Received February 5, 2021, accepted February 14, 2021, date of publication February 18, 2021, date of current version March 2, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3060150

COLREGS-based Path Planning for Ships at Sea Using Velocity Obstacles

WENJUN ZHANG[1], CHENGYONG YAN[1], HONGGUANG LYU[1], PINGLIN WANG[1], ZONGYAO XUE[1], ZEHUA LI[1], AND BAI XIAO[2]

[1]Navigation College, Dalian Maritime University, Dalian 116026, China

[2]Dalian Port Pilot Station, Dalian 116026, China

Corresponding author: Chengyong Yan (chengyyan@163.com)

This work was supported in part by the National Key Research and Development Program of China under Grant 2019YFB1600602, in part by the Natural Science Foundation of Liaoning Province of China under Grant 20180551040, in part by the Key R&D Program of Liaoning Province of China under Grant 2018228002, in part by the National Natural Science Foundation of China under Grant 52071049, and in part by the Fundamental Research Funds for the Central Universities under Grant 3132020128.

ABSTRACT Recent studies have made significant development in path planning for ships. However some studies blindly obey rules of COLREGS (International Regulations for Preventing Collisions at Sea) or only adopt turning to starboard ignoring actual practice, like, turning to port and considering deviation from the planned route when taking actions for collision avoidance. In view of the COLREGS and ordinary seamen practice, this paper proposes collision avoidance actions before encounter situation and collision avoidance actions in an encounter situation. Based on the different stages of the encounter situation, it will add more choices for ships when taking action. To specify different stages of encounter situation clearly and take proper collision avoidance actions, this paper makes a quantitative analysis of three primary encounter situations; velocity obstacles (VO) is employed to find allowed velocity space for own ship (OS); by making further analysis of the relationship among distance at the closest point of approach, bow cross, and COLREGS, the method gives a clear direction for OS to search the best velocity in allowed velocity space for three primary encounter situations; VO utility function is applied to search specific value of the best velocity and is useful for different encounter situations. Simulations show that the results are effective and deterministic for collision avoidance. This method not only prevents blindly obeying rules of COLREGS but also promotes reducing deviation from the planned route.

INDEX TERMS COLREGS, route planning, collision avoidance, velocity obstacles, utility function.

I. INTRODUCTION

Today, with the rapid progress of technology development in autonomous driving, collision avoidance techniques of ships at sea have been promoted significantly. Numerous studies used different kinds of path planning algorithms for ships at sea, such as Evolutionary Algorithms [1], Fuzzy Logic [2]–[4], A* Algorithm [5], the Fast Marching Method [6], Ant Colony algorithm method [7], Artificial Potential Fields(APF) [8], and Velocity Obstacles [9], [10]. Most of these approaches can be categorized into two kinds, including deterministic approaches and heuristic approaches. Deterministic approaches, such as APF, have features of following some defined steps to get collision-free paths, and the result is consistent for each calculation. Whereas heuristic approaches, like Evolutionary Algorithms, search for a solution in search space without rigorous procedures, the advantage of heuristic approaches is solving multi-optimization problems [6]. All these approaches not only increase efficiencies of path planning but also could reduce human errors.

Another popular method for collision avoidance is cooperative path planning [11]–[13]; it is proficient at multi-ship encounter situations and could give each ship a proper velocity for collision avoidance. This method depends on that all ships could communicate with each other and take cooperative collision avoidance actions.

Furthermore, a decision support system is applied in collision avoidance for ships [14], [15]. The decision support system could help users make good judgment and proper decisions in complex situations using artificial intelligence or other techniques.

The associate editor coordinating the review of this manuscript and approving it for publication was Heng Wang.

TABLE 1. Comparisons between different methods.

	EA	FL	FMM	ACO	TBA	APD	Velocity Obstacle		
Authors	Tam and Bucknall	Perera et al.,	Liu and Bucknall,	Lazarowska	Lazarowska	Lyu and Yin,	Kuwata et al.,	Huang et al.,	Zhang et al.,
year	2010	2012	2015	2015	2017	2019	2014	2019	This paper
COLREGS compliance	low	med	no	high	high	high	high	high	High
Static obstacles	yes	no	yes	yes	yes	yes	yes	no	Yes
Dynamic obstacles	yes	yes	yes	yes	yes	yes	yes	yes	Yes
Repeatability of results	no	yes	yes	yes	yes	yes	yes	yes	Yes
Run time	high	?	very low	med	very low	very low	low	low	Low
Change of speed /course (TSs)	course	no	no	no	no	yes	yes	yes	Yes
Speed change (OS)	no	yes	yes	no	no	no	yes	no	Yes
Course change (OS)	Port& starboard	starboard	Port& starboard	starboard	starboard	starboard	starboard	starboard	Port& starboard

Note: symbol "?" means that this subject is not specified or presented clearly in corresponding papers

However, there are still a few remaining problems yet to be solved. On one aspect, some studies mainly paid attention to collision avoidance, ignoring International Regulations for Preventing Collisions at Sea (COLREGS) [16]; COLREGS have specific provisions for different situations, especially for the two-ship-encounter scenario. On the other aspect, although many path planning approaches comply with COLREGS, they contradict actual practice. The action for collision avoidance is only turning to starboard ignoring other measures, like, turning to port. Turning to starboard does not always solve problems efficiently, especially in complex multi-ship encounter scenarios. Sometimes blindly following rules of COLREGS will result in a large deviation from the planned route and more energy consumption. Little attention is paid to this.

To tackle these problems and get high-quality conflict-free paths, this paper proposes a novel method of collision avoidance actions that includes collision avoidance actions before encounter situation (CAAB) and collision avoidance actions in encounter situation (CAAI), based on the different stages of the encounter situation. By combining velocity obstacles (VO) with distance at the closest point of approach (DCPA) and time to the closest point of approach (TCPA), COLREGS, and other parameters of encounter situations, own ship (OS) could easily find allowed velocity space. The current paper employs the VO utility function to choose the best velocity in allowed velocity space for collision avoidance.

Table 1 shows a comparison among some representative methods of path planning for ships. The methods were evaluated according to the fulfilment of eight requirements/features: COLREGS compliance(a degree of fulfilment is specified as no, low, medium(med abbreviation in the table), or high), Static obstacles, Dynamic obstacles, Repeatability of results, Run time, Change of speed /course (target ships(TSs)), Speed change (OS), and Course change (OS). Some features are evaluated based upon fulfilment (yes in the table) or failure of fulfilment (no in the table) of a defined criterion. The computational time has its own scale of evaluation, where the time can be very low (milliseconds), low (seconds), medium (several or tens of seconds) or high (hundreds of seconds). In the last column this paper's method is evaluated for comparison with existing approaches.

The current paper is organized as follows: Section II describes different stages of encounter situations; collision check is included in Section III; Section IV makes a brief introduction of VO; Section V presents three primary encounter situations; VO utility function is introduced in Section VI; simulation results of the proposed method are given in Section VII.

II. DIFFERENT STAGES OF ENCOUNTER SITUATION

From previous studies and provisions of COLREGS, ships' encounter situation can be divided into four stages in general [14], [17], as shown in Fig. 1.

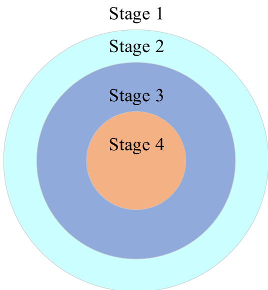

FIGURE 1. Stages of encounter situation.

Stage 1: At long range, outside of the requirement of COLREGS, ships are free to take actions.

Stage 2: When the encounter situation of COLREGS occurs, both ships have to take actions according to COLREGS specifications.

Stage 3: When the give-way ship does not take appropriate actions according to COLREGS specifications, the stand-on ship has to take proper actions, like, giving the whistle signal prescribed in rules.

Stage 4: When in a close-quarters situation, the stand-on ship has to take the best aids to avoid a collision.

