Ocean Engineering 170 (2018) 351–360

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A two-level dynamic obstacle avoidance algorithm for unmanned surface vehicles

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ARTICLE INFO

Keywords:
Unmanned surface vehicle
Velocity obstacles
Potential field
Obstacle avoidance
Emergency situation

ABSTRACT

The unmanned surface vehicles (USVs) are required to perform a dynamic obstacle avoidance during a task. This is essential for USV safety in case of an emergency and this work has been proved to be difficult. However, little research has been done in this area. This paper focuses on an obstacle avoidance problem where the USVs are confronted with a moving ship. A two-level dynamic obstacle avoidance algorithm is introduced by combining the velocity obstacle (VO) algorithm with the improved artificial potential field (APF) method in a non-emergency situation, by using the VO algorithms to establish the velocity vector relationship between the USV and obstacles, both the obstacle avoidance and the goal approaching are considered. During an emergency, a compound potential field is formed around the obstacles. The field is composed of a repulsive potential field and a centrifugal potential field. Under its influence, only the collision avoidance is considered to ensure safety. Finally, numerical simulations are performed with the help of the particle swarm optimisation (PSO) method in order to improve the computational efficiency and accuracy. The results validated the feasibility and validity of the two-level dynamic obstacle avoidance algorithm.

1. Introduction

An Unmanned Surface Vehicle (USV) is a kind of ship which navigates on the water and is controlled by an automated algorithm or a remote. The USV is a complicated system, which involves object identification, autonomous obstacle avoidance, autonomous path planning, overturn-preventing, control technology, wireless data communication technology, etc.(Campbell et al., 2012). Among them, the autonomous obstacle avoidance skill is the foundation for a USV to perform tasks, and is also the reflection of an USV's intelligence (Larson et al., 2007; Simetti et al., 2010).

In 1972, the International Maritime Organization (IMO) approved the International Regulations for Preventing Collisions at Sea (COLREGS, short for COLlision REGulationS) (U.S.Dept. Homeland Security et al., 2010). The regulation specified certain navigation rules when a ship is at a risk of a collision. A large number of investigations shows that one of the major causes for marine accident is the ship maneuvers in violation to the collision regulations. Some researchers have used various algorithm to achieve the USV obstacle avoidance based on COLREGS, including evolutionary algorithms (Colito, 2007), genetic algorithm (Qu et al., 2013), ant colony asexual reproduction optimisation (Asl et al., 2014), neural networks (Liu and Shi, 2005; Zhao et al., 2016), 2-D grid maps (Choi and Yu, 2011; Kim et al., 2012), etc. However, these methods do not behave well in case of multiple obstacles and in case of multiple COLREGS rules. In most of the current research, the obstacles follow the COLREGS, moving and turning slowly. Their movements do not extremely threat the navigation of the USV, therefore, the USVs are not in emergency situation. However, the inobservance of the rules, the uncertainty of the movement, and the impact of the flow could all threat the navigation safety of the USV(Liu and Bucknall, 2015). To make a reasonable movement planning in a dangerous circumstance is an important issue. At present, little research is conducted within this area.

Currently, the collision avoidance methods used in USVs include heuristic A* algorithm, artificial potential field approach, visibility graph method, etc., Most of these methods are improved and integrated based on methods initially used in robots. The Velocity Obstacle (VO) approach was first used in the robot field (Fiorini and Shiller, 1998),

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https://doi.org/10.1016/j.oceaneng.2018.10.008
Received 8 January 2017; Received in revised form 3 October 2018; Accepted 5 October 2018
Available online 02 November 2018

also. It was first proposed for robot path planning in 1998, and then recreated and redeveloped continually, which lead to cooperative form of collision avoidance (Berg et al., 2008a), probabilistic velocity obstacles (Kluge, 2004), and crowd simulation (Berg et al., 2008b). The VO method forms a cone-shaped space on the obstacle, and ensures that the USV never collides the obstacle if it remains outside the space. Since the algorithm is quite efficient, it ensures the robots to react quickly. But for USVs moving in a high speed, in a complex circumstance, and against dynamic obstacles, the avoidance effect is hard to achieve. Besides, owing to the limitation of the power system, a USV is often incapable of executing the motion project planned by the algorithm (Soulignac, 2011; Isern et al., 2011; Yang et al., 2011). Therefore, the limitation of USV's speed and motion change capability should be taken into consideration in the path planning.

The Artificial potential field was proposed by O.Khatib in 1986 (Khatib, 1986).Soon after, the method was used in robot path planning (Wang et al., 2008; Ge and Cui, 2002). In this method, the motion space of a robot is considered as a potential field which overlaps an attraction force originated from the goal and a repulsive force field originated from the obstacle. The attraction force increases with the distance between the robot and the goal and the force points to the goal. The repulsive field is maximum around the obstacle and decreases with the distance between the robot and the obstacle. The repulsive force points opposite to the obstacle. Since the robot movements follow the negative gradient of the field, the regular potential field method has some limitations, such as shaking behavior near the obstacles, incapability of finding a path between nearby obstacles, incapability of getting away from the steady area, difficulty in dynamic obstacle avoidance applications, Also, if the obstacle is close to the goal, the repulsive force is too big which prevent the robot from reaching the goal. Many scholars have researched about these questions. Most of these researches concentrate on the improvement of the field and the combination with other algorithm (Yang et al., 2007). Additionally, by taking time as one dimension of the planning model, the artificial potential field could be used in dynamic obstacle avoidance. However, the method need to assume that the robot track is a known variable, which is difficult to apply in actual application. Even though there is deficiency when artificial potential field used in multiple obstacles and complicated motion situation this theory could be improved and used as a part of the USV dynamic obstacle avoidance and play an important role.

For this reason, a two-level dynamic obstacle avoidance algorithm is proposed; it is based on the VO algorithms and the improved artificial potential method. The movement relationship between the USV and the obstacles is divided into non-emergency situations and emergency situations according to the risk of a collision. In the non-emergency situation, the primary task of the USV is to move to the next path target point while avoiding any obstacles. The first level of the algorithm is VO algorithm, which is inspired by the dynamic path planning of robots. The velocity vector model of the USV and the obstacles is established, which determines the avoiding strategy of the USV. The particle swarm optimisation algorithm is used to calculate the parameters according to the strategy. In an emergency situation, the USV need to move away from the obstacle immediately. The second level of the algorithm is the improved artificial potential method. A compound potential field which consists of a repulsive potential field and a centrifugal potential field is formed around the ship obstacles. The USV adjusts its speed and direction based on the compound potential field.

The obstacles in this paper are ships equipped with AIS (Automatic Identification System). Compared to radars, an AIS can provide the movement data with a higher precision, a lower latency, and a better stability. Thus, the observation error of the obstacles can be ignored.

2. The motion model of the USV and the traffic boats

Given a USV with shape **A** and a moving ship with shape **B**, and their velocity vectors to be v_R and v_o, respectively. The identification zone of the USV is given as **C**, which is determined by the AIS range and the reaction demand of avoidance. As an obstacle enters the zone, the USV should choose whether to avoid it. The domain of the moving ship is **D.** A∈ C, B∈ D. When circles are more convenient for designing the obstacle avoidance algorithm, the moving parameters of the USV could be calculated faster. **C** and **D** are defined as circles (see Fig. 1).

