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Ship's Trajectory Planning for Collision Avoidance at Sea Based on Modified Artificial Potential Field

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***Abstract*—This paper presents an autonomous trajectory planning algorithm for ships or unmanned surface vehicles (USVs) to navigate safely in dynamic environments based on the modified artificial potential field (APF). The algorithm not only addresses collision avoidance (CA) for stationary and moving hazards, but also applies the International Regulations for Preventing Collisions at Sea (known as COLREGS, for COLlision REGulationS). Furthermore, the algorithm is still effective for the USV to prevent a collision once other ships disregard their responsibility under COLREGS. Assumptions, a concise description of the method developed and results of simulated navigational situations are included. The developed solution can be applied in decision support systems on board a ship or in an intelligent Obstacle Detection and Avoidance system.**

Keywords-ship; USV; trajectory planning; collision avoidance; artificial potential field

I. INTRODUCTION

In recent years, path planning of unmanned vehicles in dynamic environments is a growing and challenging area of research within marine domains. Many different approaches to solving the problem have been developed so far. These methods can be divided into three categories: (1) traditional mathematical method, (2) artificial intelligence and soft computation, and (3) hybrid intelligent systems [1], [2].

The algorithm of Artificial Potential Field (APF) based on traditional mathematical principles, has the advantage of sample mathematical model, which is easy to understand and implement, and facilitate the underlying control. However, application of traditional APF has the problems of local minimum, destination unreachable, and poor accuracy of algorithm. Therefore many modified APF methods such as adaptive artificial potential field (AAPF), Vector Field Histogram VFH+ and VFH∗ methods [3]-[5] are presented and applied widely in Robotic fields. However, in path planning or collision avoidance of ship domains, there are not plentiful related research. Lee [6] proposed an algorithm, named Modified Virtual Field Forces (MVFFs) in addition to fuzzy expert rule based logic, for collision avoiding autonomous navigation of marine vehicles under some of the COLREGS guidelines. However, the complete system incorporates over 200 fuzzy rules and presents only single encounter scenarios [7]. Xue developed a CA algorithm with potential field method to be used in an automatic navigation simulation system. This algorithm incorporates the key provisions in COLREGS, however, doesn't consider the extreme encounter cases such as more moving ships and stationary obstacles, own ship's emergency actions when a giving-way ship violating COLREGS, change of speed and moving target [8]. Shi introduced harmonic potential field method to generate navigation route and avoid collisions with obstacles automatically in constrained water areas such as Traffic Separation Schemes and narrow channels, however, this method was inapplicable in large environment, and its computation time increased fast with the map grid size [9]. Xie proposed a method of static obstacle avoidance planning of USV based on improved APF and demonstrated its feasibility using MATLAB for obstacles with variety of shapes [10]. Hong proposed a balance APF hybrid method to realize the USV track-keeping and static obstacles avoidance in narrow passage [11].

Based on the current state of the art analysis concerning the problem of path planning for collision avoidance at sea, even though some methods resolving the problems of local minimum and destination unreachable of APF methods can be found in the current literature, it is apparent that the algorithms developed so far have some limitations, for example the results presented of simulation tests in a large part only cover static environment, simple situations with few dynamic obstacles, or non-compliance of COLREGS.

This paper is organized as follows: Section II describes the traditional APF model used in marine field. Section III makes some assumptions, environment representations and CA requirements under COLREGS. In Section IV, the modified APF model is presented. Section V includes results of simulation tests performed with input data of navigational situations with the evaluation of the method efficiency. The last section summarizes the achievements and limitations of the solution.

II. THE TRADITIONAL APF MODEL

APF was proposed by Khatib in 1986 [12]. In two-dimensional (2-D) workspace, the control of the USV with respect to obstacles can be carried out in the commonly used APF model [13], [10], as in (1)–(3).

$$U_{att}(p) = \frac{1}{2}\varepsilon\rho^2(p_s, p_g) \tag{1}$$

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$$U_{rep}(p)=\begin{cases}\frac{1}{2}\eta(\frac{1}{\rho(p_s,p_o)}-\frac{1}{\rho_o})^2\rho^2(p_s,p_g), & if\ \rho(p_s,p_o)\le\rho_o \\ 0, & if\ \rho(p_s,p_o)>\rho_o\end{cases} \quad (2)$$