At different stages, ships can take different collision avoidance actions. It is necessary to specify the stages of an encounter situation clearly. This paper primary pays attention to actions of ships in stage 1 and stage 2. Therefore, the limit between stage 1 and stage 2 is very important. To specify stage 1 and stage 2 clearly, this paper makes a quantitative interpretation of three primary encounter situations in Section V. Occurrence of three primary encounter situations is the limit between stage 1 and stage 2. COLREGS have specific provisions for the ship's manoeuver in stage 2; for example, turning to port is prohibited in crossing situation. However, turning to port may be a good choice under some other conditions, and turning to port exists in actual practice. To comply with COLREGS and acquire the best velocity for collision avoidance, this paper introduces CAAB in stage 1 and CAAI in stage 2. CAAI is turning to starboard in stage 2, while CAAB (turning to port or speed changes) should be taken in stage 1. Therefore, CAAB should be taken before occurrence of three primary situations. This will enable ships to have more choices in the velocity spaces for collision avoidance. This paper assumes that CAAB in stage 1 is an abidance of COLREGS. The conditions for choosing different collision avoidance actions will be discussed in the following sections.

III. COLLISION CHECK

According to specific provisions for different encounter scenarios, the first step for OS is to check collision risk with targets (moving and stationary obstacles); *DCPA* and *TCPA* are commonly used to evaluate the potential risks in practice; this paper applies the same parameters to check the risk of collision and makes further analysis for different encounter situations.

Fig. 2 shows the relative position of two encountering ships based on the applied coordinate systems. The ships are assumed to sail in the earth-fixed coordinate system. OS' coordinate (x_0, y_0), speed v_A (v_{x0}, v_{y0}), course φ_0; TS' coordinate (x_1, y_1), speed v_B (v_{x1}, v_{y1}), course φ_1 [18];

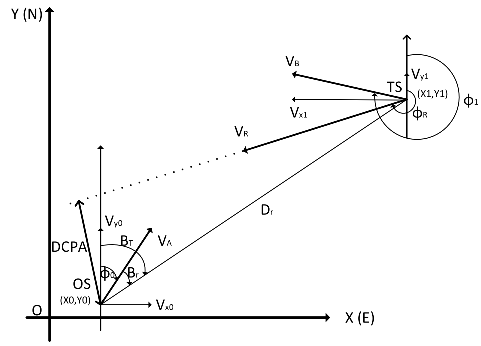

FIGURE 2. The relative position between OS and TS based on earth fixed coordinate system.

Relative velocity: v_R (v_{Rx}, v_{Ry})

$$\begin{cases} v_{Rx} = v_{x1} - v_{xo} \\ v_{Ry} = v_{y1} - v_{yo} \end{cases} \tag{1}$$

$$v_R = \sqrt{v_{Rx}^2 + v_{Ry}^2} \tag{2}$$

The course of relative velocity: φ_R

$$\varphi_R = \arctan\frac{v_{Rx}}{v_{Ry}} + \alpha$$
$$\alpha = \begin{cases} 0°, & \text{if } v_{Rx} \geq 0,\ v_{Ry} \geq 0 \\ 180°, & \text{if } v_{Rx} < 0,\ v_{Ry} < 0 \\ 180°, & \text{if } v_{Rx} \geq 0,\ v_{Ry} < 0 \\ 360°, & \text{if } v_{Rx} < 0,\ v_{Ry} \geq 0 \end{cases} \tag{3}$$

Relative distance of the target: D_r

$$D_r = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} \tag{4}$$

True bearing of the target:

$$B_T = \arctan\frac{x_1 - x_0}{y_1 - x_0} + \alpha 1$$
$$\alpha 1 = \begin{cases} 0°, & \text{if } x_1 \geq x_0,\ y_1 \geq y_0 \\ 180°, & \text{if } x_1 < x_0,\ y_1 < y_0 \\ 180°, & \textit{if } x_1 \geq x_0,\ y_1 < y_0 \\ 360°, & \text{if } x_1 < x_0,\ y_1 \geq y_0 \end{cases} \tag{5}$$

Relative bearing: B_r

$$B_r = B_T - \varphi_0 \tag{6}$$

If $B_r < 0$, $B_r = B_r + 360°$.

The distance at the closest point of approach: *DCPA*

$$DCPA = D_r * sin\left(\varphi_R - B_T - 180°\right) \quad (7)$$

Time to the closest point of approach: *TCPA*

$$TCPA = D_r * cos\left(\varphi_R - B_T - 180°\right)/v_R \quad (8)$$

DCPA has positive and negative values according to (7); combining with different values of B_r, it can get the following conclusions as shown in Table 2:

TABLE 2. Different conditions of BC.

BC +	BC-
B_r< 180º&*DCPA* > 0	B_r < 180º & *DCPA* < 0
B_r> 180º &*DCPA* < 0	B_r > 180º & *DCPA* > 0

BC: bow cross
BC +: TS crosses the bow of OS
BC-: OS crosses the bow of TS

Few studies pay attention to the sign of DCPA and BC, Table 2, most of them only focused on the value of DCPA, but the sign of DCPA and BC are important factors for collision avoidance actions. In practice, the duty officer has to know whether OS will pass the bow of TS for the present situation when considering collision avoidance actions, especially in a crossing situation. For example, in a crossing situation, OS is a give-way vessel, BC-, *DCPA* is −0.9 nm (nautical mile); however, safe distance needs to be 1 nm, OS just needs to turn to port a little to keep 1 nm away from TS and will not deviate from planned route too much. If OS chooses to turn to starboard, *DCPA* will firstly change from −0.9 to 0 and then increases to 1. OS needs a substantial angle to turn to starboard and deviates from planned route far away. The result will lead to an increase in the distance of the route and more energy consumption. However, turning to port is not allowed in the crossing situation; therefore, this paper puts forward CAAB that OS could turn to port in stage 1 before the crossing rule applying. Taking advantage of BC, OS can identify which side is better for turning course.

IV. VELOCITY OBSTACLES (VO)

This section makes a brief introduction to the VO approach. VO approach was first proposed by Fiorini and Shiller [19] for robot route planning. VO approach transforms a dynamic collision avoidance situation into a static situation by introducing circular or other geometric shapes in velocity space. VO approach generates a cone-shaped obstacle in the velocity space, and the robot's velocity has to be out of VO to maintain safety [20]. Since first introduced, VO has been widely used and further developed by many studies. Van den Berg introduced the reciprocal VO, assuming that the other agents take similar collision avoidance actions [21]; Wilkie *et al.* proposed generalized VO(GVO), considering the constraints of car-like robots [22]; Snape *et al.* used hybrid reciprocal VO addressing undesirable oscillations in trajectory [23]; Kuwata *et al.* used VO to plan the route for USV considering COLREGS and applied corresponding rules of COLREGS for the future obstacles [9]; Huang *et al.* applied GVO algorithm for preventing ship collisions at sea [10].

Concept of velocity obstacles: both OS at position P_A and TS or obstacle at position P_B have disc-shaped with radii r_A and r_B; let V_A and V_B be the velocity of OS and TS respectively; the velocity obstacle VO_B^A means a set of velocity V_A for OS that will lead to a collision with TS moving with velocity V_B in the future. This can be expressed as:

$$VO_B^A(V_B) = \left\{V_A|\lambda\left(P_{A,}V_A - V_B\right) \cap (B\oplus -A) \neq \emptyset\right\} \quad (9)$$

$A\oplus B = \{a+b|a \in A, b \in B\}$ is the Minkowski sum of OS and TS; $-A = \{-a|a \in A\}$; let $\lambda(P, V) = \{P+Vt|t \geq 0\}$ be a ray starting at position P with the direction of V; equation (9) can be interpreted as that a ray starting from OS and going in the direction of the relative velocity $(V_A - V_B)$ intersects the obstacle B expanded by OS size A, as shown in Fig. 3. The condition for avoiding collision is that the OS's velocity lies outside the *VO*, supposing that TS maintains a constant velocity when OS calculates *VO*.

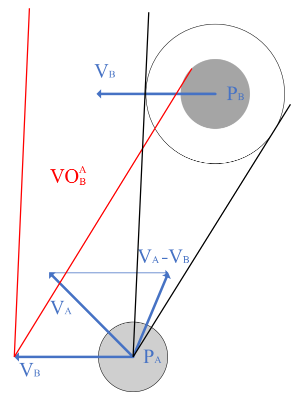

FIGURE 3. VO_B^A.

If the relative velocity of OS $(V_A - V_B)$ is inside the cone area formed by OS center and the expanded obstacle $B\oplus -A$ can lead to a collision. *VO* of TS for OS is the cone area shifted by V_B.