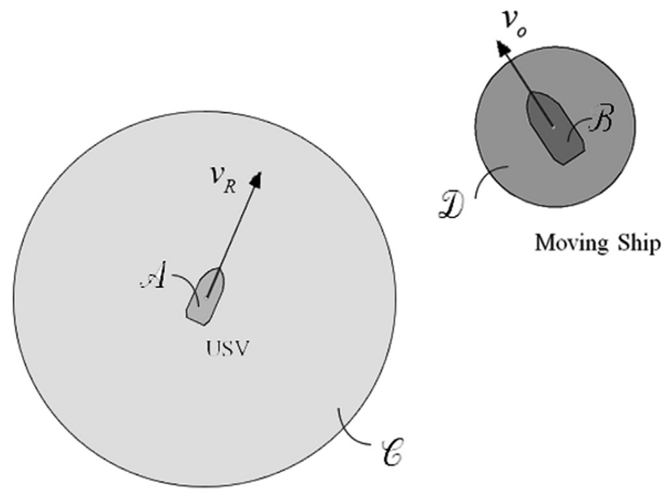

Fig. 1. The motion model of USV and traffic boats.

According to the moving relations between the USV and the obstacles, the reaction of the USV could be Safe, Crashed, Non-emergency, or Emergency.

Safe, represented as λ_0: $\{B \cap C \in \varnothing\}$, means the ships have not entered the identification zone of USV.

Crashed, represented as λ_1: $\{A \cap B \notin \varnothing\}$, states that the USV and ships have overlapped.

3. The first-level avoidance algorithm: the velocity obstacle (VO) approach for non-emergency situation

The USV and the velocity obstacle are shown in Fig. 2. R stands for the USV, the circle O stands for the domain around the obstacle, the velocity of the USV could be represented as (v_R, α), the velocity of the obstacle is (v_o, β).$\alpha = \measuredangle(X, v_R)$, $\beta = \measuredangle(X, v_o)$, $\beta = \measuredangle(X, \mathrm{RO})$, $\psi = \measuredangle(X, \Delta v)$, $\gamma = \measuredangle(RO, \Delta v)$, $\phi = \measuredangle(\Delta v, v_R)$, $\eta = \measuredangle(v_o, \Delta v)$, $\mu = \sphericalangle(\mathrm{RO}, \mathrm{RT})$, $\lambda = \sphericalangle(v_o, v_R)$, Among them, “ $\measuredangle(a, b)$ ” is the angle that the line a rotate to the line b through the minor arc, so it can be either positive or negative depending on whether the rotation is in anticlockwise direction or clockwise direction. However, $\sphericalangle(c, d)$ is the angle between the line c and the line d, it is a positive value. RT (RT_1 and RT_2) represents two tangents from R to the domain of the obstacle O.

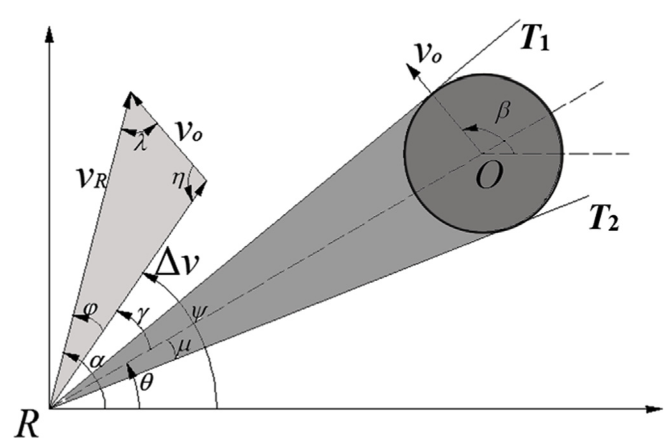

Fig. 2. The USV and the velocity obstacle.

Fig. 2 shows that the USV is impossible to collide with the obstacle if $abs(\gamma) \geq \mu$ is always valid.

Based on the velocity vector triangle formed by v_R, v_o and Δv (Fiorini and Shiller, 1998),

$$\begin{cases} v_o \sin(\alpha-\beta) = -\Delta v \sin\phi \\ v_R - v_o\cos(\alpha-\beta) = \Delta v\cos\phi \\ v_R^2 + v_o^2 - 2v_R v_o\cos(\alpha-\beta) = \Delta v^2 \\ v_R\sin(\beta-\alpha) = \Delta v\sin\eta \\ v_o - v_R\cos(\beta-\alpha) = \Delta v\cos\eta \end{cases} \tag{1}$$

$$\gamma = \tan^{-1}\frac{v_R\sin(\alpha-\theta) - v_o\sin(\beta-\theta)}{v_R\cos(\alpha-\theta) - v_o\cos(\beta-\theta)} \tag{2}$$

If the velocity vector Δv is between the two triangles RT_1 and RT_2, the obstacle avoidance program is required. The situation could be written as:

Non-emergency situation: λ_2: $abs(\gamma) < \mu$

Taking a derivative of equation (2):

$$d\gamma = \frac{\sin\phi}{\Delta v}dv_R + \frac{v_R\cos\phi}{\Delta v}d\alpha + \frac{-\sin\eta}{\Delta v}dv_o + \frac{v_o\cos\eta}{\Delta v}d\beta \tag{3}$$

So, if the obstacle velocity v_o, angle β, their changing velocity Δv_o and $\Delta\beta$ is known, $\Delta\gamma$ could be altered by adjusting the USV velocity v_R and the angle α.

The obstacle avoidance algorithm is to adjust γ to satisfy $|\gamma + \Delta\gamma| \geq \mu$. Apparently, the USV could adjust its velocity vector from both sides. Since the USV should follow the COLREGS, it is recommended that the avoidance direction should be determined according to COLREGS (Perera et al., 2011; Kuwata et al., 2014; Fiorini and Shiller, 1998). This paper addresses the following three primary COLREGS situation:

1) Overtaking: if $\Delta\theta$, the navigation angle difference between the USV and the obstacle, satisfies$\Delta\theta < 45°$, they are dangerously close, and the USV's speed is quicker, it represents the Overtaking situation, the USV should pass the traffic boat by its port side(Wu, 2007).
2) Head-on: if $\Delta\theta$ satisfies $|180° - \Delta\theta| < 15°$ and they are dangerously close. The USV should alter its course toward the starboard, so that it could pass the traffic boat by its port side.
3) Crossing: if $\Delta\theta$ satisfies $45° \leq |\Delta\theta| \leq 165°$ and they are dangerously close. The USV should avoid the boat from its back.

The angle division of these situations is shown in Fig. 3.

The avoid course of USV in different situations are shown in Fig. 4. The dark pentagon-shape body in the figure represents the traffic ship in motion. The other ship represents the USV.

Therefore, the method is to obtain the optimal Δv_R and $\Delta\alpha$ that satisfies both equation (4) and COLREGS rules. The work presented in this paper adopts the PSO algorithm, where Δv_R and $\Delta\alpha$ are set to be (x_1, x_2), two free variables of one particle. The requirement is:

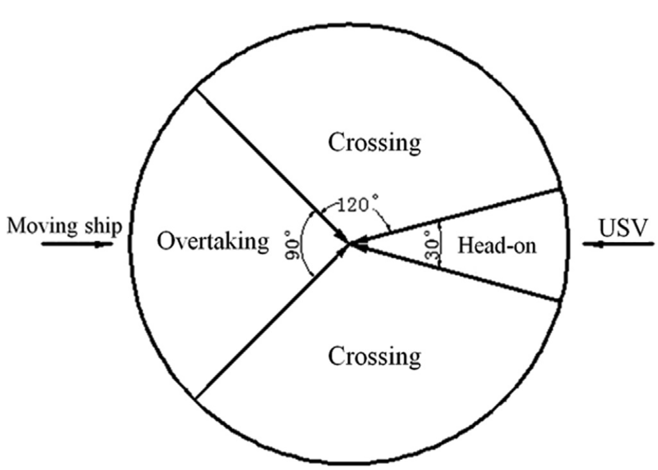

Fig. 3. Three dangerous situations described in COLREGS.

