Indian Journal of Geo Marine Sciences
Vol. 48 (07), July 2019, pp. 1037-1047

Collision risk assessment based artificial potential field approach for multi-ships avoidance

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Artificial potential field (APF) is widely used for obstacles avoidance of autonomous surface vessel (ASV). However, its performance is poor for the case that the ASV encounters multiple ships. The collision may happen since the APF method is only taking distance and velocity into account. To solve this problem, a collision risk assessment based approach is proposed. A fuzzy logic system is applied to assess the collision risk with distance of close point of ppproaching (DCPA) and time of close point of approaching (TCPA). The collision risk is used to modify the APF for the ASV to avoid multiple ships. A critical encounter scenario is simulated to test the proposed approach. The simulation results indicate that the proposed method overcomes the problem to help an ASV successfully avoids the ship collision.

[**Keywords:** Artificial potential field; Obstacles avoidance; Autonomous surface vehicle; Collision risk assessment.]

Introduction

Water transportation is an ancient mode of transportation. More than 90% of the global trades are achieved by water transportation[1]. Owing to several advantages, namely, large volume of transport, low energy consumption, low cost, less space occupied, the made of water transportation has irreplaceable advantages in the comprehensive transportation system of the world. With the development and increasing demands of shipping, the number of floating crafts/ships is increasing rapidly at sea. The risks of marine traffic accidents such as collision of ships and collision of ships with bridges are also increasing, which seriously threaten the safety of navigation of ships and the ecological environment of the sea. Thus it becomes more challenging to deploy an autonomous surface vehicle (ASV) at the sea – without colliding or crashing into the other ships/boats.

The obstacles avoidance is the one of the essential abilities for the autonomy of ASVs. Artificial potential field (APF), which was first proposed by Khatib for mobile robot obstacles avoidance[2], is widely used in local path planning and obstacle avoidance because of its simplicity and effectiveness. It is assumed that the robot is in the environment with virtual attractive and repulsive potential fields that are generated by the goal and obstacle respectively and thus the robot is navigated by the resultant force.

Besides its capability to perform single obstacle avoidance, the APF method is also able to perform multiple obstacles avoidance, where the robot's motion is determined by the resultant force of multiple obstacles. However, the existing APF related methods only use position and velocity information for obstacles avoidance. The collision may happen when the ASV encounters multiple ships since the APF method does not take into account the heading angle and bearing information. The APF method will navigate the ASV to the position where the potential is smaller; however, this position might not be the minimum collision risk point. For the multiple ships encounter case, the ASV may collide with one of the ships. Therefore, in this paper the collision risk assessment is combined with the APF method to improve the multiple obstacles avoidance performance.

Several concepts were proposed to evaluate the collision risk, such as distance of close point of approaching (DCPA) and time of close point of approaching (TCPA), ship domain, ship arana and so on[3]. DCPA and TCPA were first proposed to assess the collision risk independently. Each of them alone is inaccurate to assess collision risk since insufficient information is used to calculate the collision risk. Thus, some researchers proposed a weight method which adopted both DCPA and TCPA to evaluate the collision risk[4,5]. However, there is still a problem in this method due to the different dimension of DCPA and TCPA. It may produce wrong risk estimation for some special occasions.

Artificial intelligence algorithms are integrated with DCPA and TCPA to perform an expert system for collision risk assessment. Mariners' experience is added to the expert system to improve the accuracy of the evaluation. Zhang et al. presented a fuzzy logic method to evaluate collision risk for ships in close range encounters, wherein the marine traffic rules COLREGs are integrated[6]. Bukhari et al. introduced a collision risk assessment for real-time multi vessels by a fuzzy expert system[7]. Variance of compass degree (VCD) was integrated into the fuzzy expert system to modify the accuracy of assessment.

Materials and Methods

Collision risk assessment by fuzzy logic

Collision risk is a basic concept in the field of collision avoidance. Due to the fuzziness and uncertainty of collision risk, there is still no unified calculation method. It is mentioned in The International Regulations for Preventing Collisions at Sea (COLREGs) several times[8]; however, a clear definition is not given.

Collision risk (CR) is the possibility degree that collision may happen for the encountered ships. It is in the range of 0~1, there is no risk of collision if CR=0 while the collision is sure to happen if CR=1. The value of CR is to indicate the degree of risk.