V. THREE PRIMARY ENCOUNTER SITUATIONS

A. QUANTITATIVE INTERPRETATION OF THREE PRIMARY ENCOUNTER SITUATIONS

COLREGS encompasses different kinds of encounter situations; the focus of this paper is about three primary encounter situations, head-on, overtaking and crossing. Although rules 13-15 give the definitions of three encounter situations, it is somewhat unclear. According to previous studies, these three encounter situations could be illustrated by Fig. 4 which is divided into three regions with different relative bearings of TS. However, it is still not a quantitative analysis; this

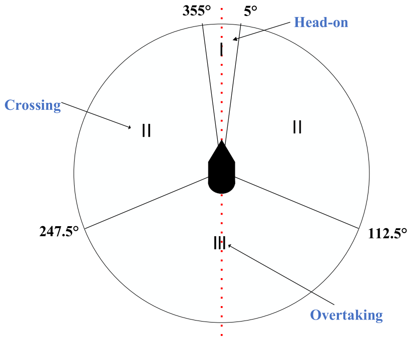

FIGURE 4. Encounter situation.

paper proposes some parameters to make a quantitative interpretation:

D_r is the distance between OS and TS.

$D_1(D_2, D_3)$ is a compulsory distance for rule 14 (13,15) starting to apply when D_r arrives at D_1; according to the ordinary practice of seamen, the outer limit of D_1 is 5-8 nm, D_2 2-4 nm, and D_3 4-6 nm.

D_{safe1}, D_{safe2}, D_{safe3} are safe distances to keep between OS and TS for each encounter situation, which are decided by OS.

$TCPA > 0$ means that two ships are still in encounter situations.

I, II, III are parts of Fig. 4, which are divided by relative bearing; $P_t \in$ I means that TS' position belongs to I area of OS; $P_o \in$ III indicates that OS' position belongs to III area of TS.

B. APPLICATION OF VO IN THREE PRIMARY ENCOUNTER SITUATIONS

In this paper, we suppose that ship's equipment (RADAR, AIS, etc.) can get targets' information from long range (like, 8-10 nm); $D_1 = 6$ nm, $D_2 = 3$ nm; $D_3 = 6$ nm; $D_{safe1} = D_{safe2} = D_{safe3} = 1$ nm.

1) HEAD-ON SITUATION

According to Table 3 and Table 4, OS detects TS navigating in reciprocal or nearly reciprocal courses from long range ($D_r >$ D$_1$), and it involves the risk of collision for OS. Before a head-on encounter scenario occurs, OS can firstly analyze the conditions of the situation and then search for a proper velocity for collision avoidance by using BC, VO, and other parameters rather than directly turning to starboard to avoid a collision.

TABLE 3. Three primary encounter situations.

parameters	Head-on	Overtaking	Crossing
D_r	$D_r < D_1$	$D_r < D_2$	$D_r < D_3$
Course/ B_r	abs(180°-abs(φ_0-φ_1))< 5°	112.5°< B_r< 247.5°	abs(180°-abs(φ_0-φ_1))≥ 5°
abs(DCPA)	abs($DCPA$) < D_{safe1}	abs($DCPA$) < D_{safe2}	abs($DCPA$) < D_{safe3}
TCPA	$TCPA > 0$	$TCPA > 0$	$TCPA > 0$
AREA	$P_t \in$ I	$P_t \in$ III or $P_o \in$ III	$P_t \in$ II

TABLE 4. Ships' information for calculating VO.

	ship	Position	Speed	Course	DCPA
Head-on 1	OS	(0,1)	15 Kn	0°	0.5 nm
	TS	(-0.5,7)	15 Kn	180°	
Head-on 2	OS	(0,1)	15 Kn	0°	-0.5 nm
	TS	(0.5,8)	15 Kn	180°	

In Fig. 5a, collision risk exists between OS and TS; the conditions of Head-on 1 and Head-on 2 are different; therefor OS takes different actions to avoid collision. In Fig. 5b, the red part of circle velocity space is not allowed to choose for keeping safety; the green part stands for safe velocity for OS; considering of less deviation from the planned route, it is easier to see that turning to starboard is a good choice for OS in head-on 1; whereas for head-on 2, turning to port is a better choice. To make it easier to distinguish the better side of velocity space and obey rules of COLREGS, this paper adopted the following parameters, as shown in Table 5:

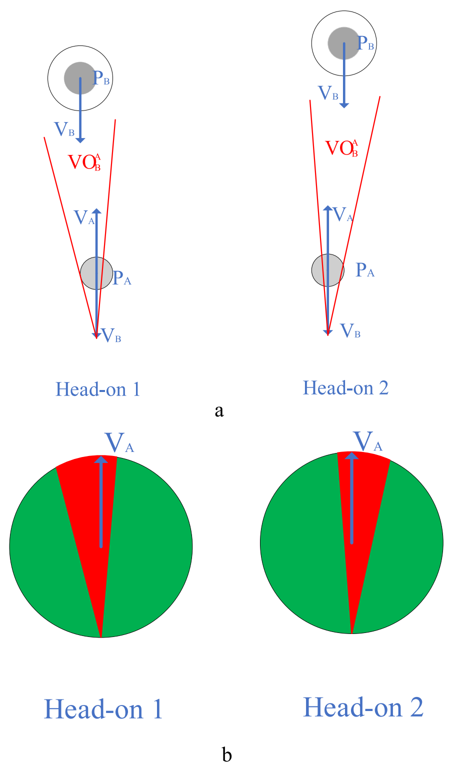

FIGURE 5. a. Head-on situation b. Head-on VO.

In head-on 2, turning to port is not allowed; therefore, the OS has to take actions earlier ($D_r > D_1$) in stage 1. After determining the side to turn, OS could only search this side of velocity space to get the best velocity; it will contribute to improving calculation speed.

TABLE 5. Conditions for taking collision avoidance actions.

Condition	$B_r \le 180°$& D_{safe1}> $DCPA \ge 0$	$B_r \le 180°$& $DCPA < 0$ & abs($DCPA$) < D_{safe1}& $D_r > D_1$,	$B_r > 180°$& D_{safe1}> $DCPA \ge 0$	$B_r > 180°$& $DCPA < 0$ & abs($DCPA$) < D_{safe1}& $D_r > D_1$,
BC	BC+	BC-	BC-	BC+
Action of OS	Turning to starboard	Turning to port	Turning to starboard	Turning to port
If the head-on situation occurs, OS has to turn to starboard without considering the conditions in the table				

2) OVERTAKING SITUATION

According to Table 6 and Fig. 6a, the overtaking situation occurs and is going to take place in overtaking 1 and overtaking 2, respectively. To keep a safe distance with TS and deviate less from the planned route, OS adopts different actions for overtaking 1 and overtaking 2. Although rules of COLREGS do not specify which side to overtake, this paper gives clear instruction for OS by making use of parameters in Table 5. The difference for the overtaking situation in Table 5 is the condition $D_r > D_2$. Fig. 6b shows VO of overtaking. If overtaken by TS, OS needs to keep course and speed.

TABLE 6. Ships' information for calculating VO.

	Ship	Position	Speed	Course	DCPA
Overtaking 1	OS	(0,4.5)	30 Kn	0°	0.2 nm
	TS	(0.12,7.21)	15 Kn	352°	
Overtaking 2	OS	(0,3)	30 Kn	0°	-0.2 nm
	TS	(-0.23,6.47)	15 Kn	8°	

3) CROSSING SITUATION

According to Table 7, the crossing situation takes place in crossing 1 and is going to occur in crossing 2. From Fig. 7a and Fig. 7b, turning to starboard is a good choice for OS in crossing 1 and turning to port is better in crossing 2.

OS will make a choice easier by employing Table 8; the condition ($v_A/v_B \ge 0.95$) is added when OS turns to port; the reason is that if OS's speed is very low compared with TS' speed, turning to port is not useful in crossing 2. In a crossing situation, if $B_r > 180°$, OS needs to keep course and speed.