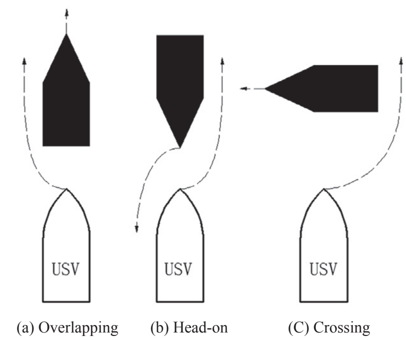

Fig. 4. The avoid course of USV in different situation.

$$\begin{cases} \frac{\sin\phi}{\Delta v}x_1 + \frac{v_R\cos\phi}{\Delta v}x_2 + \frac{-\sin\eta}{\Delta v}dv_o + \frac{v_o\cos\eta}{\Delta v}d\beta \geq \mu - \gamma \text{ if } \gamma \geq 0 \\ \frac{\sin\phi}{\Delta v}x_1 + \frac{v_R\cos\phi}{\Delta v}x_2 + \frac{-\sin\eta}{\Delta v}dv_o + \frac{v_o\cos\eta}{\Delta v}d\beta \leq -\mu - \gamma \text{ if } \gamma < 0 \end{cases} \tag{4}$$

The goal of the optimisation is shown as equation (6). It minimized the change of the USV speed while the avoidance goal can be reached.

$$f(x_1, x_2) = \min(m_1x_1 + m_2x_2) \tag{5}$$

m_1 and m_2 are weights of the optimized objective function. By the change of the weights, the priority of changing speed and changing course is adjusted. The particle's initial angle dimension should not be restricted, which means $\Delta\alpha$ could be chosen in the range of $(-\pi, \pi)$ randomly. The reason is that on some occasions, if the distance between the USV and the ship is dangerously close, the collision can only be avoided via drastically altering the course. If $\Delta\alpha$ has a boundary, the equation may not have a solution.

The resulting particle (x_1, x_2), which correspond to the optimal Δv_R and $\Delta\alpha$, could enable the USV to successfully avoid the obstacle in one cycle. However, the USV may not be able to achieve the required Δv_R and $\Delta\alpha$ in one cycle owning to the limitation of its motion capacity. For instance, supposed one cycle equals to 5 s, and the required solution is $\Delta v_R = 0$, $\Delta\alpha = \pi$. In theory, the USV would definitely pass the traffic boat by remaining the same of speed and taking a sharp turn within 5 s. However, apparently, this is hard for the motion system of the USV. Therefore, the motion of USV is also limited by $\bar{v}_R$、$\bar{a}$ and $\bar{w}$, $\bar{v}_R$ represents the speed limit of the USV, $\bar{a}$ represents the speed change capability, and $\bar{w}$ represents the course change capability.

If $\Delta v_R > \bar{a}$ or $v_R + \Delta v_R > \bar{v}_R$, it means the expected acceleration exceeds the speed change capability, or the expected speed exceeds the speed limit, then:

$$\Delta\tilde{v}_R = \frac{v_R}{|v_R|}\min(\bar{v}_R - v_R, \bar{a}) \tag{6}$$

$$\Delta\tilde{\alpha} = \begin{cases} \min\left(\bar{w}, \max\left(0, \frac{(\mu-\gamma)\Delta v + \Delta v_o\sin\eta - v_o\Delta\beta\cos\eta - \Delta v_R\sin\phi}{v_R\cos\phi}\right)\right) & \text{if } \gamma > 0 \\ \max\left(-\bar{w}, \min\left(0, \frac{(-\mu-\gamma)\Delta v + \Delta v_o\sin\eta - v_o\Delta\beta\cos\eta - \Delta v_R\sin\phi}{v_R\cos\phi}\right)\right) & \text{if } \gamma < 0 \end{cases} \tag{7}$$

If $\Delta\alpha > \bar{w}$, it means the expected angular velocity exceeds the course change capability, then:

$$\Delta\alpha = \frac{\Delta\alpha}{|\Delta\alpha|}\bar{w} \tag{8}$$

$$\Delta\tilde{v}_R = \begin{cases} \min\left(\bar{a}, \max\left(0, \frac{(\mu-\gamma)\Delta v + \Delta v_o\sin\eta - v_o\Delta\beta\cos\eta - \Delta\alpha v_R\cos\phi}{\sin\phi}\right)\right) & \text{if } \gamma > 0 \\ \min\left(\bar{a}, \max\left(0, \frac{(-\mu-\gamma)\Delta v + \Delta v_o\sin\eta - v_o\Delta\beta\cos\eta - \Delta\alpha v_R\cos\phi}{\sin\phi}\right)\right) & \text{if } \gamma < 0 \end{cases} \tag{9}$$

The $\Delta\tilde{v}_R$ and $\Delta\tilde{\alpha}$ above are the collision avoidance parameters that consider the dynamic performance of USV itself. Because of the limitation of $\bar{v}_R$ $\bar{a}$ and $\bar{w}$, the USV is not capable avoid the traffic boat in one circle on some occasions. Fortunately, since it is the avoid action in a non-emergency situation, there is enough time for the USV to adjust its motion in order to pass the ship safely.

The process of the first-level avoidance are as below:

Step1. Initialize the particles swarm.

Step2. Judge if the particle satisfies the avoidance condition in equation (5). If the condition is satisfied, calculate the fitness value by equation (6). If it is not satisfied, the fitness value of this particle is set to infinity.

Step3. All particles update the position and velocity of their two dimensions toward the best particle in the swarm.

Step4. Check if the terminal condition is fulfilled. If it is fulfilled, output the two dimensions, Δv_R and $\Delta\alpha$, of the best particle. Then proceed to Step5. If not, then go back to Step 2.

Step5. Check if Δv_R and $\Delta\alpha$ exceed the motion capacity of the USV, If they do, follow equation (7)–(10), and achieve the avoidance strategy $\Delta\tilde{v}_R$ and $\Delta\tilde{\alpha}$ at the local cycle by compromising to the motion capacity of the USV. If no, Δv_R and $\Delta\alpha$ are the avoidance method.

4. The second-level avoid algorithm: the improved artificial potential field method for emergency situation

The emergency situation is the scene that the USV does not successfully avoid obstacles in non-emergency situation, and the USV is in urgent need for getting away from the traffic boat. The work in this paper defines the emergency situation as two kinds: general emergency and overtaking stalemate.

4.1. General emergency situation

λ_3:$\{(A \cap D) \wedge (B \cap C) \wedge (A \cap B \in \varnothing)\}$

This means if the USV enters the domain of a traffic boat, the general emergency situation happens.

4.2. Overlapping stalemate emergency situation

Overlapping stalemate is a special issue of overtaking situation. As the name implies, the USV navigates after the traffic boat, but can hardly get to the top of it. In other words, the two ships almost keep pace. Theoretically, in the first level, after making a judgment that the obstacle is ahead of it, the USV will only speed up when it is certain that it can pass the boat. However, the USV may not be capable of passing the boat for two reasons: the first reason is that $\bar{v}_R$ is not remarkable greater than the speed of the boat, the USV need a long period of time to pass the obstacle. For example, Fig. 5 gives the locations of USV and traffic boat for 6 continuous cycles, the dark one is the USV and the colored one is the boat. The USV and the ship in one cycle are linked with one green line. In the Non-emergency situation, as required by COLREGS, the USV chooses to pass the obstacle through the portside.

Fig. 5. The first kind of Overlapping Stalemate emergency situation.

