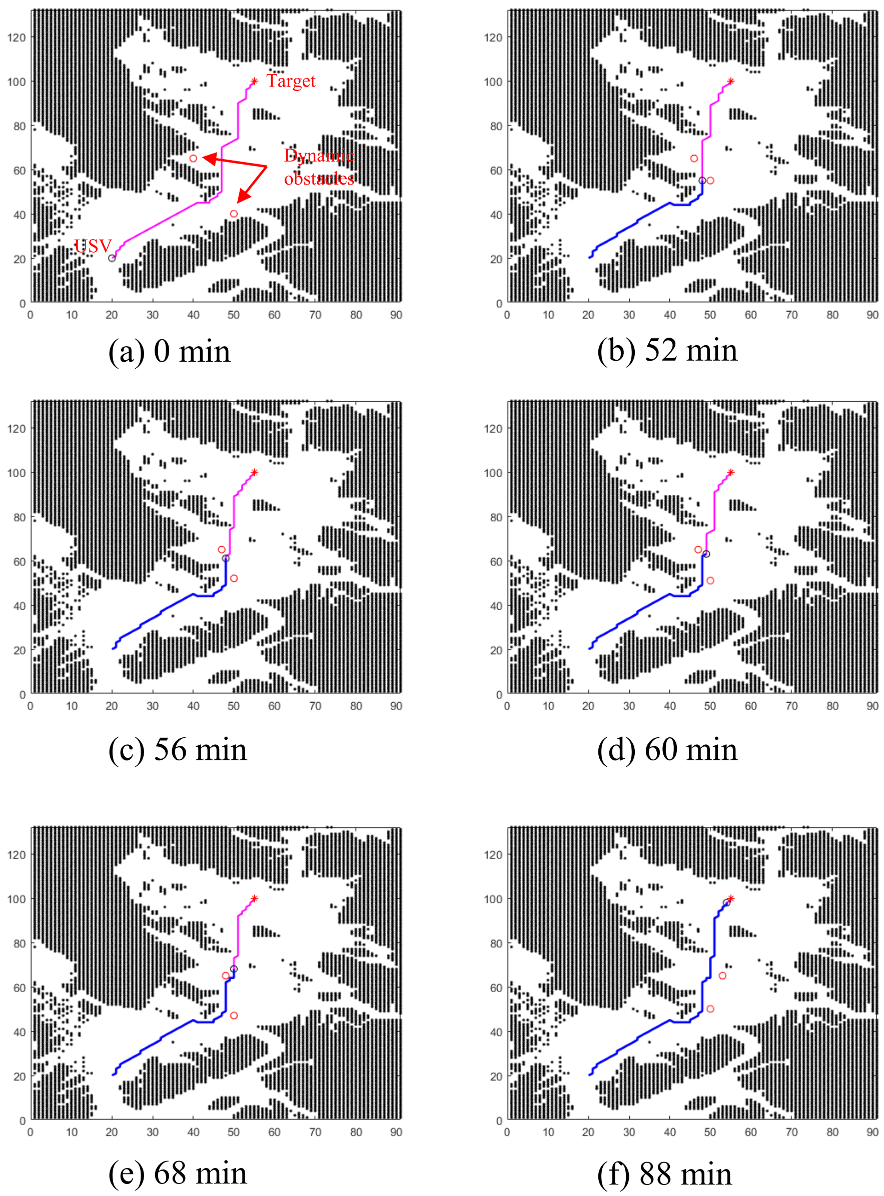

FIGURE 9. Planning results with A3-simulation.

following the local target point which is the intersection of the global path and the local map, and the path planned using A4 is smoother than A3. Subsequently, Fig.10b-d show the USV detects the first dynamic obstacles and avoids it with A4 and Fig.10e-g show the USV detects the second dynamic obstacles and avoids it with A4. Moreover, the Fig.10h shows that the USV gets a global optimal path and reaches the target point successfully with A4 in complex environment with consideration of dynamic obstacles and sea state level.

Table.2 shows the results of simulation with different algorithm. However, although the proposed algorithm takes a little longer, it is still real-time for the path planning of USV. The distance of the path generated by A4 is 9126 m compared to 9352 m generated by A3. That is to say, the distance of the path generated by A4 is 97.6% of A3. It can be seen that the number of course changes of the path has be reduced significantly from 27 to 8 by using the hybrid path planning algorithm. And the number of course changes of A4 is 29.6% of A3, which reflects that the path planned by the proposed path planning algorithm is smoother than that of A* algorithm with safety distance constraints.

TABLE 2. The results of simulation.