VI. VELOCITY OBSTACLE UTILITY FUNCTION

From the figures of VO, it is easier to judge whether the velocity is safe for OS, but it is hard to find the best one (specific value of velocity) among allowed velocity space. In figures of VO, each velocity has already been judged by

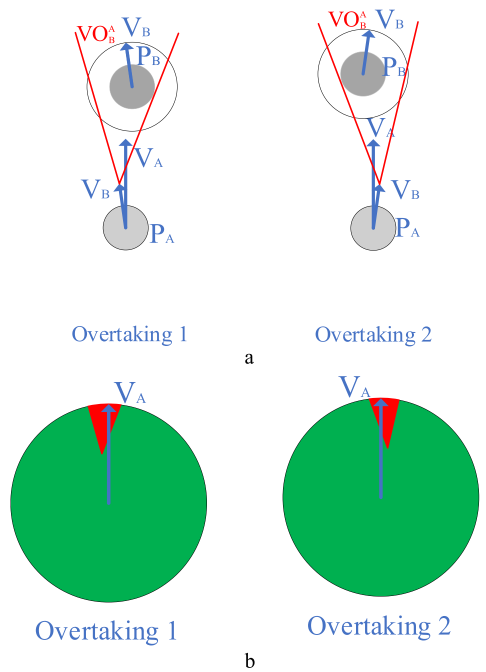

FIGURE 6. a. Overtaking situation b. Overtaking VO.

TABLE 7. Ships' information for calculating VO.

	Ship	Position	Speed	Course	DCPA
Crossing 1	OS	(0,1.5)	15 Kn	0°	0.7 nm
	TS	(3.64,6.13)	15 Kn	270°	
Crossing 2	OS	(0,1)	15 Kn	0°	-0.7 nm
	TS	(5.13,5.14)	15 Kn	270°	

TABLE 8. Conditions for taking collision avoidance actions.

Condition	$B_r < 180°$&D_{safe3}> $DCPA \ge 0$	$B_r < 180°$& DCPA < 0&abs(DCPA) $\le$ Dsafe3& Dr >D3 & $v_A/v_B \ge 0.95$
BC	BC+	BC-
Action of OS	Turning to starboard	Turning to port
If the crossing situation occurs, OS (Br ≤ 180°) has to turn to starboard without considering the conditions in the table		

using a step function (10), Fig. 8, [24]:

$$f(\varphi, v) = \begin{cases} 0, & if\ abs\,(DCPA) < safe\ DCPA \\ 1, & if\ abs\,(DCPA) \ge safe\ DCPA \end{cases} \quad (10)$$

To find the optimum velocity, it needs to use another function to evaluate velocity with explicit values instead of the binary allowed or excluded method. The velocity inside VO should be excluded but other velocities in the allowed velocity space should have different utility values compared with the original (present) velocity. In this paper it supposes that the original (present) velocity is the desired velocity. The quadratic function is used for evaluating each allowed

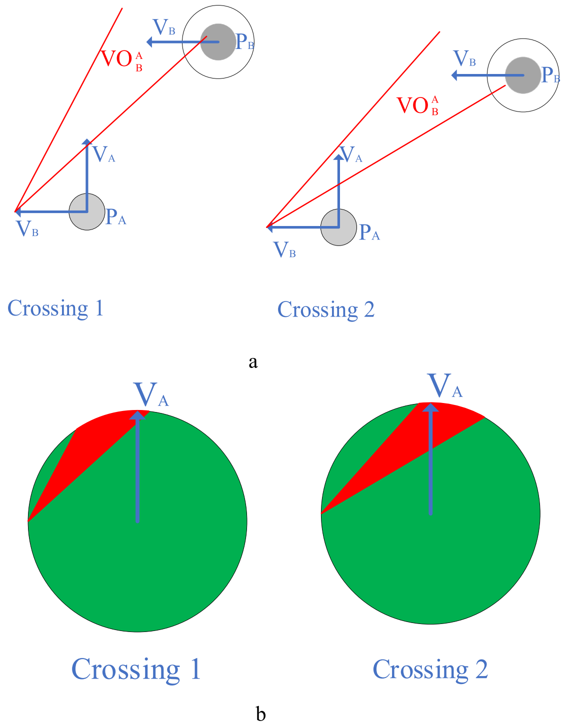

FIGURE 7. a. Crossing situation. b. Crossing VO.

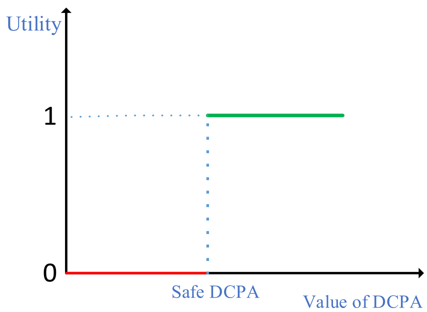

FIGURE 8. Step function of VO.

velocity, as shown in Fig. 9. For one velocity, it will get two utilities from $Q(\varphi)$ and $Q(v)$, respectively; the final utility of velocity is:

$$Q = Q(\varphi) * Q(v) \tag{11}$$

The utility function:

$$f(\varphi, v) = \begin{cases} 0, & if\ abs\,(DCPA) < safe\ DCPA \\ Q, & if\ abs\,(DCPA) \geq safe\ DCPA \end{cases} \tag{12}$$

The utility of velocity inside VO is still zero, whereas a quadratic function calculates other utilities. When the risk of collision exists, it just needs to search for a velocity with the maximum utility.

In Fig. 10, two peaks stand for allowed velocity utilities, the higher the better. The space at the bottom represents undesirable utilities; the peak on the left stands for the starboard side of allowed velocity space; the right peak means the port side of allowed velocity space; therefore, it is much easier to get the best velocity.

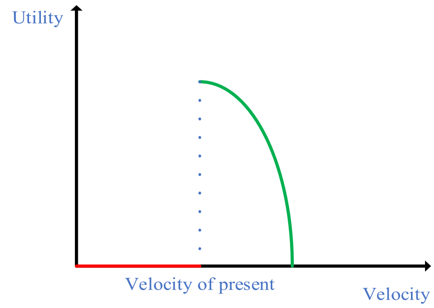

FIGURE 9. Quadratic utility function.

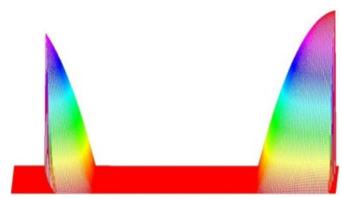

FIGURE 10. Utilities of velocities.

VII. SIMULATION EXAMPLES

In simulations the velocity space of OS is set that the maximum of turning is ±90° and the speed range is from 0.5*v (v is the original (present) speed of OS) to v. OS searches the best velocity among allowed velocity space by using VO utility function. It assumes that the target's velocity vectors are constant over time. If the velocity of the target changes over time, the OS could take proper collision avoidance actions on the base of new information. Due to the large distance between OS and TS when OS takes collision avoidance actions, the time for taking action is ignored and is very small compared with TCPA. The simulations are performed in a PC with an Intel Core i3 380 M 2.53 GHz processor, and 2 GB RAM. The operating system is 32-bit win7, and the algorithm is executed in the MATLAB environment. The execution time of the algorithm in each cycle is almost real-time."

A. Algorithm Flow for simulations

1) The first step is to calculate *DCPA* and *TCPA* between OS and TSs. OS pays attention to TSs within the scope of 10 nm, by checking if *TCPA* >0 and abs(*DCPA*) < D_{safe}.

2) If collision risk exists, OS has to identify whether one of three primary encounter situations occurs or is going to occur by using parameters in Table 3.

3) If the encounter situation occurs, OS has to take CAAI for collision avoidance by using VO.

4) If the encounter situation is going to occur, OS could choose to take CAAI or CAAB for collision avoidance by searching the best velocity among allowed velocity space.