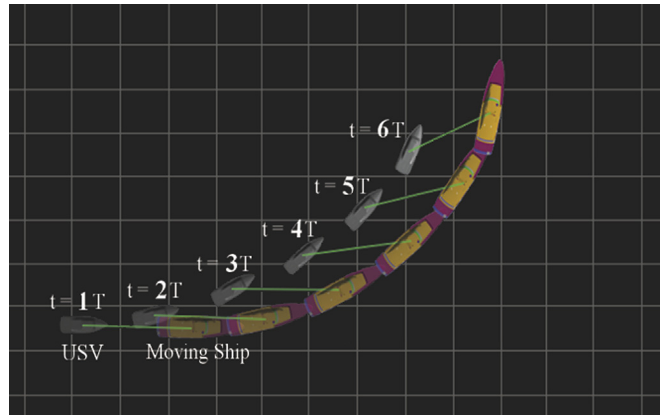

Fig. 6. The Second kind of Overlapping Stalemate emergency situation.

Since the boat moves fast, it is hard for the USV to get ahead of it quickly. The other reason is that the boat turns to the USV at the moment the USV is about to overtake it. As the first level algorithm described, even the USV tries to turn its course to avoid the obstacle, it still is not capable pass the boat, as Fig. 6 shows.

Actually, in Fig. 6, the traffic boat being the “stand-on” vessel, should not alter its path according to COLREGS rules. However, after the USV execute the avoid operation, the boat persistently makes the dangerous turn which makes the situation worse.

From the view of mathematics, the Overlapping Stalemate emergency situation could be described as follow:

$$\lambda_4\text{: } [\lambda_2 \wedge (\frac{v_R - v_o}{v_o} \in (-0.1,\ 0.2)) \wedge (\lambda \in (0,\ \frac{\pi}{6}))]_{\widehat{5T}} \tag{10}$$

In the above expression, λ_2 means that the USV is under the circumstance of needing collision avoidance. According to the first level strategy in Non-emergency situation, the USV must have taken the VO method to make efforts to avoid the obstacle. $\frac{v_R - v_o}{v_o} \in (-0.1, 0.2)$ represents that the speed difference between the USV and the boat is not that remarkable. $\lambda \in (0, \frac{\pi}{6})$ indicates that the course difference between the USV and the boat is not remarkable. The $\widehat{5T}$ at the lower right corner means the expression in the bracket is true for 5 continuous cycles.

The expression (11) indicates that, in a period of time (at least 5 continuous cycles), the USV is in danger and takes the relevant measures to avoid the obstacle. However, the bad situation is not improved, the unruly obstacle counteracts the avoid behavior of the USV.

4.3. The improved artificial potential method

Once the USV enters the emergency situation, that is the general emergency situation or the Overlapping Stalemate emergency situation, it need to suspend the navigation mission and take effective measures to avoid the traffic boat immediately. However, the VO model aims at avoiding obstacle with minimum variation in velocity vector in order to reduce the impact on navigation task. Therefore, if we keep using the VO method in the emergency situation, the condition can be worse. The work in this paper takes the artificial potential field as a reference. The field is built around the obstacle. The classical artificial potential field is a complicated force field consists of a repulsive force and an attractive force. The improved field in this paper is a superposition of two forces: the repulsive force and the centrifugal force. The repulsive force gives the USV an effect to leave the boat, which makes the USV safer, as Fig. 7 shows. The centrifugal force gives the USV an effect to move toward the stern around the boat, as the Fig. 8 shows. The composite field shows as Fig. 9.

The potential field model of the repulsive force can be described as:

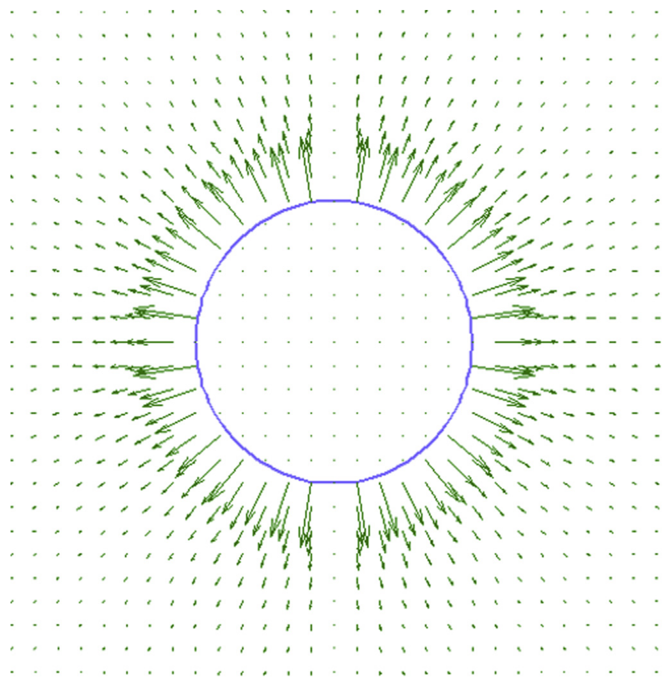

Fig. 7. The repulsive force field.

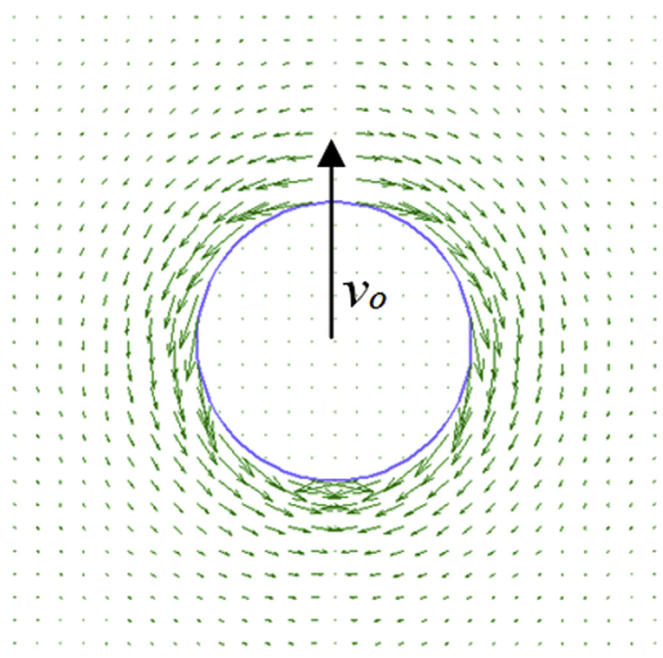

Fig. 8. The centrifugal force field.

$$U_{\mathrm{Re}} = \begin{cases} \frac{1}{2}\eta(\frac{1}{\rho} - \frac{1}{\rho_0})^2 & \text{if } \rho < \rho_0 \\ 0 & \text{Else} \end{cases} \tag{11}$$

In the above equation (Khatib, 1986), η is the direct proportion position gain constant coefficient, ρ is the distance between the USV and the traffic boat at the moment, ρ_0 is effective influential distance. The nearer the distance is, the bigger the impact is, while if the USV is far away from the boat, the force is extremely small.

The repulsive force F_{Re} is the negative gradient of the repulsive potential field function. The centrifugal force F_{Rot} has the same scalar with F_{Re}. The scalar of the forces shows in equation (13), however, it points to the direction that the repulsive force rotates 90° toward the stern.