$$U_{\text{total}}(p)=U_{\text{att}}(p)+U_{rep}(p) \quad (3)$$

where U_{att}, U_{rep} and U_{total} represent attraction potential field, repulsion potential field and artificial potential field respectively. Where ξ and η are positive scaling factors in attractive and repulsive position field respectively; p_s, p_g, and p_o are the positions of the ship, goal and obstacle respectively; $\rho(p_s,p_g)$ and $\rho(p_s,p_o)$ are the Euclidean distances between the ship and the goal or obstacle respectively; ρ_o is the influence range of obstacle. The virtual attractive force F_{att} and repulsive force F_{rep} are defined as the negative gradient of the attractive and repulsive potential field in terms of position, and the total force F_{total} applied to the USV is the sum of the attractive force and the repulsive force, i.e.,

$$F_{att}=-grad[U_{\text{att}}(p)]=\varepsilon\rho(p_s,p_g)\overrightarrow{n_{sg}} \quad (4)$$

$$\begin{aligned}F_{rep}&=-grad[U_{\text{rep}}(p)]\\&=\begin{cases}F_{rep1}\overrightarrow{n_{os}}+F_{rep2}\overrightarrow{n_{sg}}, & if\ \rho(p_s,p_o)\le\rho_o\\0, & if\ \rho(p_s,p_o)>\rho_o\end{cases}\end{aligned} \quad (5)$$

$$F_{rep1}=\eta(\frac{1}{\rho(p_s,p_o)}-\frac{1}{\rho_o})\frac{\rho^2(p_s,p_g)}{\rho^2(p_s,p_o)} \quad (6)$$

$$F_{rep2}=\eta(\frac{1}{\rho(p_s,p_o)}-\frac{1}{\rho_o})^2\rho(p_s,p_g) \quad (7)$$

$$F_{\text{total}}=F_{\text{att}}+F_{rep} \quad (8)$$

where $\overrightarrow{n_{sg}}$ and $\overrightarrow{n_{os}}$ are two unit vectors pointing from the ship to the goal and from the obstacle to the ship respectively. Obviously, the first component of the repulsive force $F_{rep1}\overrightarrow{n_{os}}$ repulses the robot away from the obstacle and the second component $F_{rep2}\overrightarrow{n_{sg}}$ attracts the robot toward the goal. The above model can solve the problem, goals non-reachable with obstacles nearby (GNRON) effectively by taking account of the relative distance between the ship and the goal.

III. PROBLEM REPRESENTATIONS AND METHODS

A. Review of COLREGs

For two ships in sight of one another under COLREGs, three primary encounter situations: crossing, head-on, and overtaking are considered in this paper. The action of the two ships potentially involved in a collision is defined as shown in Table I, with the corresponding 5 regions illustrated in Fig. 1. These regions are divided according to the relative bearings (Q) of obstacle ships, such as 10°, 112.5°, etc. [14]. It should be noted that the give-way ship shall, so far as possible, take early and substantial action to keep well clear. In addition, one ship in 'stand on' obligation may however take action to avoid collision by her manoeuvre alone, as soon as it becomes apparent to her that the ship required to keep out of the way is not taking appropriate action in compliance with these Rules.

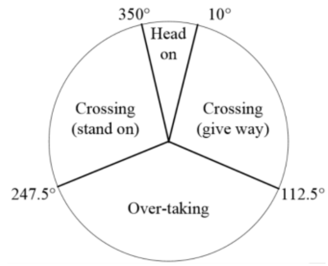

Figure 1. An illustration of the encounter situations in COLREGs.

TABLE I. ENCOUNTERS AND ACTIONS

Encounter	Ship 1	Ship 2	Action by give-way vessel
Head-on	Give way	Give way	Alter course to starboard
Crossing	Give way	Stay on	Avoid crossing ahead of the other ship if the circumstances of the case admit
Crossing	Stay on	Give way	
Overtaking	Stay on (if slower)	Give way	Keep out of the way of the vessel being overtaken, and not relieve the duty until she is finally past and clear.
Overtaking	Give way (if faster)	Stay on	

In this paper it is assumed that the obstacle ships do not change their courses and speeds, i.e. she can't take action to keep out of the way.