The method of the algorithm could avoid OS blindly turning to starboard when collision risk exists. OS takes different

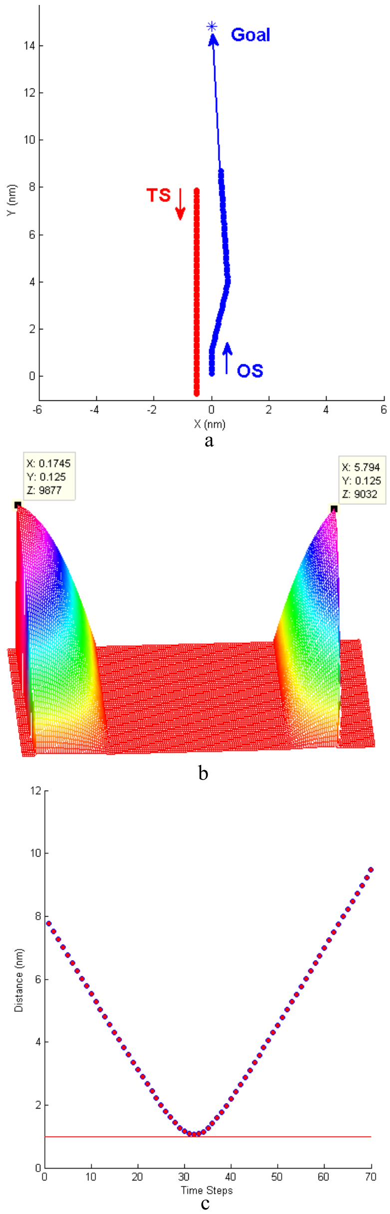

FIGURE 11. a. Simulation of head-on1 b. Utilities of velocities of head-on1 c. Distance between OS and TS.

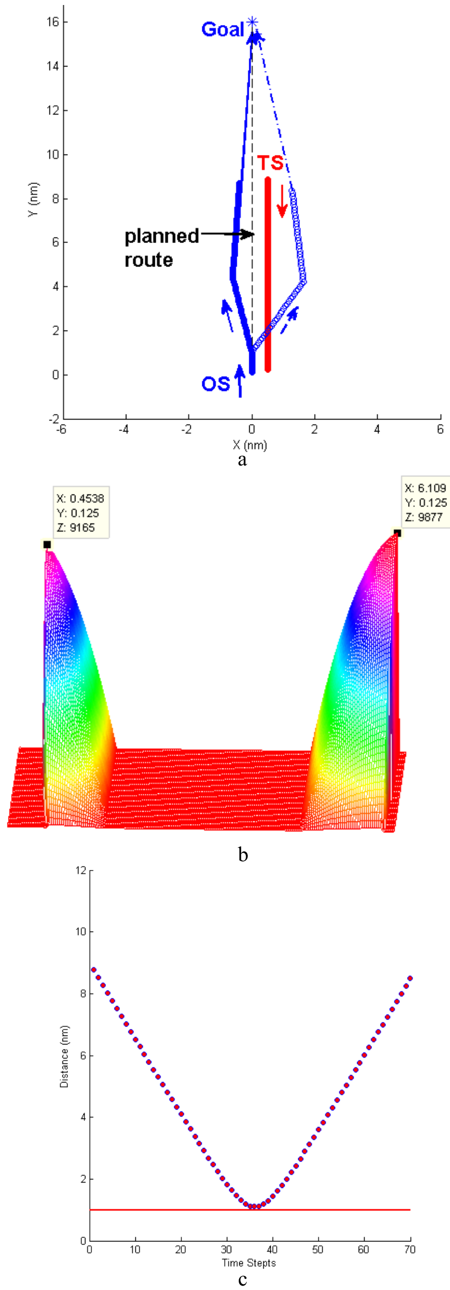

FIGURE 12. a. Simulation of head-on 2 b. Utilities of velocities of head-on 2 c. Distance between OS and TS.

actions to avoid collisions by making a full analysis of the encounter situation. This not only adds more choices for collision avoidance but also makes OS deviate less from the planned route.

B. First of all, simulations are for three primary encounter situations in Section V: for each encounter situation, OS could find the best velocity by using VO and utility function; to make a comparison, figures of utilities of velocity give whole velocity space.

Head-on situation: In head-on 1, Fig. 11a; OS finds the best velocity in the left peak of Fig. 11b and takes it for collision avoidance. The distance between OS and TS is not less than 1 nm during the whole encounter situation, Fig. 11c; the red line in Fig. 11c is D_{safe} ($D_{\text{safe}} = 1$ nm) which needs to be kept for safety

In head-on 2 (Fig. 12a), the best velocity to avoid a collision for the OS is in the right peak (Fig. 12b), therefor OS turns to port when the distance is about 7 nm from TS; the collision-avoidance action belongs to CAAB. To compare with [9], [10], this paper gives a simulation of OS turning to starboard for avoiding collision in Fig. 12a; turning to port generates a small deviation from planned route comparing with turning to starboard. OS keeps at least 1 nm away from TS in head-on 2, as shown in Fig. 12c.

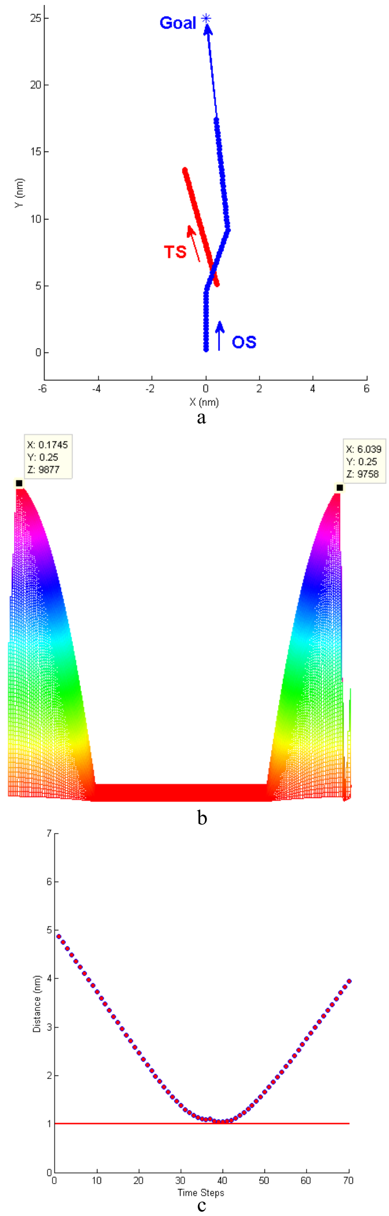

FIGURE 13. **a. Simulation of overtaking 1 b. Utilities of velocities of overtaking 1 c. Distance between OS and TS1.**

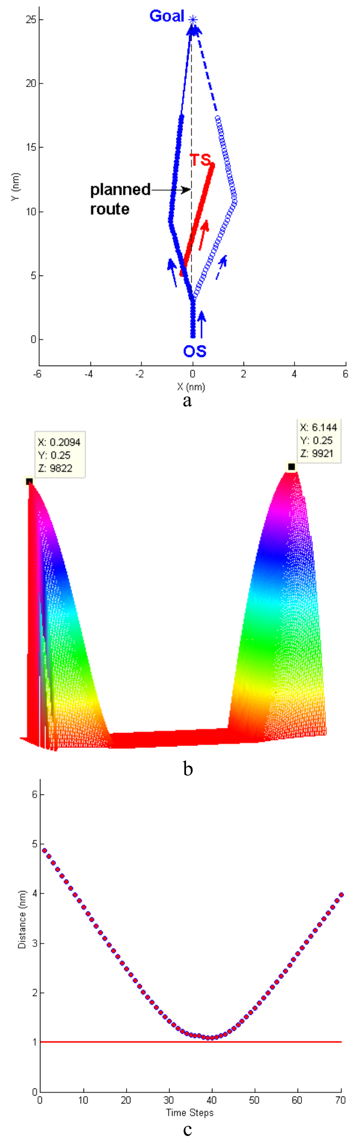

FIGURE 14. **a. Simulation of overtaking 2 b. Utilities of velocities of overtaking 2 c. Distance between OS and TS1.**

Overtaking situation: from Fig. 13b and Fig. 14b, OS can get the best velocity for overtaking 1 and overtaking 2. OS overtakes TS by starboard and port of TS, respectively, as shown in Fig. 13a and Fig. 14a. To compare with [9], [10], turning to starboard is simulated in Fig.14a; obviously, turning to port is much better. In Fig. 13b and Fig. 14b, although the difference of utilities between the right peak and the left peak is small, OS could avoid passing bow of TS and deviates less from the planned route by taking the best velocity; Fig. 13c and Fig. 14c show that the distance between OS and TS is always bigger than 1 nm.

Crossing situation: In crossing 1 (Fig. 15a), acquiring the best velocity from Fig. 15b, OS turns to starboard when crossing situation occurs (the distance between OS and TS is about 5.9 nm). OS always keeps a safe distance from TS in crossing 1, as shown in Fig. 15c.