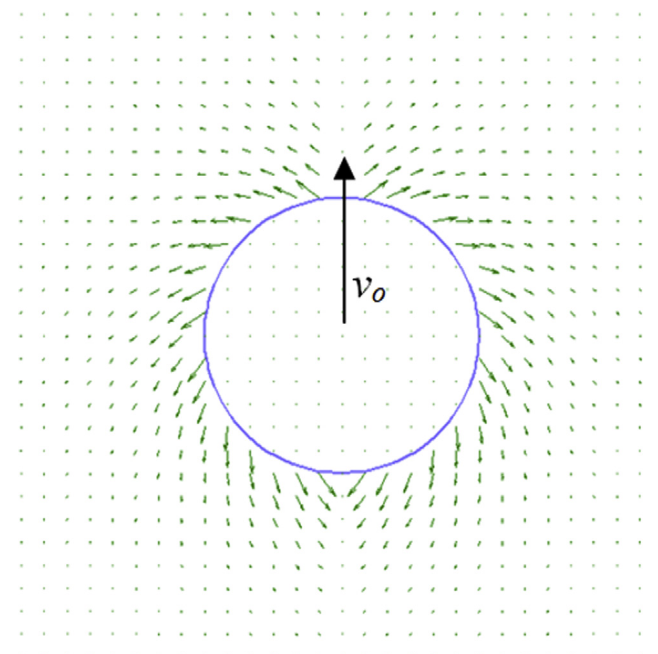

Fig. 9. The composite field.

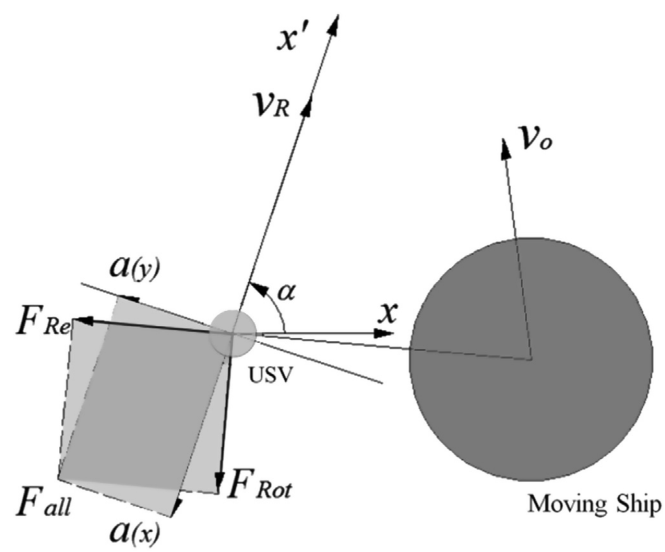

Fig. 10. The composite force at the spot of USV.

$$F_{\mathrm{Re}} = F_{Rot} = \eta(\frac{1}{\rho} - \frac{1}{\rho_0})\frac{1}{\rho^2}\nabla\rho \tag{12}$$

The composite potential force on USV is shown as Fig. 10. It represents F_{all}.

$$F_{all} = \omega_1 F_{\mathrm{Re}} + \omega_2 F_{Rot}$$

The priority between the two force components is adjusted via changing the weight distribution, ω_1 and ω_2.

The combined force determines the amount and direction of the velocity vector change for USV. The field force in the global coordinate system is required to rotate to the USV local coordinate system to get the accelerated speed of each axis, in the local system, the horizontal axis x' point to the direction of v_R. The accelerated speed is:

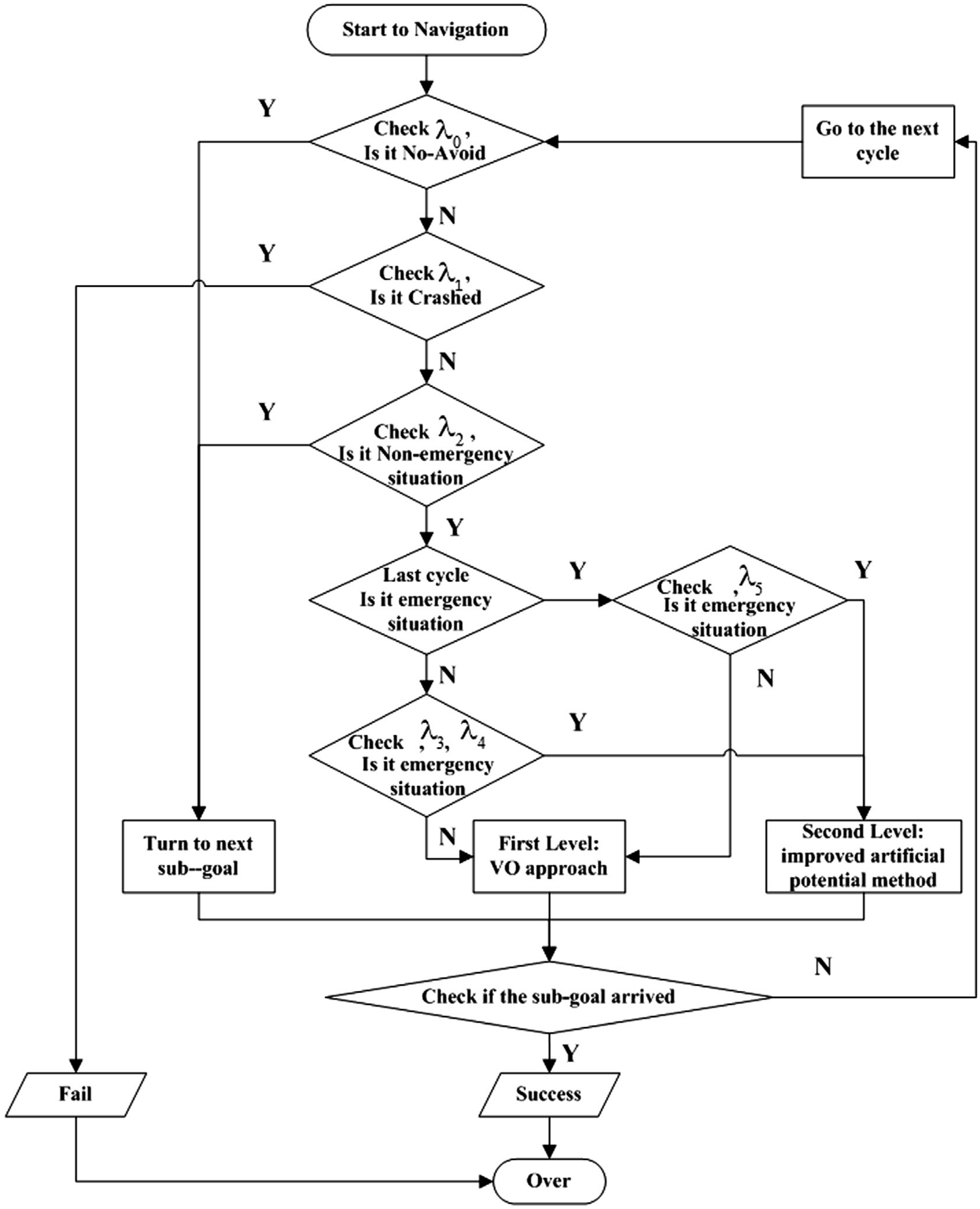

Fig. 11. Flow chart.

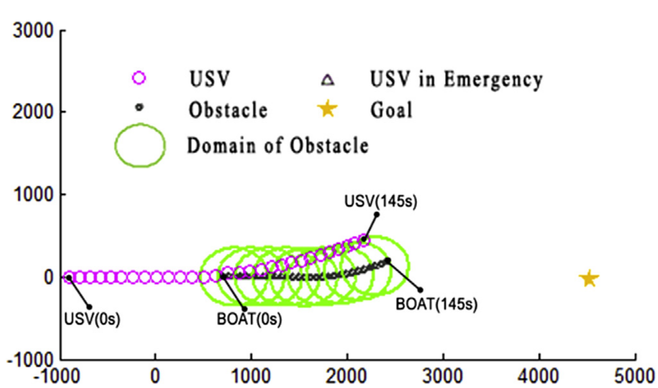

Fig. 12. The symbols meaning and the first-level avoidance.