B. Collision Avoidance Prediction

The navigational environment may consist of a set of stationary obstacles such as rocks, reefs, shoals, navigational marks etc. and some dynamic restrictions mainly the obstacle ships. For a navigator, an important issue is to determine which obstacle have potential collision risk and when to take CA action. It is reasonable to assume that the most crucial factor determining this is the distance between the ship and obstacle. The distance at which a ship begins to make a scrutiny into the collision risk is termed collision risk checking range C_R here [8]. The magnitude of C_R depends on the prevailing visibility, sailing waters, ship speed, etc. Obviously, it's not the only one factor. In the algorithms based on traditional APF model, the repulsive force F_{rep} take effect when the distance between the own ship and the obstacle $\rho(p_s,p_o)$ is less than or equal to ρ_o. Actually even the $\rho(p_s,p_o)$ is smaller than ρ_o, maybe there is not the collision risk, CA action by own ship is redundant in this situation. Consequently, beside the distance it's necessary to find other factors to determine when the F_{rep} take effect so that own ship take CA action in time.

It's supposed that the real-time data of all obstacles such as the positons, velocities can be acquired by ship's sensors. All obstacles are regarded as circles with different radii (R_o) related to obstacle features. The principle of CA strategy for two-ship encounter situation is illustrated in Fig. 2.

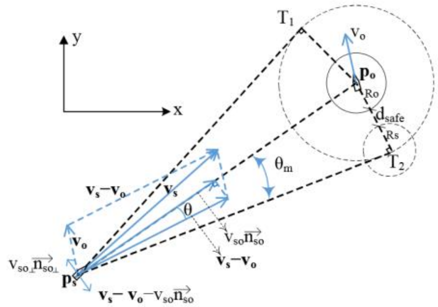

Figure 2. The vector relations and CA strategy of two-ship encountering.

The position and velocity of own ship and the obstacle ship at time t are denoted by $\boldsymbol{P_s}$, $\boldsymbol{V_s}$, $\boldsymbol{P_o}$, and $\boldsymbol{V_o}$ respectively. The safe boundary of obstacle ship is expanded to some extent according to domain radius (R_s) of own ship [15] and the allowable shortest safe distance (d_{safe}) between the boundary of own ship domain and obstacle circle. The own ship is taken as a point mass, so the expanded circle's radius d_m=R_s+d_{safe}+R_o. Two tangent lines are drawn from the P_o to the expanded circle. Then θ_m is defined as the angle between any tangent line and the relative position vector $\boldsymbol{P}_{\mathbf{so}}$(i.e. $\boldsymbol{P_o}-\boldsymbol{P_s}$), as in (9).

$$\theta_{\mathrm{m}} = \arctan(d_m / \sqrt{\rho^2(p_s, p_o) - d_m{}^2}) \tag{9}$$

The θ=|θ_{pso}-θ_{vos}| is the angle between the $\boldsymbol{P}_{\mathbf{so}}$ and the relative speed vector $\boldsymbol{V_{os}}$ (i.e. $\boldsymbol{V_s}-\boldsymbol{V_o}$), where the θ_{pso} and θ_{vos} are the angles between the positive direction of X axis and the corresponding vectors $\boldsymbol{P}_{\mathbf{so}}$ and $\boldsymbol{V_{os}}$ respectively. If the distance between the own ship and the obstacle ship $\rho(p_s,p_o)$ is less than the range of collision checking C_R which is deemed as the sum of d_m *and* ρ_o, where ρ_o is defined as k times the radius of the obstacle (k is positive integer). Then the own ship starts to check if the collision risk exists. The risk of collision exists when the extension line of the $\boldsymbol{V_{os}}$ crosses the circle of radius d_m around the obstacle ship. This condition can be formalized as $\theta<\theta_m$ [8], [5].

C. Dynamic Envirement Requirements

At sea, a ship or USV should be able to avoid all these obstacles and reach the goal or waypoint even moving target. For example, the USV maybe need to reach moving mother ship after execution of the task. The adaptability of traditional APF method is poor when the obstacles and the goal are moving, mainly because it is only the position function which cannot fully reflect the environmental information. Therefore, the relative speed information, the CA prediction method, and the key rules of COLREGs will be considered in a modified APF model so as to accommodate complex maritime traffic environment.

IV. Modified APF Model

A. Attractive Potential Field Function

In the case of a dynamic goal, the attractive potential field consists of two parts at least: the relative position and the relative velocity potential field, the modified attractive potential field function can be wrote as (10).

$$U_{\mathrm{att}} = U_{\mathrm{att}}(p) + U_{\mathrm{att}}(\mathrm{v}) = \frac{1}{2}\varepsilon_{\mathrm{p}}\left\|p_g - p_s\right\|^2 + \frac{1}{2}\varepsilon_v\left\|v_g - v_s\right\|^2 \tag{10}$$

The attractive force of a ship (F_{att}) here is the resultant force of the attractive force about relative position (F_{attp}) and the attractive force about relative velocity (F_{attv}), as in (11).