In crossing 2 (Fig. 16a), the best velocity for OS to avoid a collision is turning to port (Fig. 16b); to comply with rules of COLREGS, OS turns to port when the distance is about 6.6 nm; the action belongs to CAAB. To compare with [9], [10], the track of OS turning to starboard is provided in Fig.16a. The distance between OS and TS is always larger than 1 nm, as shown in Fig.16c.

A. COMPLEX SITUATION

1) SITUATION 1

In Fig. 17a, in the beginning, TS's course and OS's course is crossing but does not involve risk of collision. The DCPA is −2.2 nm (Table 9); if two ships keep course and speed, they

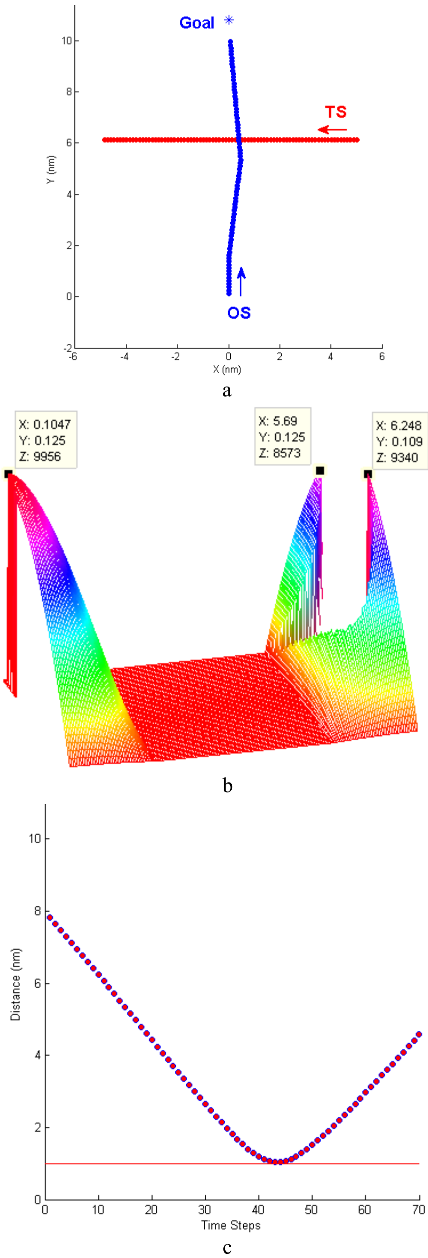

FIGURE 15. a. Simulation of crossing 1 b. Utilities of velocities of crossing 1 c. Distance between OS and TS.

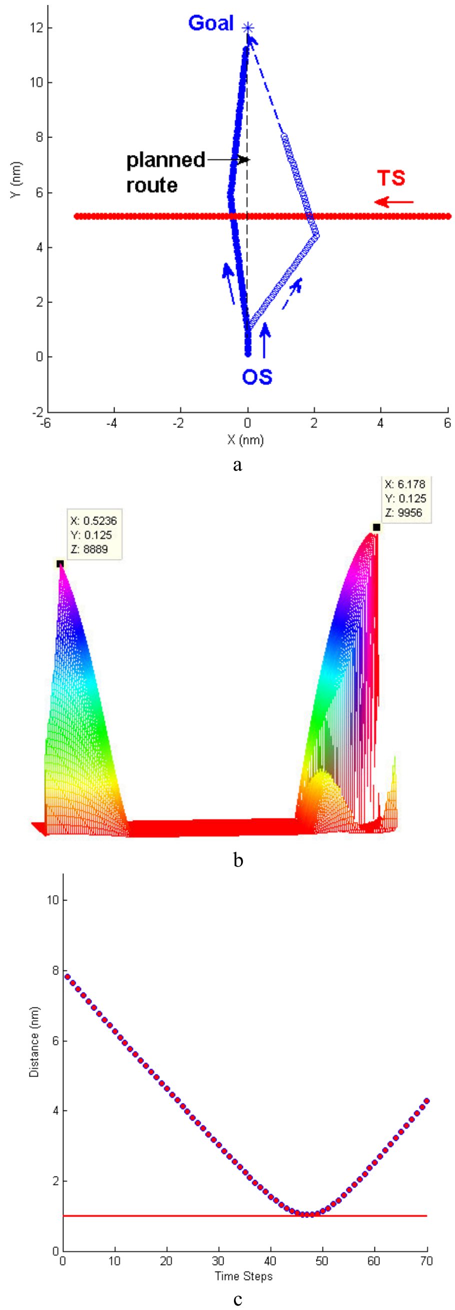

FIGURE 16. a. Simulation of crossing 2 b. Utilities of velocities of crossing 2 c. Distance between OS and TS.

TABLE 9. The initial information of ships.

	ship	Position	Speed	Course	DCPA
Situation1	OS	(0,0)	15 Kn	0°	-2.2 nm
	TS	(-5,6)	18 Kn	80°	

will pass safely, and TS will pass the bow of OS. However, TS suddenly alters 30° to the starboard side and reduces speed to 15 Kn, making DCPA almost zero. Due to rule 17 of COLREGS, turning port is not allowed for OS, although it has bigger utility, in Fig. 17b; therefore, OS could only search the right part of velocity space to get the best velocity; after altering 29° to starboard, OS keeps 1 nm from TS, as shown in Fig. 17c.

2) SITUATION 2

In situation 2, the courses of OS and TS1 are crossing and there is an anchored ship (TS2) near the meeting area. According to Table 10, collision risk only exists between OS and TS1. Therefore, OS has to take actions to avoid a collision. If OS blindly turns to starboard, OS will have collision

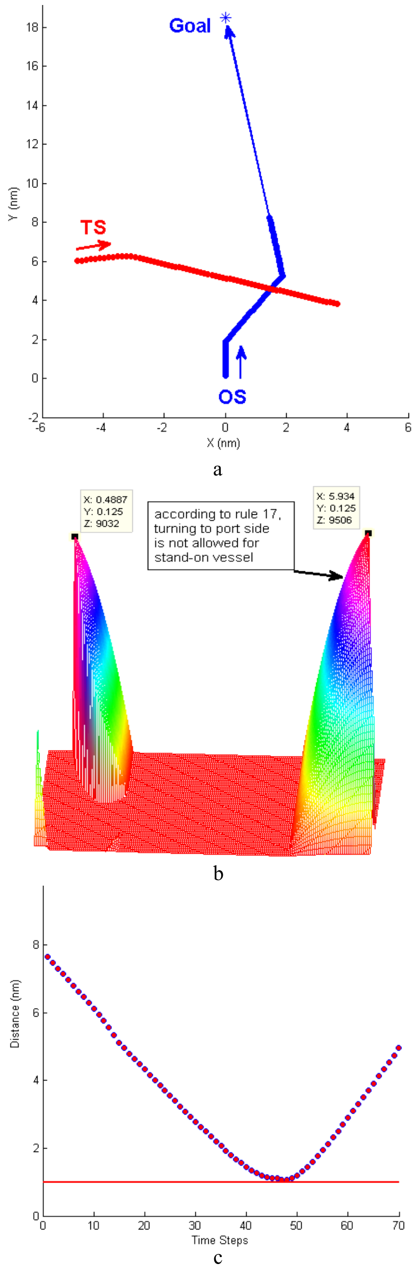

FIGURE 17. a. Simulation of Situation1 b. Utilities of velocities of Situation1 c. Distance between OS and TS.