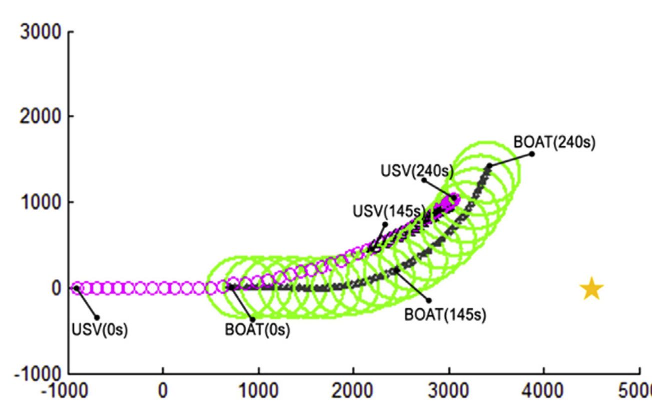

Fig. 13. The USV proceed the second-level avoidance.

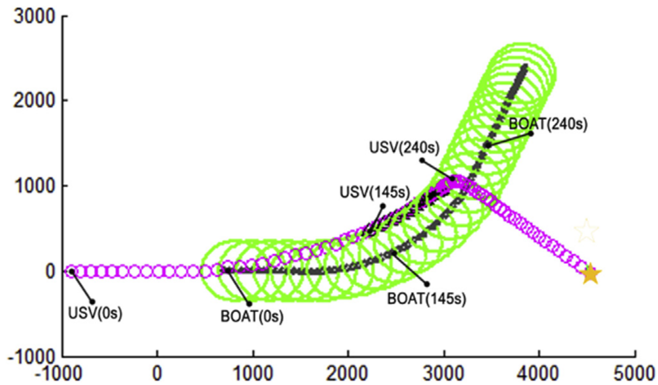

Fig. 14. The USV avoid the obstacle and reach the destination.

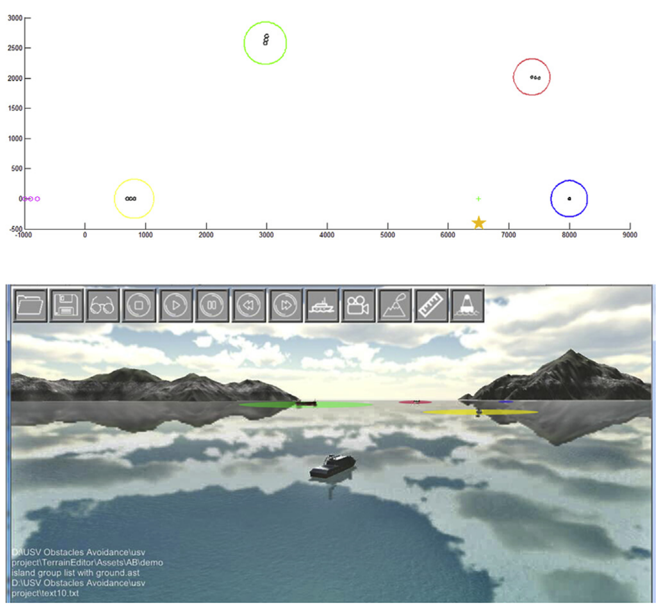

Fig. 15. The initial position of the USV and obstacles.

$$\begin{bmatrix} a(x) \\ a(y) \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} F_{all}(x) \\ F_{all}(y) \end{bmatrix} \tag{13}$$

Like the first-level avoidance, the $a(x)$ and $a(y)$ in equation (14) should be converted to the adjustments in the speed and the course. What is more, the motion of USV is still limited by $\bar{v}_R$ $\bar{a}$ and $\bar{w}$. Hence the variation in speed and course in emergency situation are shown as below.

$$\Delta\tilde{v}_R = \min(\bar{v}_R - v_R, \min(\bar{a}, \sqrt{(v_R + a(x))^2 + a(x)^2 - v_R})) \tag{14}$$

$$\Delta\tilde{\alpha} = \min(\tilde{w}, \max(0, \frac{(\mu - \gamma)\Delta v + \Delta v_0 \sin\eta - v_0\Delta\beta\cos\eta - \Delta v_R \sin\phi}{v_R\cos\phi})) \tag{15}$$

4.4. The cancellation of the emergency situation

The cancellation of the emergency situation is not an inverse process of entering it. Otherwise the USV will constantly enter and exit the emergency situation. To make sure that the cancellation of emergency situation is trustworthy, the judgment method is:

$$\lambda_5: \{(RO \geq d_2) \cap (TCPA < 0)\} \tag{16}$$

In expression (17), $TCPA = |RO|\cos(|\gamma|)/|\Delta v|$

The TCPA indicates the time to the closest point of approach: a bigger TCPA indicates a more dangerous situation while a negative TCPA indicates that the USV is kept away from the traffic boat (Kearon, 1977; Imazu and Koyama, 1984). The formula expresses that the USV is outside the boat's arena and these two ships are moving away from each other at the moment. The USV is temporarily safe, so the emergency situation could be canceled.

Supposing that the USV had planned a global path which consists of a series of sub-goals and there are a few traffic boats navigating around the global path, the two level dynamic obstacle avoidance algorithm flow is given by Fig. 11.

5. Simulation experiment

With the numerical simulation software Matlab and the 3D development software Unity, the USV obstacle avoidance simulation about difference models were performed, which include one and several traffic boats, one and several different situations. The simulation is used to analyze whether the USV could stay safe or not, judge whether the COLREGS is considerate, and to study the efficiency and intellectuality of the two-level obstacle avoidance algorithm.

The data of dynamic performance of the USV used in this paper is measured by the USV platform of Harbin Engineering University in China; specifically, the cruising speed is 20 knots and the minimum avoidance velocity is set as 15 knots, and the maximum sensor detecting distance is 1000 m. The radar information for boat updates every 5 s, we set the steering angle of collision avoidance to be no more than 3° under general cases and no more than 5° in emergency cases in this paper, and the coupling relationship between speed and heading during the steering process is ignored for simplicity. The motion capacity is considered to be controlled and implemented, for the above dynamic performance is set as the standard value in this study and parameters set above are within the limit power range of the boat.

In all simulation models, the USV simulates real conditions, it is unaware of the following movement of obstacles while could only react based on boats' existing motion. All symbols that will be used in the simulations is listed in Fig. 12. The simulation cycle is 5 s, which means the movements of USV and obstacles are recorded in every 5 s. To reduce the complexity of figures, we draw it once in every 3 cycles instead of showing the domain of obstacle for each cycle.

5.1. Simulation about one obstacle in the overlapping stalemate situation

The initial position of USV is (−1000,0), the initial position of boat is (700,0), the velocity of both the USV and the boat points towards the east, the goal is located at (4500,0), the unit of the distance is meter. Fig. 12 shows that the kinematic relation is overtaking, the USV implements the operation of tuning left and speeding up to pass the traffic boat, and these are reaction from VO method in the first-level avoidance. However at the same time, the boat also turns left, this is an irregular motion.

As Fig. 13 shows, although the USV keeps adjusting its speed and course, the boat keeps approaching the USV all the same. The USV is unable to pass the boat according to the first-level avoidance strategy which lead to the emergency situation in the "△" spot. And it is overlapping stalemate emergency situation. The USV needs to get away from the obstacle immediately. At this moment, the potential field force starts to play a role while the USV proceeds to the second-level avoidance based on the repulsive force and the centrifugal force. From Fig. 13, the USV persistently turns left and slows down.

From Fig. 14, we could observe that the second-level avoidance plays an important role. When the emergency situation is released, the boat have already been outside the arena of the USV. The USV re-judges the goal and the obstacles after confirming that it is safe. Then the USV speeds up and turns to the goal gradually until it reach the goal.