$$F_{\mathrm{att}} = F_{\mathrm{att}}(p) + F_{\mathrm{att}}(\mathrm{v}) = \varepsilon_{\mathrm{p}}\left\|p_g - p_s\right\|\overrightarrow{n_{psg}} + \varepsilon_v\left\|v_g - v_s\right\|\overrightarrow{n_{vsg}} \tag{11}$$

where $\overrightarrow{n_{psg}}$ is the unit vector pointing to the goal positon from the own ship position, $\overrightarrow{n_{vsg}}$ is the unit vector of the relative velocity about the goal in relation to the own ship, ξ_p and ξ_v are positive scaling factors in attractive relative position and velocity field respectively [16].

B. Repulsive Potential Field Function

Based on the analyses above, a new subdivided repulsive potential field function is proposed and the following factors such as stationary and dynamic obstacles, multi ship collision avoidance, and collision avoidance in close distance or at sufficient sea-room are considered prudently, so as to enhance its adaptability for more complicated encounter situation. It is noted that there are some zones where the resultant repulsive potential field is weakened or zero even in the vicinity of an obstacle for the traditional APF model. A close range emergency repulsion potential field function is added and it can produce the bigger repulsion potential field than usual so that the own ship could take appropriate course alternation action immediately for the safe passage of the obstacles. The modified APF model is shown in (12)

$$U_{rep} = \begin{cases} \eta_{\mathrm{d}} R_o [e^{\theta_{\mathrm{m}} - \theta} - 1](\frac{1}{d - d_m} - \frac{1}{\rho_o})^2 d_g{}^2, & if\ v_o \neq 0,\ \mathrm{d_m} < d \leq \mathrm{C_R}\ \text{and}\ \theta < \theta_{\mathrm{m}} \\ \eta_{\mathrm{s}} R_o (\frac{1}{d\text{-}\tau} - \frac{1}{\rho_o})^2 d_g{}^2, & if\ v_o = 0,\ \mathrm{d_m} < d \leq \mathrm{C_R}\ \text{and}\ \theta < \theta_{\mathrm{m}} \\ \eta_{\mathrm{e}} R_o [(\frac{1}{d\text{-}\tau} - \frac{1}{\rho_o})^2 + (\left\|\mathbf{v_{os}}\right\|\cos\theta)^2] d_g{}^2, & if\ d \leq d_m\ \text{and}\ \mathrm{n} \geq 3 \\ 0, & \text{others} \end{cases} \tag{12}$$

where η_d, η_s and η_e are the positive scale factors for the dynamic obstacles and static obstacles at long distance, and the near obstacles respectively. d_g=$\rho(p_s,p_g)$, d=$\rho(p_s,p_o)$,τ is a small positive parameter which guarantees that at the boundary of the obstacle circles, the repulsive potential and repulsive force are sufficiently large but bounded [13].

It can be seen that at condition of d_m<d≤C_R and $\theta<\theta_m$, the own ship detects the collision risk and has entered the scope of the repulsive potential field, therefore it will be repulsed from obstacles. And when the d approach to d_m, repulsive field will tend to infinity. When θ is more close to θ_m, it indicates that the collision risk with obstacles is small, also the repulsive field is smaller. In order to prevent collision with other ships in the extreme multi-ship encounter situations (the number of obstacle ships n≥3), once other ships occur in the own ship's domain, namely d is not more than d_m, a fast APF model is adopted as an emergency CA action which does not take account the optimal path only for safe. When d is greater than $C_R=d_m+\rho_o$ and θ is bigger than θ_m, there is not the risk of collision and repulsion field.

The new repulsive force is defined as the negative gradient of the repulsive potential in terms of positions and velocities. In a long distance to detect the risk of collision, the collision avoidance for static obstacles can be to port or starboard side, the collision avoidance for dynamic ships should be to starboard in order to meet the requirements of COLREGs and mariners' practice. For the emergency CA action, the forces of turning left or turning right are chosen based on the minimum time to avoid collision. Repulsive force function is modified as in (13) to (23).