The closest point of approach (CPA) is an estimated point in which the distance between the own ship and another object target will reach the minimum value. CPA is an essential factor of the ship safety especially when the ship is avoiding the collision. The concept of CPA is presented in the automatic radar plotting aids (ARPA) initially to estimate the collision risk directly. CPA method includes two factors, DCPA and TCPA. DCPA is used to measure the space collision risk and TCPA is used to measure the time collision risk. The collision risk can be evaluated by DCPA and TCPA. It is assumed that all the motion states of the target ships can be obtained from automatic identification system (AIS). The motion states of the own ship and the target ship is illustrated in Figure 1.

Assuming that the own ship with position (x_0 y_0), velocity v_0, heading angle φ_0 and the target ship

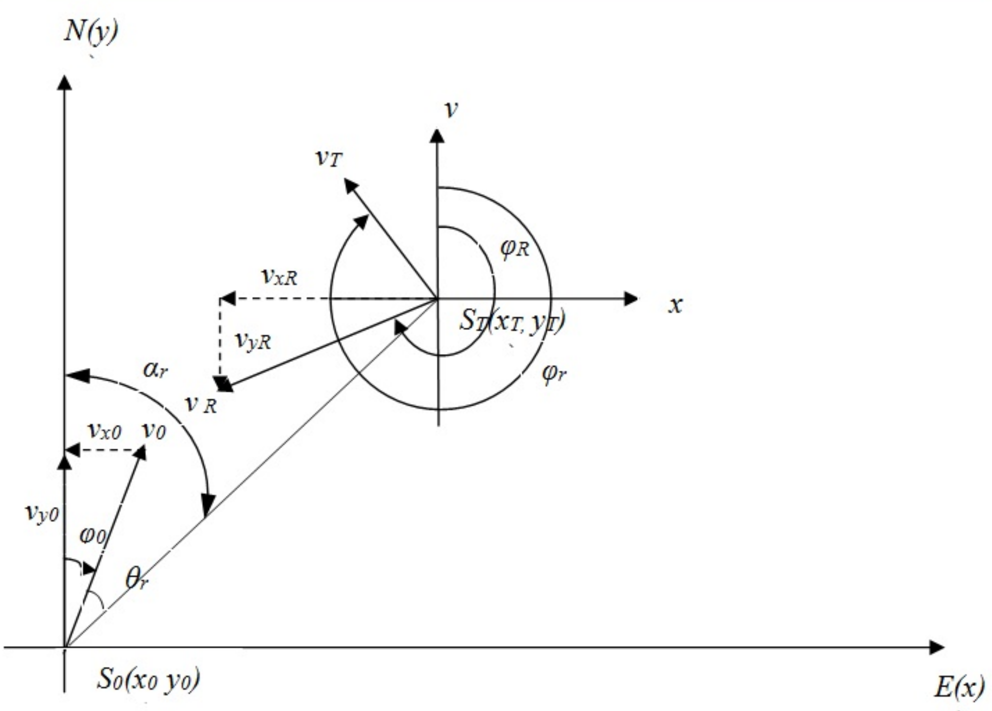


Fig. 1 — Ship relative motion elements for CPA method[9].

with position (x_T y_T) speedm v_T, heading angle φ_T (obtained from AIS), then DCPA and TCPA are calculated as:

The velocity components of own ship on *x* and *y* axes,

$$\begin{cases} v_{x0} = v_0 \cdot \sin\varphi_0 \\ v_{y0} = v_0 \cdot \cos\varphi_0 \end{cases} \quad \text{... (1)}$$

The velocity components of target ship on *x* and *y* axes,

$$\begin{cases} v_{xT} = v_T \cdot \sin\varphi_T \\ v_{yT} = v_T \cdot \cos\varphi_T \end{cases} \quad \text{... (2)}$$

The relative velocity vector between the own ship and target ship.

The components of relative velocity vector on *x* and *y* axes,

$$\begin{cases} v_{xR} = v_{xT} - v_{x0} \\ v_{yR} = v_{yT} - v_{y0} \end{cases} \quad \text{... (3)}$$

The amplitude of the relative velocity

$$v_R = \sqrt{{v_{xR}}^2 + {v_{yR}}^2} \quad \text{... (4)}$$

The heading angle of the relative velocity

$$\varphi_R = \arctan\frac{v_{xR}}{v_{yR}} + \alpha \quad \text{... (5)}$$

where

$$\alpha = \begin{cases} 0^o, & if: \ v_{xR} \ge 0, v_{yR} \ge 0 \\ 180^o & if: \ v_{xR} < 0, v_{yR} < 0 \\ 180^o & if: \ v_{xR} \ge 0, v_{yR} < 0 \\ 360^o & if: \ v_{xR} < 0, v_{yR} \ge 0 \end{cases}$$

The true bearing of the target ship for the own ship,

$$\varphi_T = \arctan\frac{x_T - x_0}{y_T - y_o} + \beta \quad \text{... (6)}$$

where

$$\beta = \begin{cases} 0^o, \quad if: x_T - x_0 \ge 0, y_T - y_0 \ge 0 \\ 180^o, if: x_T - x_0 < 0, y_T - y_0 < 0 \\ 180^o, if: x_T - x_0 \ge 0, y_T - y_0 < 0 \\ 360^o, if: x_T - x_0 < 0, y_T - y_0 \ge 0 \end{cases}$$

The α and β above are used to keep the DCPA and TCPA positive.