In the avoidance about only one traffic boat, the work have proceed 100 simulations, among them, the obstacle motion include uniform, variable, rectilinear and curvilinear, the success rate of collision

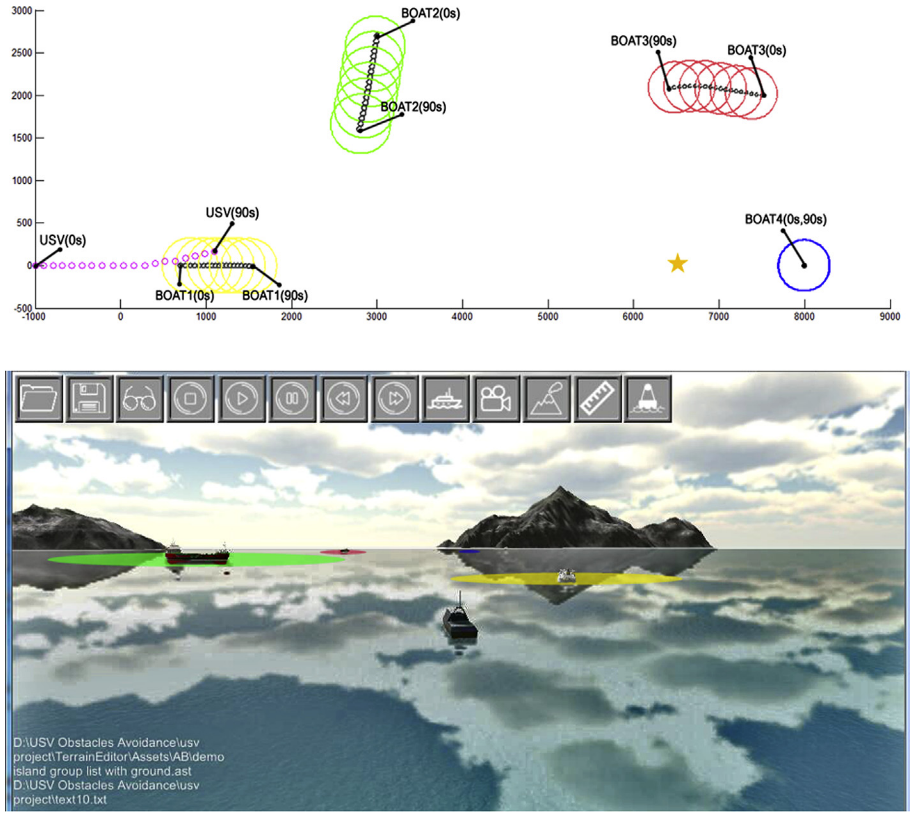

Fig. 16. The USV avoids traffic boat 1.

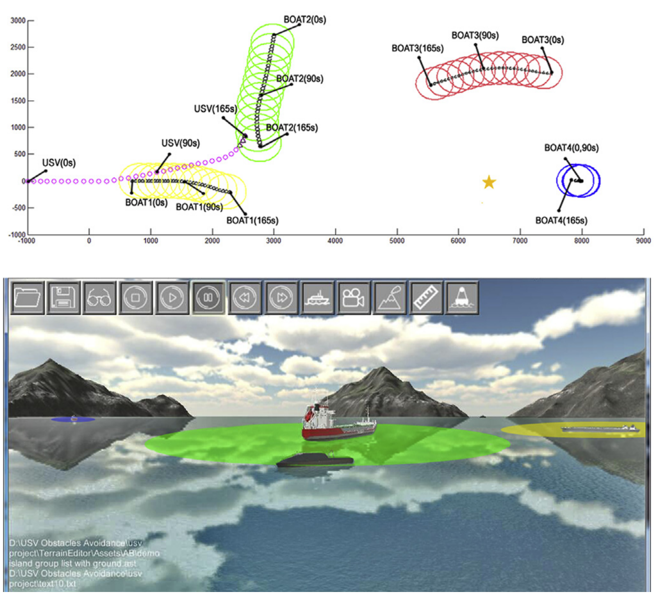

Fig. 17. The USV is avoiding obstacle, navigates out of range of boat 2.

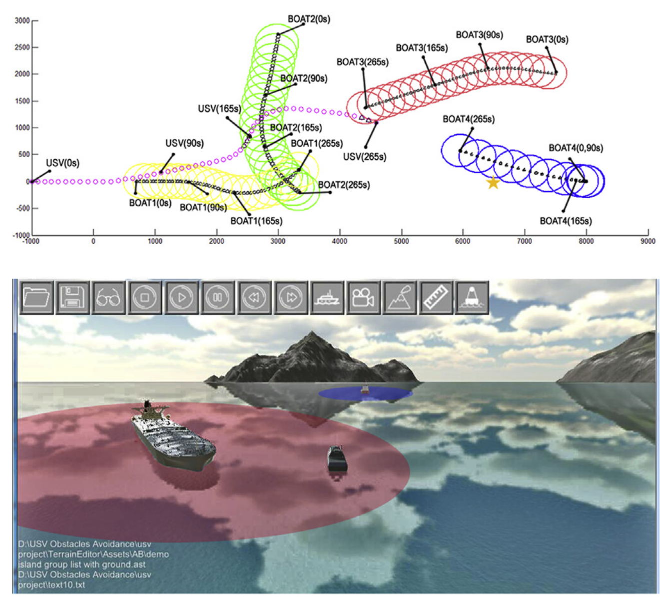

Fig. 18. The USV is avoiding obstacle, navigates out of range of boat 3.

avoidance is 99%.

5.2. Simulation about multi-obstacles in multiple situations

In the following simulation, there are several traffic boats. In order to easily distinguish them, based on the simulation by Matlab, the researcher uses the Unity to construct a 3D view. The work is programmed in C# script which linked the Matlab calculation with the C# simulation by dynamic link library. The development platform is Visual Studio.

The initial position of the USV is (-1000,0), its velocity points to the east. The traffic boat 1 which is enclosed by the yellow circle is locates at (700,0), its velocity also points to the east. The traffic boat 2, which is enclosed by the green circle is locates at (3000,2700), its velocity points to the south by east. The traffic boat 3, which is enclosed by the red circle is locates at (7500,2000), its velocity points to the west by north. The traffic boat 4, which is enclosed by the blue circle is locates at (8000,0) and remains still at the beginning. The USV have done the global path planning in the static obstacle environment and gotten the global path before the following simulation, the next sub-