$$\mathbf{F_{rep}}=\begin{cases}\mathbf{F_{rd1}}+\mathbf{F_{rd2}}+\mathbf{F_{rd3}}, & if\ v_o\neq 0,\ \mathrm{d_m}<d\leq \mathrm{C_R}\ \text{and}\ \theta<\theta_\mathrm{m}\\ \mathbf{F_{rs1}}+\mathbf{F_{rs3}}, & f\ v_o=0,\ \mathrm{d_m}<d\leq \mathrm{C_R}\ \text{and}\ \theta<\theta_\mathrm{m}\\ \mathbf{F_{re1}}+\mathbf{F_{re2}}+\mathbf{F_{re3}}, & if\ d\leq d_m\ \text{and}\ \mathrm{n}\geq 3\\ 0, & \text{others}\end{cases} \tag{13}$$

where

$$\mathbf{F_{rd1}}=-\eta_d R_o {d_\mathrm{g}}^2[(\frac{1}{d-d_m}-\frac{1}{\rho_o})e^{\theta_\mathrm{m}-\theta}$$
$$(\frac{d_m}{d\sqrt{d^2-{d_m}^2}}+\frac{\sin\theta}{\|v_{os}\|})+\frac{e^{\theta_\mathrm{m}-\theta}-1}{(d-d_m)^2}-F_{os0}]\overrightarrow{n_{so}} \tag{14}$$

$$\mathbf{F_{rd2}}=\pm\eta_d R_o {d_\mathrm{g}}^2[(\frac{1}{d-d_m}-\frac{1}{\rho_o})e^{\theta_\mathrm{m}-\theta}$$
$$(\frac{1}{\|p_{so}\|}+\frac{\cos\theta}{\|v_{os}\|})+\frac{\|v_{so\perp}\|(e^{\theta_\mathrm{m}-\theta}-1)}{d(d-d_m)^2}-F_{os\perp}]\overrightarrow{n_{so\perp}} \tag{15}$$

$$\mathbf{F_{rd3}}=\eta_d R_o d_\mathrm{g}[(\frac{1}{d-d_m}-\frac{1}{\rho_o})(e^{\theta_\mathrm{m}-\theta}-1)\overrightarrow{n_{sg}} \tag{16}$$

$$F_{os0}=(\frac{1}{d-d_m}-\frac{1}{\rho_o})(\frac{d_m}{d\sqrt{d^2-{d_m}^2}}+\frac{\sin\theta_\mathrm{m}}{\|v_{os}\|}) \tag{17}$$

$$F_{os\perp}=(\frac{1}{d-d_m}-\frac{1}{\rho_o})(\frac{1}{\|p_{so}\|}+\frac{\cos\theta_\mathrm{m}}{\|v_{os}\|}) \tag{18}$$

$$\mathbf{F_{rs1}}=-\eta_\mathrm{s} R_o(\frac{1}{d\text{-}\tau}-\frac{1}{\rho_o})\frac{{d_\mathrm{g}}^2}{d^2}\overrightarrow{n_{so}} \tag{19}$$

$$\mathbf{F_{rs3}}=\eta_\mathrm{s} R_o d_\mathrm{g}(\frac{1}{d\text{-}\tau}-\frac{1}{\rho_o})^2\overrightarrow{n_{sg}} \tag{20}$$

$$\mathbf{F_{re1}}=-2\eta_\mathrm{e} R_o(\frac{1}{d\text{-}\tau}-\frac{1}{d_m})\frac{{d_\mathrm{g}}^2}{(d\text{-}\tau)^2}\overrightarrow{n_{so}} \tag{21}$$

$$\mathbf{F_{re2}}=2\eta_\mathrm{e} R_o\frac{d_\mathrm{g}}{d}\|\mathbf{v_{os}}\|^2(\cos\theta\sin\theta)\overrightarrow{n_{so\perp}} \tag{22}$$

$$\mathbf{F_{re3}}=2\eta_\mathrm{e} R_o d_\mathrm{g}[(\frac{1}{d\text{-}\tau}-\frac{1}{d_m})^2+\|\mathbf{v_{os}}\|^2\cos^2\theta]\overrightarrow{n_{sg}} \tag{23}$$

The $\mathbf{F}_{rd1}$, $\mathbf{F}_{rs1}$ and $\mathbf{F_{re1}}$ are related to the relative position between the own ship and obstacle ship, and they will keep the own ship away from the obstacle ship at different conditions. $\overrightarrow{n_{so}}$ is the unit vector pointing to the obstacle ship from the own ship, and $\overrightarrow{n_{so\perp}}$ is also a unit vector which is perpendicular to $\overrightarrow{n_{so}}$ (see Fig. 2). $\mathbf{F}_{re2}$ will automatically make the own ship avoid danger from the right or left side of the line $\boldsymbol{P}_{\mathbf{so}}$ depends on the vector $\boldsymbol{V}_{os}$ is in which side of $\boldsymbol{P}_{\mathbf{so}}$ line. $\mathbf{F}_{rd2}$ only makes the own ship alter course to starboard at a longer distance based on seafarers' practice. $\mathbf{F_{rd3}}$, $\mathbf{F_{rs3}}$ and $\mathbf{F_{re3}}$ make the own ship to move to the goal.