The distance between the own ship and target ship,

$$R_T = \sqrt{(x_T - x_0)^2 + (y_T - y_0)^2} \quad \text{... (7)}$$

The relative bearing θ_T,

$$\theta_T = \alpha_T - \varphi_0 \quad \text{... (8)}$$

The DCPA between the own ship and the target ship,

$$DCPA = R_T \cdot \sin(\varphi_R - \alpha_T - \pi) \quad \text{... (9)}$$

The TCPA between the own ship and the target ship,

$$TCPA = R_T \cdot \cos(\varphi_R - \alpha_T - \pi) / v_R \quad \text{... (10)}$$

Positive TCPA means that the target ship has not reached the closest point and negative TCPA means that the target ship has passed the closest point.

As discussed above, DCPA and TCPA are used to calculate the space and time collision risks, respectively; however, either of them may get wrong estimation result if they are used alone. Thus, a fuzzy inference system is utilized for the collision risk assessment.

Fuzzy set theory was first proposed by Zadeh in 1965 to solve the imprecise problems. Fuzzy systems define inputs, outputs and state variables as fuzzy sets, which is a generalization of the deterministic system[10]. The fuzzy system is able to describe the fuzzy characteristics of human thought and high-level knowledge, thus it is suitable to imitate people’s inference and solve the problems that are difficult to be solved by conventional mathematical methods, such as nonlinear problems. It has been widely used in automatic control, pattern recognition, decision analysis, etc. More specifically, fuzzy logic system has been applied to marine robotic vehicles as a guidance and control system[11,12,13].

Since collision risk is a linguistic and subjective concept, fuzzy system is suitable for collision risk assessment. Hasegawa proposed a fuzzy inference system to estimate the collision risk with DCPA and TCPA values[14,17]. The experts experience is adopted in the fuzzy system to get a reasonable result. Hasegawa’s collision risk assessment method is adopted in this paper. The Mamdani fuzzy inference system is selected since it has better performance[15]. Triangular type fuzzy membership functions are used to simplify the calculation. DCPA and TCPA are the inputs of the fuzzy inference system, whereas the collision risk is the output. The DCPA and TCPA are defined by five and eight linguistic variables with membership functions shown in Figures 2 and 3, respectively. The collision risk is determined by eight linguistic variables with membership functions as shown in Figure 4. Different from others, the collision risk is defined between [-1,1], the positive value denotes before passing by CPA and negative value denotes after passing by CPA. The collision risk is determined by the Mamdani fuzzy reasoning rules table shown in Table 1.

The fuzzy collision risk assessment is able to judge the situation of encountered ships; however, it is not able to navigate the ships to make an avoidance manoeuvre.

Artificial potential field for multiple objects avoidance

The principle of artificial potential field method is shown in Figure 5. The ASV in this paper is with assumptions as follows:

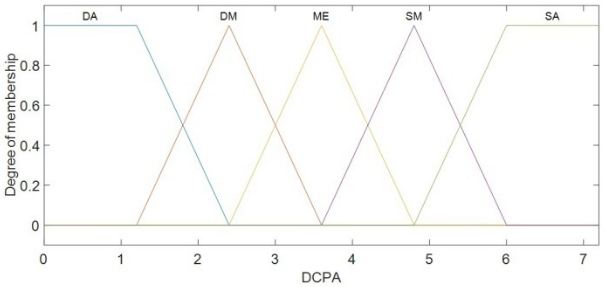


Fig. 2 — Member functions for DCPA

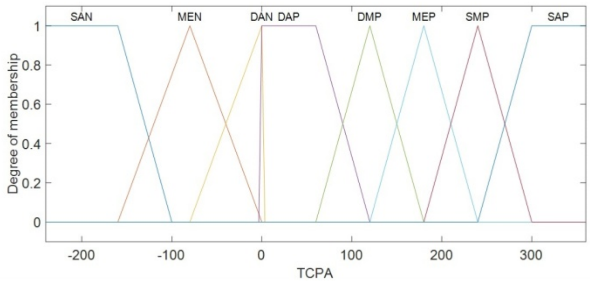


Fig. 3 — Member functions for TCPA

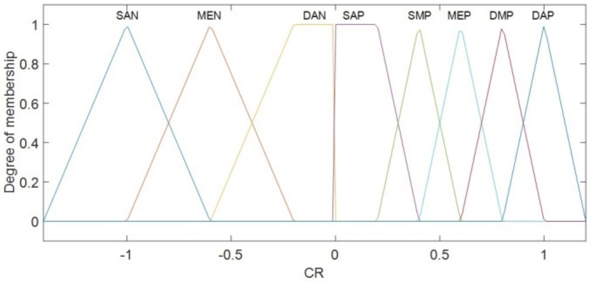


Fig. 4 — Member functions for collision risk.

The ASV is moving with a constant speed of 7 m/s, thus the APF is only used to control the heading of the ASV.

a. The trajectory of the ASV is determined by the predefined waypoints which are denoted as Cartesian coordinates, waypoints (x_i, y_i) for i=1,…,n. These waypoints can be generated by onboard computer or predefined by human and stored as a database that consists of:

$$\text{wpt.pos}= \{(x_0,y_0),(x_1,y_1),\ldots,(x_n, y_n)\} \qquad \text{... (11)}$$

As shown in Figure 5, the attractive force is determined by the waypoints,

$$F_{att} = m\times\alpha_p \times\left\|P_{wp(t)} - P_{(t)}\right\| \qquad \text{... (12)}$$

where $P_{(t)}$ and $P_{wp(t)}$ is the current position of ASV and next waypoint position respectively; m is constant and α_p is a scaling parameter which is determined by the experiment; F_{att} is the attractive force of APF method.

When the ASV encounters with obstacles (target ships), it will change the heading angle to achieve an avoiding manoeuvre. The virtual repulsive force is provided by the target ships which is expressed as[18,19]

$$F_{rep}(p,v) = \begin{cases} F_{rep1}+F_{rep2}, & 0<\rho(p,p_{obs})-\rho_m(v_{RO})<\rho_o \quad \textit{and} \quad v_{RO}>0 \\ \text{not difined}, & v_{RO}>0 \quad \textit{and} \quad \rho_s(p,p_{obs})<\rho_m(v_{RO}) \end{cases} \qquad \text{... (13)}$$

where

$$F_{rep1} = \frac{-\eta}{(\rho_s(p,p_{obs})-\rho_m(V_{RO}))^2}(1+\frac{v_{RO}}{a_{\max}})n_{RO} \qquad \text{... (14)}$$

$$F_{rep2} = \frac{\eta v_{RO} v_{RO\perp}}{\rho_s(p,p_{obs})a_{\max}(\rho_s(p,p_{obs})-\rho_m(v_{RO}))^2} n_{RO\perp} \qquad \text{... (15)}$$

where $\mathbf{n}_{RO}$ is a unit vector pointing from the ASV to the obstacle; a_{max} is a maximum deceleration of

Table 1 Fuzzy reasoning table for Collision Risk[15]

		TCPA							
		SAN	MEN	DAN	DAP	DMP	MEP	SMP	SAP
DCPA	DA	SAN	MEN	DAN	DAP	DMP	MEP	SMP	SAP
	DM	SAN	SAN	MEN	DMP	MEP	SMP	SAP	SAP
	ME	SAN	SAN	SAN	MEP	SMP	SAP	SAP	SAP
	SM	SAN	SAN	SAN	SMP	SAP	SAP	SAP	SAP
	SA	SAN	SAN	SAN	SAP	SAP	SAP	SAP	SAP

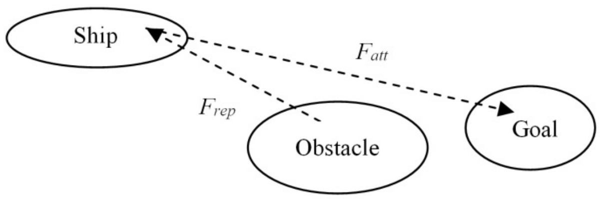


Fig. 5 — Illustration of artificial potential field.

magnitude of the ASV; p is the position, v is the velocity, ρ_0 is the obstacle influence range, and η is a constant parameter. Parameter ρ_0 determines the distance range that the obstacle generates repulsive force to the robot. The repulsive force will be zero when the distance between the ASV and target ship $\rho_s > \rho_0$.