Performance	A3	A4
Times(ms)	116	151
Distance cost(m)	9352	9126
No. of turns	27	8

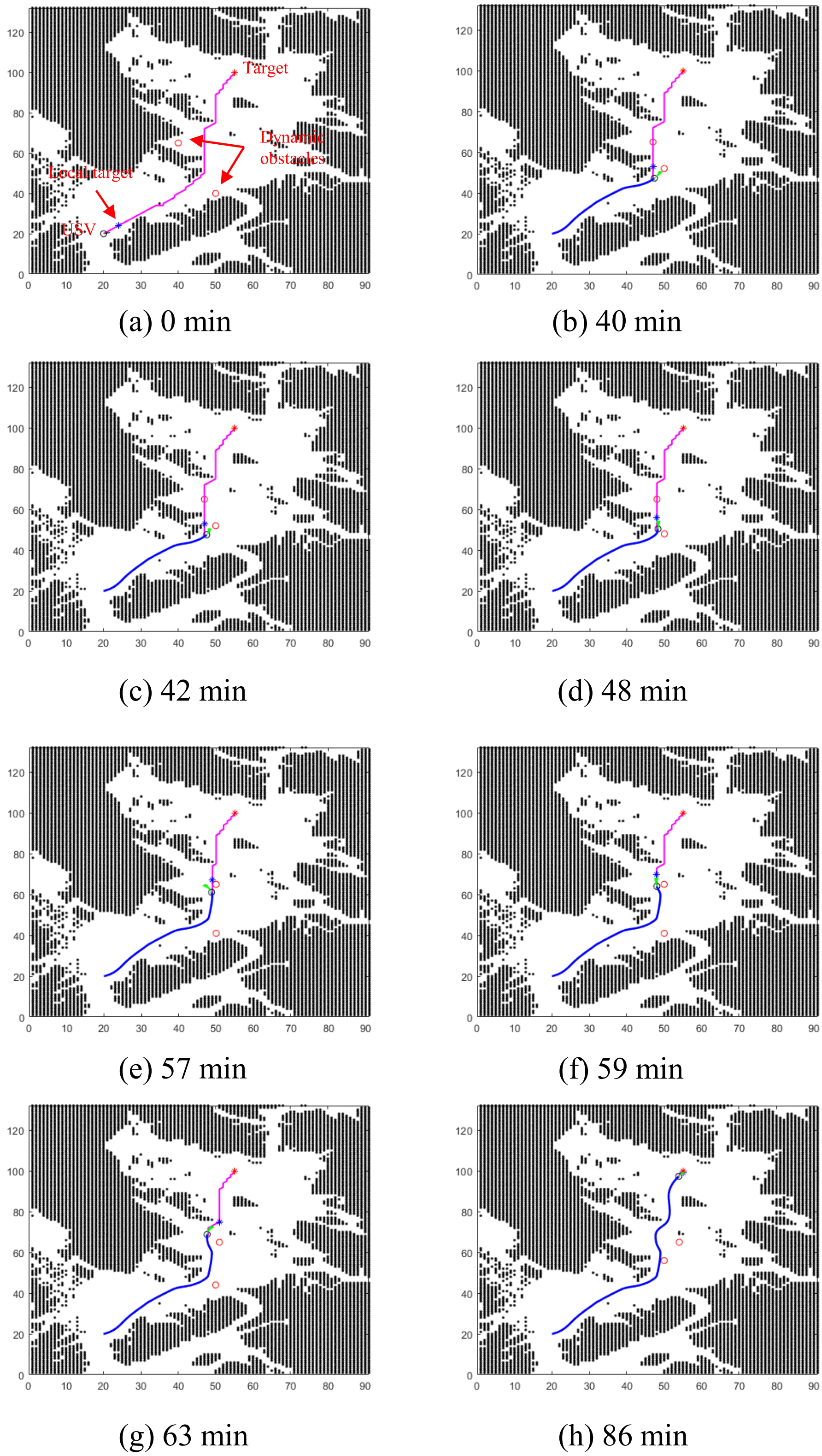

FIGURE 10. **Planning results with A4-simulation.**

Based on simulation results with different kinds of path, it can be seen that the proposed path planning algorithm has higher real-time performance and the path is smoother compared to A3, which verifies the

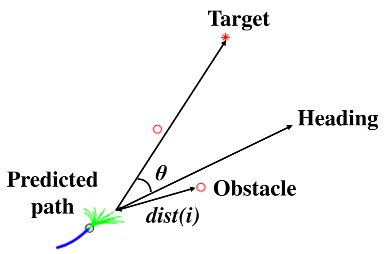

FIGURE 11. The local path predicted by DWA.

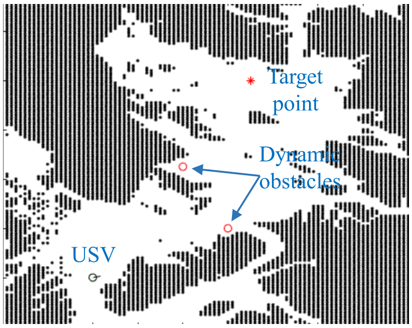

FIGURE 12. The dynamic environment.

priority and effectiveness of proposed path planning algorithm.

VI. CONCLUSION

In this paper, a hybrid path planning algorithm is proposed with the combination of global and local path planning algorithm for USV in complex environment with consideration of dynamic obstacles and sea state level. The local target point, which is the intersection of the global path and the edge of the local map whose size is determined by the detection range of radar, is proposed in this paper to combine global and local planning of hybrid path planning algorithm. Firstly, the A* algorithm is used to generate a global path for USV in the global map, and the USV sails to the target point by following the path. Subsequently, the DWA is used to generate a local path for USV to avoid dynamic obstacles according to maximal acceleration and velocity constraints, and track the global path by following the local target point. The weight coefficient considering sea state is added in the objective function of DWA, where the security of USV can be guaranteed by reducing the weight of velocity and increasing the weight of distance when the sea state level becomes high. Thus, USV can get a global optimal path and reach the target point in complex environment with dynamic obstacles and ocean currents via the proposed hybrid algorithm. The comparative simulation is carried out in the realistic map of Qiandao lake, and the results validate that USV can obtain an effective path to reach the target point and avoid the dynamic obstacles by using the hybrid path planning algorithm in complex environment with the consideration of dynamic obstacles and sea state level.

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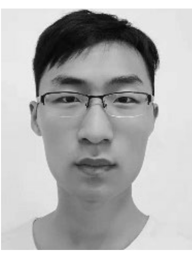

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