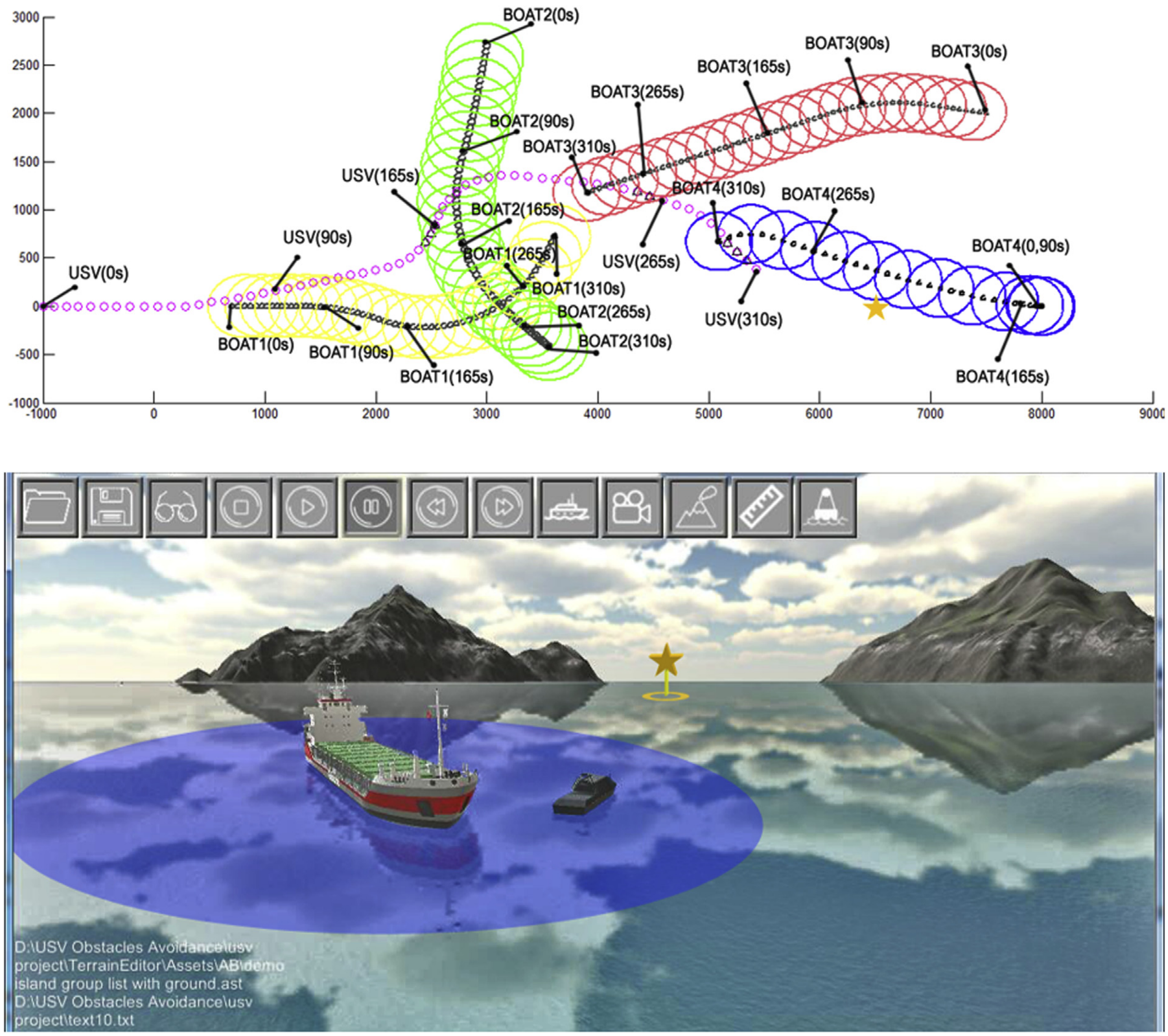

Fig. 19. The USV is avoiding obstacle, navigates out of range of boat 4.

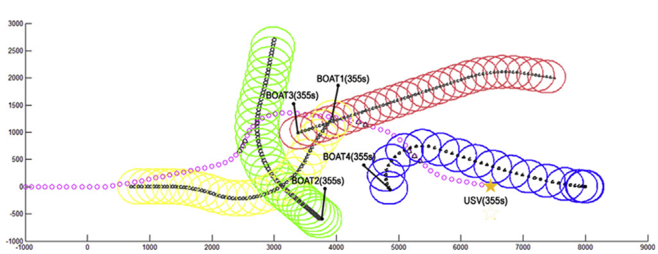

Fig. 20. The USV reached the sub-global path point.

global goal is located at (6700,0). The initial relative position is shown in Fig. 15. The simulation also involves the multi-obstacles collision avoidance method named the Switched Urgent Obstacles algorithm. The paper does not introduce this part since it is not the emphasis of this paper.

At the beginning, among all the traffic boats that appear in the USV arena, obstacle 1 is the one that needs first consideration. The USV and boat 1 is in the overlapping situation. After the Non-emergency situation judgment, the USV chooses the first-level avoidance strategy and accelerates to pass boat 1 by its portside according to the COLREGS. Fig. 16 shows the situation.

In Fig. 17, during the avoidance process for boat 1, the boat 2 entered the range and its risk rises continually. After confirming that boat 1 is no longer a threat, the USV starts to avoid the boat 2 immediately. It is the crossing situation, according to the first-level avoidance strategy, which is used for non-emergency situation. Therefore, the USV should continue turning left to avoid the boat from its back. However, the avoidance operation for boat 1 affects the opportunity and the USV enters the domain of boat 2, which triggers the emergency situation. With the mechanical action of the composite potential field in the second-level avoidance strategy, the USV substantially turns left and finally leaves the domain of boat 2 after the avoidance operation of three cycles. Besides, the boat 4 starts to navigate now.

In Fig. 18, after pass the boat 2 successfully, the USV turns to the sub-goal slowly and accelerates. But soon, the traffic boat 3 enters its range and result in a head-on situation. According to COLREGS, in Non-emergency situations, the USV should avoid the obstacle through its portside. The distance left for collision avoidance is short and the velocity of both the USV and boat 3 are fast. Also, the head-on navigation accelerates their encounter. Therefore, there is not enough time for the USV to completely avoid the boat 3 and the USV enters the domain of boat 3 and triggers an Emergency situation. Both the repulsive effect and the centrifugal effect of potential field play a guided role here to repel the USV from the boat 3. At this moment, the boat 4 enters the range of USV.

The motion of boat 4 is set to always navigate towards the USV in the simulation. Therefore, its course will be adjusted according to the position of the USV. At the moment when the USV just passed the boat 3, boat 4 have moved directly in front of it and head directly to the USV with a high speed. The motion relation is also the head-on situation in which the USV needs to avoid the obstacle through its portside. According to the first-level avoidance strategy, the USV turns right based on the VO method. However, boat 4 also changes its course to chase after the USV. Inevitably, the USV enters the domain of boat 4 with close distance. At this time, the potential field generates a large repulsive force and a larger centrifugal force. Under the guidance of the second-level avoidance strategy, the USV rapidly navigates outside the domain of boat 4. Now it is impossible for the boat 4 to reach the USV (See Fig. 19).

Fig. 20 shows that after passing all the traffic boats, there is no boat in the arena of the USV and the USV adjusts its course and speed up to reach the sub-goal.

In avoiding multi-obstacles, 100 simulations about 2–5 traffic boats have been tested. The success rate of collision avoidance is 95%. The 5% examples of avoidance failures in the paper are inevitable because more than four obstacle ships were set to deliberately block and crash on the USV and the speed of some obstacles even exceed the maximum motion capacity of the USV in these five cases of failure. In view of this situation, even if the manual operator is used, the collisions are unavoidable for the own ship whose dynamic is smaller than obstacles does not have any advantage when obstacles actively collide with the own ship especially in the case of multi-obstacles teamwork.

6. Conclusion and future work

If the obstacle navigates without following the COLREGS rules, the USV may fail to avoid it with regular avoidance algorithm. Concerning this issue, this paper presents a two-level dynamic avoidance algorithm. At first, various avoidance situations are classified and the mathematical meanings of both the Non-emergency situation and the Emergency situation are defined. And the research identifies the goals of both situations. In the formal situation, the USV need to take both obstacle avoidance and goal approaching into consideration, while in the later situation, getting away from the obstacle is the only requirement. To fulfill the demand, the research uses the Velocity Obstacle approach to implement the regular avoidance that according to the COLREGS rules in non-emergency situation. And in emergency situation, an improved potential filed composed of repulsive field and centrifugal field is put forward to guide the USV avoid the obstacle by altering speed and course. The algorithm is proved in the simulation experiments. In further research, the avoidance strategy will be established when the USV is sandwiched, encircled and crashed by multiple obstacles purposefully.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51809203 and 51709214) and the Fundamental Research Funds for the Central Universities (WUT: 2017IVA008 and 2017IVA006).

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