Therefore, the own ship will take CA actions under the total virtual force $\mathbf{F_{rep}}$ and $\mathbf{F_{att}}$ for different conditions and reach the goal even it is moving or close to an obstacle.

V. Simulation Experiments and Analysis

The modified APF model has been implemented in the MATLAB language. Two situations have been chosen to prove the problem solving capability of the modified APF model and the efficiency of the received solutions. The calculations have been conducted with the use of a PC with an Intel Core i5 3230m 2.6 GHz processor, 6GB RAM, 64-bit Windows 7 Professional.

The following values of parameters have been used in the presented simulation tests: η_d,=2000, η_s=300000, η_e=2000, τ=0.3 nautical mile (nm), $R_s=0.5nm$, $d_{safe}=0.5nm$, $\rho_{omin}=3nm$, step=1h/120, ρ_o=max[k*R_o, ρ_{omin}], k=5.

In the following simulations, the trajectories are found by assuming that the own ship steers at constant speed, v_s=10kn and the resultant virtual force applied to it only determines its course of CA action. It is limited to alter course 5° at one step taking account the manoeuvre capability of the own ship. The workspace is within a 12 nm×12 nm restricted waters and there are some designated stationary obstacles and dynamic obstacle ships scattered in it. Define the origin of the global frame at the lower left corner of the workspace and the true north 000° is the positive direction of Y axis.

A. Simple Situations

Set the starting position of the own ship at point (0.0, 0.0), with the intended course 045° to the goal position (10.0, 10.0). And the goal is near a stationary obstacle (9.3, 9.3) with the radius R_o=0.5nm. The radius of obstacle ship is 0.3nm. Three typical encounter situations: head-on, crossing and overtaking in sight of one another are chosen. The data input and results are shown in Table II and Fig.3～5. The second and third columns include the initial position and speed vector data of obstacle ships. The fourth and fifth columns contains the range and relative bearing (Q) of the obstacle ships at the time of CA action, marked by step numbers, with respect to the own ship in nautical miles and degrees respectively. The sixth column includes the detailed course alternation (A/C) degrees of action to avoid collision for own ship. The last column contains the distance to closest point of approach (d_{cpa}) after the CA action.

Note that both head-on and "crossing from the right" situation, COLREGS require that the give-way ship alter course to the starboard. The simulations shown in Fig. 3 and Fig. 4 correspond to these constraints. And the actions to avoid collision are early (more than 4.2 nm away from obstacle ship) and substantial (alter course 50° and 30°), in complying with COLREGS Rule 8. For overtaking situation, see Fig.5, the own ship alters course to starboard 15° at range of 4.3 nm to keep clear of the overtaken vessel until she is finally past and clear at the range of 1.1 nm. Even a stationary obstacle is nearby the goal and at the same line with the start point and goal, the own ship could pass and clear it with safe distance 0.9 nm and reach the goal at last. Based on these simulations, the effectiveness of the modified APF method in solving the local minima and GNRON problem for trajectory planning of USV and complying with COLREGS for actions to avoid collision to the other ship is illustrated effectively.

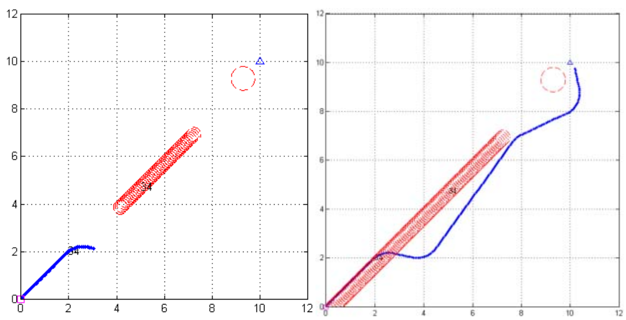

Figure 3. Own ship alters course to starboard at step 34 for head-on situation.