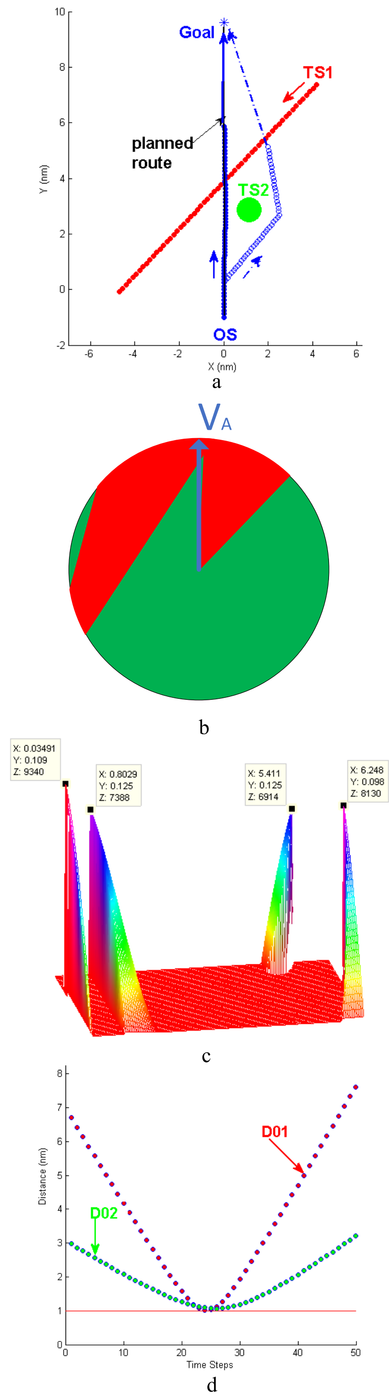

FIGURE 18. a. Simulation of situation 2 b. VO of situation 2 c. Utilities of velocities of situation 2 d. Distance between OS and TSs.

TABLE 10. Ships' information for calculating VO.

	ship	Position	Speed	Course	DCPA(OS&TS)
Situation 2	OS	(0,0.25)	15 Kn	0°	0.75 nm
	TS1	(2.65,6.09)	24 Kn	270°	
	TS2	(1.15,2.88)	0 Kn	0°	1.15 nm

risk with TS2; in order to keep clear with TS2, OS needs to continue turning to starboard. In Fig. 18a, OS deviates too much from panned route after turning at least 46° to starboard. From Fig. 18b and Fig. 18c, reducing speed is a better choice for OS; after reducing speed from 15 Kn to 13 Kn and turning 2° to starboard (6.5 nm from target 1), OS could keep a safe distance from TS1 and TS2 in the whole encounter situation, Fig. 18d. D01 in Fig. 18d indicates the distance between OS and TS1.

3) SITUATION 3

OS is crossing with TS1 and TS2 (Fig. 19a); according to Table 11, TS1 will pass stern of OS, and TS2 will pass bow

TABLE 11. **Ships' information for calculating VO.**

	ship	Position	Speed	Course	DCPA(OS&TS)
Situation 3	OS	(0,1)	15 Kn	0°	-0.7 nm
	TS1	(5.51,5.46)	15 Kn	270°	
	TS2	(-3.25,6.92)	22.8 Kn	125°	-0.6 nm

TABLE 12. **Ships' information for calculating VO.**

	Ship	Position	Speed	Course	DCPA(OS&TS)
Situation 4	OS	(0,0.5)	15 Kn	0°	
	TS1	(2.89,5.55)	24 Kn	230°	0.1 nm
	TS2	(0.56,7.48)	15 Kn	180°	-0.6 nm
	TS3	(-5.22,5.66)	13.2 Kn	90°	0.5 nm
	TS4	(-0.83,3.21)	3.6 Kn	0°	0.8 nm

of OS; DCPA for TS1 and TS2 is 1.8 nm. From Fig. 19b and Fig. 19c, turning to port is the best choice for OS to avoid collisions. When OS turns to port, the distances between OS and TSs (TS1, TS2) are 7.1 nm and 6.8 nm, respectively. After passing clear with TS2, OS searches for the next course to the goal and keeps TS1 clear at the same time. To compare with [9], [10], the track of OS turning to starboard to avoid a collision is provided in Fig. 19a. In Fig. 19d, OS keeps safe distances from TSs in the whole process.

4) SITUATION 4

OS is in a complex multi-ship encounter scenario (Fig. 20a); three primary situations are included, Table 12; for the reason that TCPA of each situation for OS is close, OS could regard these TSs as a union when taking collision avoidance. The VO of TSs is in Fig. 20b; from Fig. 20c, OS could seek out the best velocity for the complex situation. The distances between OS and TSs are always bigger than 1 nm (Fig. 20d); all TSs pass safely with each other.

B. DISCUSSION

Comparison between this paper and other VO approaches in [9] and [10], 1) This paper puts forward the CAAB and CAAI method which adds more choices for OS to avoid collisions instead of only turning to starboard. OS could turn to port or starboard, and change speed for avoiding collisions, based on COLREGS in simulations; however, to obey rules of COLREGS, the methods in [9] and [10] tend to avoid turning to port.

2) DCPA and TCPA are more specific than the binary method of GVO for checking risk of collision. DCPA and TCPA can tell different degrees of risk of collision for OS.

3) The method of this paper could reduce large deviations from the planned route when taking collision avoidance. In simulations of this paper, comparisons with blindly turning

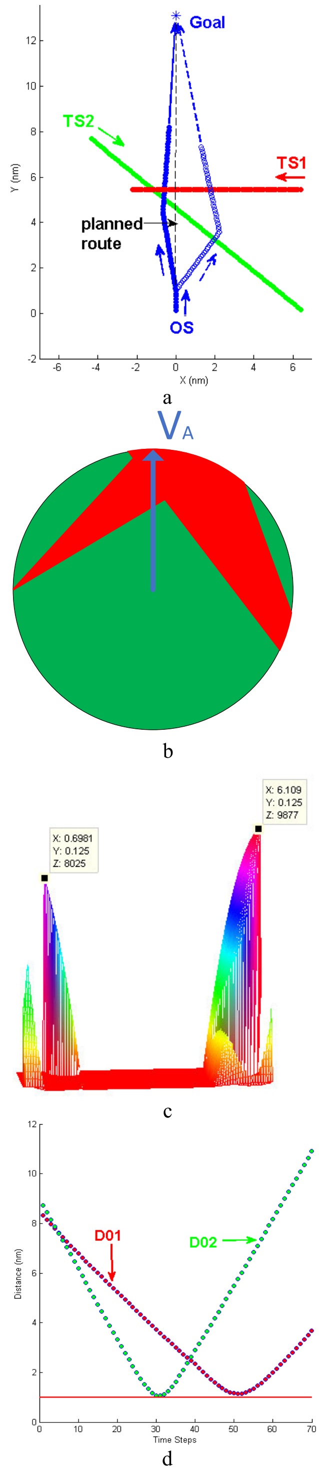

FIGURE 19. **a. Simulation of situation 3 b. VO of situation 3 c. Utilities of velocities of situation 3 d. Distance between OS and TSs.**

to starboard are given in FIGURE 12a, 14a, 16a, 18a, and 19a. It is easy to get that blindly turning to starboard could lead to large deviations from the planned route. Deviations from the planned route are not considered in [9] and [10].

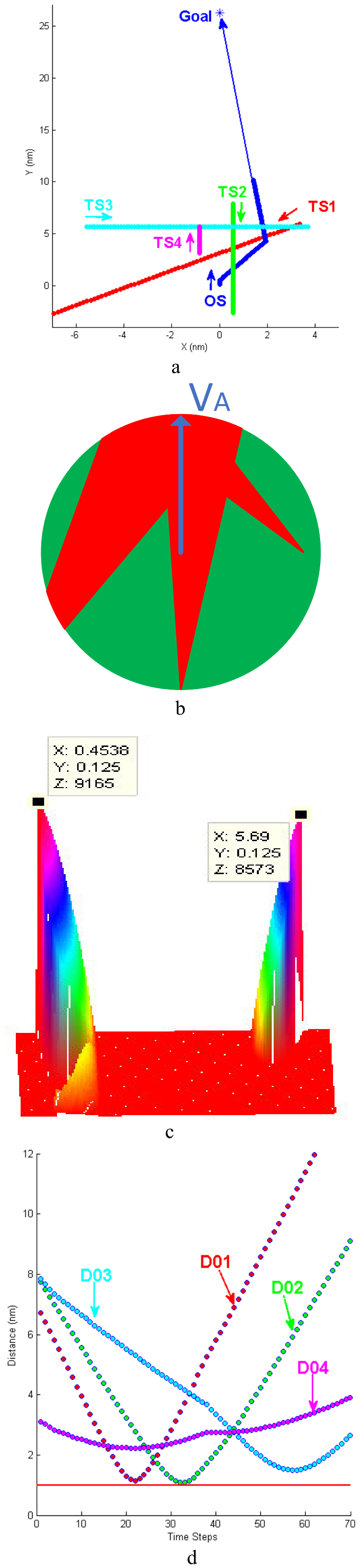

FIGURE 20. **a. Simulation of situation 4 b. VO of situation 4 c. Utilities of velocities of situation 4 d. Distance between OS and TSs.**

VIII. CONCLUSION

Based on the development of different stages of encounter situation, this paper proposes the CAAB and CAAI. It will add more choices for ships and avoid blindly obeying the rules of COLREGS when ships take collision avoidance actions. To specify stages of encounter situation clearly, this paper makes a quantitative analysis of three primary encounter situations. By introducing VO and making further analysis of DCPA, BC, and COLREGS, the algorithm gives a clear direction to find the best velocity among velocity space in three primary encounter situations. This paper applies VO utility function to search specific value of the best velocity. The results of simulations in different kinds of encounter situations show that the method promotes the development of the ship's collision avoidance actions and avoiding large deviations from the planned route. This paper pays little attention to ship' maneuverability and sea environmental condition; it can be further refined by adding these elements.

REFERENCES

[1] C. Tam and R. Bucknall, "Path-planning algorithm for ships in close-range encounters," *J. Mar. Sci. Technol.*, vol. 15, no. 4, pp. 395–407, Dec. 2010.

[2] L. P. Perera, J. P. Carvalho, and C. G. Soares, "Fuzzy logic based decision making system for collision avoidance of ocean navigation under critical collision conditions," *J. Mar. Sci. Technol.*, vol. 16, no. 1, pp. 84–99, 2011.

[3] T. Brcko and J. Švetak, "Fuzzy reasoning as a base for collision avoidance decision support system," *PROMET, Traffic Transp.*, vol. 25, no. 6, pp. 555–564, Dec. 2013.

[4] L. P. Perera, J. P. Carvalho, and C. G. Soares, "Intelligent ocean navigation and fuzzy-Bayesian decision/action formulation," *IEEE J. Ocean. Eng.*, vol. 37, no. 2, pp. 204–219, Apr. 2012.

[5] W. Naeem, G. W. Irwin, and A. Yang, "COLREGs-based collision avoidance strategies for unmanned surface vehicles," *Mechatronics*, vol. 22, no. 6, pp. 669–678, Sep. 2012.

[6] Y. Liu and R. Bucknall, "Path planning algorithm for unmanned surface vehicle formations in a practical maritime environment," *Ocean Eng.*, vol. 97, pp. 126–144, Mar. 2015.

[7] A. Lazarowska, "Ship's trajectory planning for collision avoidance at sea based on ant colony optimisation," *J. Navigat.*, vol. 68, no. 2, pp. 291–307, Mar. 2015.

[8] H. Lyu and Y. Yin, "COLREGS-constrained real-time path planning for autonomous ships using modified artificial potential fields," *J. Navigat.*, vol. 72, no. 3, pp. 588–608, May 2019.

[9] Y. Kuwata, M. T. Wolf, D. Zarzhitsky, and T. L. Huntsberger, "Safe maritime autonomous navigation with COLREGS, using velocity obstacles," *IEEE J. Ocean. Eng.*, vol. 39, no. 1, pp. 110–119, Jan. 2014.

[10] Y. Huang, L. Chen, and P. H. A. J. M. van Gelder, "Generalized velocity obstacle algorithm for preventing ship collisions at sea," *Ocean Eng.*, vol. 173, pp. 142–156, Feb. 2019.

[11] R. Szlapczynski, "Evolutionary sets of safe ship trajectories: A new approach to collision avoidance," *J. Navigat.*, vol. 64, no. 1, pp. 169–181, Jan. 2011.

[12] C. Tam and R. Bucknall, "Cooperative path planning algorithm for marine surface vessels," *Ocean Eng.*, vol. 57, pp. 25–33, Jan. 2013.

[13] S. Li, J. Liu, and R. R. Negenborn, "Distributed coordination for collision avoidance of multiple ships considering ship maneuverability," *Ocean Eng.*, vol. 181, pp. 212–226, Jun. 2019.

[14] X. Wang, Z. Liu, and Y. Cai, "The ship maneuverability based collision avoidance dynamic support system in close-quarters situation," *Ocean Eng.*, vol. 146, pp. 486–497, Dec. 2017.

[15] A. Lazarowska, "A new deterministic approach in a decision support system for ship's trajectory planning," *Expert Syst. Appl.*, vol. 71, pp. 469–478, Apr. 2017.

[16] *Conventions on the International Regulations for Preventing Collision at Sea (COLREGS)*, Int. Maritime Org., London, U.K., 1972.
[17] A. N. Cockcroft and J. N. F. Lameijer, *A Guide to the Collision Avoidance Rules: International Regulations for Preventing Collisions at Sea*, 7th ed. Oxford, U.K.: Butterworth-Heinemann, 2011, pp. 85–86.
[18] Z. Zheng and Z. Wu, "Research on automatic decision-making system of vessel collision avoidance," Ph.D. dissertation, Dept. Trans. Inf. Eng., D.M.U., Dalian, China, 2000.
[19] P. Fiorini and Z. Shiller, "Motion planning in dynamic environments using the relative velocity paradigm," in *Proc. IEEE Int. Conf. Robot. Automat.*, vol. 1, May 1993, pp. 560–566.
[20] P. Fiorini and Z. Shiller, "Motion planning in dynamic environments using velocity obstacles," *Int. J. Robot. Res.*, vol. 17, no. 7, pp. 760–772, Jul. 1998.
[21] J. van den Berg, M. Lin, and D. Manocha, "Reciprocal velocity obstacles for real-time multi-agent navigation," in *Proc. IEEE Int. Conf. Robot. Automat.*, May 2008, pp. 1928–1935.
[22] D. Wilkie, J. Van den Berg, and D. Manocha, "Generalized velocity obstacles," in *Proc. IEEE Int. Conf. Intell. Robots Syst.*, Oct. 2009, pp. 5573–5578.
[23] J. Snape, J. Van den Berg, S. J. Guy, and D. Manocha, "The hybrid reciprocal velocity obstacle," *IEEE Trans. Robot.*, vol. 27, no. 4, pp. 696–706, Aug. 2011.
[24] K. Woerner, "Multi-contact protocol-constrained collision avoidance for autonomous marine vehicles," Ph.D. dissertation, Dept. Mech. Eng., MIT, Cambridge, MA, USA, 2016.

WENJUN ZHANG received the B.Eng., M.Eng., and Ph.D. degrees from Dalian Maritime University (DMU), Dalian, China, in 2000, 2007, and 2014, respectively. He is currently an Associate Professor and the Dean of the Navigation College, DMU. His current research interests include ship motion prediction, marine wireless communication, intelligent transportation systems, and global maritime distress and safety systems.

CHENGYONG YAN received the B.Eng. degree in nautical science and maritime science and technology from Dalian Maritime University (DMU), Dalian, China, in 2013, where he is currently pursuing the M.Eng. degree in marine communication. His research interests include surface vehicles and ship collision avoidance.

HONGGUANG LYU received the B.Eng., M.Eng., and Ph.D. degrees from Dalian Maritime University (DMU), Dalian, China, in 2004, 2007, and 2019. He is currently an Associate Professor with DMU. His research interests include the intelligent navigation system for maritime autonomous surface ships (MASSs) or unmanned surface vehicles (USVs), especially in the field of autonomous collision avoidance and path planning. In 2020, he was awarded the Royal Institute of Navigation (RIN) Richey Medal for the Best Paper in the *Journal of Navigation* (RIN).

PINGLIN WANG received the B.Eng. degree from Dalian Maritime University (DMU), Dalian, China, in 2018, where he is currently pursuing the M.Eng. degree in traffic information engineering and control. His research interest includes vessel trajectory analysis.

ZONGYAO XUE received the B.Eng. degree from Dalian Maritime University (DMU), Dalian, China, in 2018, where he is currently pursuing the M.Eng. degree in traffic information engineering and control. His research interest includes marine traffic safety.

ZEHUA LI received the B.Eng. degree from Beijing Jiaotong University (BJTU), Beijing, China, in 2017, and the M.Eng. degree from Dalian Maritime University (DMU), Dalian, China, in 2020. He is currently an Assistant. His main research interest includes marine traffic engineering.

BAI XIAO received the B.Eng. degree from Dalian Maritime University, Dalian, China, in 2000, and the master's degree. He received the Sea Pilot's Certificate of First Class. His current interest includes ship maneuvering.