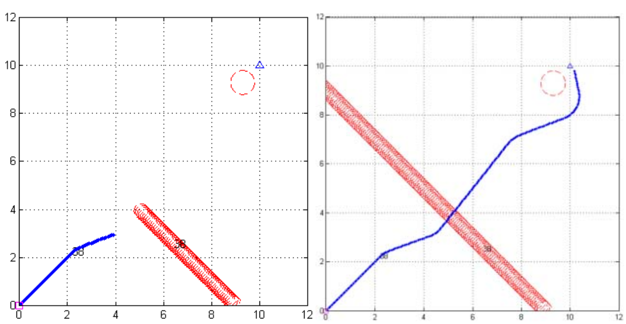

Figure 4. Own ship alters course to starboard at step 38 for crossing situation.

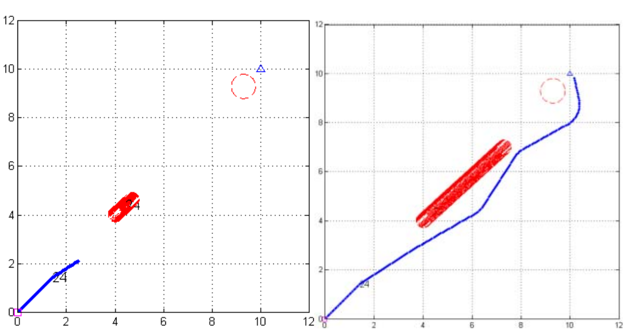

Figure 5. Own ship alters course to starboard at step 24 to overtake obstacle ship.

TABLE II. NAVIGATIONAL DATA OF SIMPLE SITUATION

Encounter Type	**Obstacle Ships**		**Own ship CA action and result**			
	Start point	***Velocity***	***Range***	***Q(°)***	***A/C (°)***	d_{cpa}
Head-on	(7.3, 7.0)	(-8.0,-8.0)	4.3	0	50	1.3
Crossing	(9.0, 0.0)	(-8.0, 8.0)	4.2	41	30	1.3
Overtaking	(4.0, 4.0)	(2.0,2.0)	4.3	0	15	1.1

B. Complex Situation

This scenario presents an encounter of the own ship (marked with the letter S) with eight moving obstacle ships marked with number 1 to 8, and five stationary obstacles marked with numbers 9 to 13, see Fig. 6. And the goal (marked with the letter g) with radius 0.1 nm, is moving from the point (10.0, 4.0) at the velocity of (0.0, 3.9), unit nm. The trajectory planning for collision avoidance and dynamic goal tracking process is illustrated on Fig.6 and the data input and the result of CA action for all obstacles (obs.) are shown in Table III.

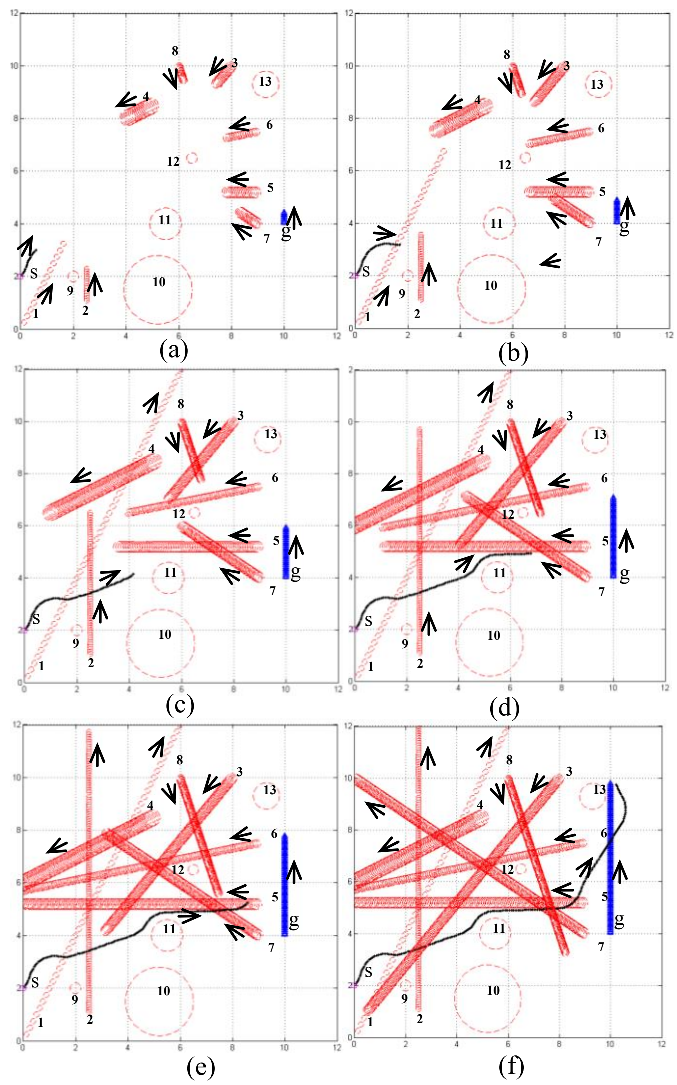

Figure 6. Graphical solution of complex situation.

TABLE III. NAVIGATIONAL DATA OF COMPLEX SITUATION

Obs. No.	Obstacle Ships			Own ship CA action and result			
	Start point	***Velocity***	R_o	***Range***	***Q(°)***	***A/C (°)***	d_{cpa}
1	(0, 0)	(15,30)	0.1	1.8	138	-30	0.9
2	(2.5,1)	(0,11)	0.1	2.2	87	75	0.8
3	(8,10)	(-5, -6)	0.2	2.2	340	60	1.4
4	(5,8.5)	(-8,-4)	0.3	-	-	-	3.5
5	(9,5.2)	(-10,0)	0.2	-	-	-	1.2
6	(9,7.5)	(-10,-2)	0.15	-	-	-	2.3
7	(9,4)	(-6,4)	0.2	3.0	348	60	1.6
8	(6,10)	(1.5,-4.5)	0.15	4.0	10	60	1.1
9	(2, 2)	(0, 0)	0.2	1.3	53	-30	1.2
10	(5.2,1.5)	(0, 0)	1.3	4.1	17	-30	2.7
11	(5.5,4.0)	(0, 0)	0.6	1.3	20	-40	0.9
12	(6.5,6.5)	(0, 0)	0.2	2.6	10	50	1.6
13	(9.3,9.3)	(0, 0)	0.5	3.5	350	15	1.0

At the beginning, the initial course of the own ship is also set to 045° and it should steer to the goal if no collision risk is detected. However, it alters course to port 30° immediately and keeps the same course as to obs1 to avoid collision until the collision risk is eliminated because the overtaking ship obs1 and obs2 don't give way to the own ship, see Fig. 6(a). Then the own ship alters its course to starboard with substantial value 75° of course alterations and passes the stern of the obs1 and obs2 clearly at ranges of 0.9 nm and 0.8 nm respectively, see Fig. 6 (b) . In Fig. 6 (c), after detecting two stationary obstacles obs9 and obs10, the own ship avoids all two obstacles by altering her path to the port 30° but without further alteration of course to the port so that the CA action does not result in another close-quarters situation with the obs5, and passes the stern of obs5 at last, that proves that the solution fulfils Rule 8(c) of COLREGs. In Fig. 6 (d), the own ship keeps the course 071° and has to take CA action to stationary obstacle obs11 at the range 1.3 nm of it. It's noted that this is conducted by emergency CA model otherwise the own ship should alter course to its port side early so as to avoid collision to obs11 at a longer range about 3 nm. Rounding navigation off obs11 and no further alteration of course to port make the own ship pass the obs3 and obs7 at safe distance 1.4 nm and 1.6 nm. Meanwhile, the new course 090° is the final result of modified APF model considering the close range obstacles and the further obstacles. In Fig.6 (e), the own ship has passed almost all obstacles in the scenario, and it should track the moving goal and pay more attention to the obstacle ship obs8. If the own ship tracks the goal firstly, it should alter course to port side early. This may reduce the safety passing distance to obs8, and cause to form a crossing encounter situation so as to involve new risk of collision. Therefore, the own ship keeps her course 090° until passing clear of obs8, then alter her course to port to track the moving goal. Fig. 6 (f) illustrates the process of achieving the dynamic goal and avoiding the stationary obstacle obs13 nearby, the distance between the own ship and the static obstacle is maintained at 1.0 nm.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents a modified APF-based solution of a ship's trajectory planning problem in a collision situation at sea, which can meet COLREGS and dynamic target tracking. The application of the modified APF model makes it possible to determine the safe trajectory of the own ship in situations when she passes a greater number of the encountered obstacle ships in restricted waters no matter whether they are dynamic or stationary. And the simulations take account of the manoeuvre capability of ships, which contributes to a smooth planning trajectory.

Future work will investigate the implementation of the speed change manoeuvre of the own ship in more complex scenarios including larger number of ships and special traffic conditions. Moreover, the reactive or uncoordinated actions of the obstacle ships potentially involved in the collision, and environment conditions such as winds and currents, will be taken into consideration when making a collision avoidance decision.

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