Thus, the resultant force is

$$F_{res} = F_{att} + F_{rep} \quad \text{... (16)}$$

The ASV is navigated by the resultant force F_{res}. Since the ASV is moving with a constant speed, the resultant force F_{res} will only determine the heading of the ASV.

Collision risk assessment based artificial potential field for multiple objects avoidance.

From Equation (16), it can be seen that the total force consists of attractive force and repulsive force, which determines the heading angle of ASV. The repulsive force comprises the distance item and relative velocity item as indicated in Equations (12) and (13), respectively. The APF method is combined with collision risk assessment to improve the multiple objects avoidance performance. In this case, the repulsive force is replaced by the collision risk item which is generated by the fuzzy inference system.

$$F_{rep} = K_C \times CR \quad \text{... (17)}$$

Where CR is the collision risk, K_c is the scale coefficient.

Therefore the heading angle of ASV is determined by Equations (12) and (17), as

$$F_{res} = F_{att} + F_{rep} = m \times \alpha_p \times \left\| P_{wp(t)} - P_{(t)} \right\| + K_C \times CR \quad \text{... (18)}$$

Different from traditional APF method, the proposed collision risk based APF method uses the collision risk value as the criteria to guide the ASV starting an avoidance manoeuvre. When the collision risk is greater than the criteria CR_C (CR_C=0.7), the ASV will turn right to fulfill the COLREGs but keeps up the speed. An urgent criterion CR_U is defined as 0.9 for the case that the ASV encounters an urgent situation. The ASV will change the heading angle and decrease the speed to half of the current speed.

Since there are multiple ships in the real environment, it is essential to apply the proposed collision risk based APF method to the multiple ships encounters. For this case, the collision avoidance strategy is described below.

When the ASV encounters multiple ships, the ship with maximum collision risk is selected as the target ship. If the collision risk of the target ship is greater than CR_C, the ASV will start an avoidance manoeuvre as presented above. When the ASV is in the avoiding mode, the collision risk for other ships is still being checked. If the collision risk of any other ship is greater, it will be selected as the new target ship and a new avoidance manoeuvre will start. In brief, the ASV always makes avoidance action to the maximum target ship.

Results and Discussion

Collision risk assessment based APF navigation

In this section, the simulation results of collision risk assessment (CRA) based APF method for ASV navigation is presented. There are two problems with the existing APF method, one is local minima and the other is unreasonable avoidance action for multiple objects. Thus, firstly the local minima problem and the proposed solution are addressed and compared. Secondly, the CRA based APF for multiple ships avoidance is simulated and compared with the traditional APF method. Finally, a challenging multiple ship encounter situation is used to test the proposed navigation method, which includes a head-on ship, an overtaking ship, and two crossing ships.

The ASV is assumed to travel in open sea following a series of predefined waypoints; and the motion states of the own ASV and the target ships can be obtained from onboard devices such as GPS, AIS etc. The target ships are assumed to move with a constant speed and heading angle and have no ability to avoid collision. The collision risk could be estimated by fuzzy system with the motion states, such as position, velocity, heading angle and bearing etc. Collision risk is a vague and linguistic concept, thus it is suitable for the fuzzy inference system to adopt the experts' experience. An existing fuzzy collision risk assessment presented by Hasegawa is utilized in this paper[15].

The ASV and the target ships are with length of 160.93 m and simulated in a 20000×20000 m^2 water area, and so as the target ship. The model of ASV and target ships and the water environment are simulated in MSS toolbox developed by Fossen and Perez[20]. The ASV is in blue color the waypoints are tagged as green '*', and the target ships are in red color.

Local minima problem of APF

One of the simple situations of local minima is that the ASV, goal, and the obstacle are in a straight line, as shown in Figure 6. The ASV is moving from south to north while the target ship is moving from north to south. They are following the same waypoints but in opposite direction. The ASV is navigated by APF method, thus the waypoints produce attractive potential and the target ship generates repulsive potential. The attractive potential and repulsive potential are exactly opposite, and so at a certain moment the resultant potential for the ASV will be zero. The speed of the ASV is set to be a constant value and the heading angle of the ASV is determined by the resultant potential. Thus the collision will happen when the ASV encounters the target ship.

To solve the local minima problem of the APF method, a minimum heading angle change is set as 5^o for avoidance manoeuvre in the system. For the case that the ASV is on avoidance mode, the heading angle changes but the speed is not reduced to 0, thus the ASV will not be trapped in the local minima.

Figure 7 shows the solution result of the local minima. As presented in Equation (18), the APF method is modified with collision risk assessment. The waypoints generate attractive potential but the repulsive potential is replaced by the collision risk. A risk criterion CR_C is set as the trigger of avoidance action. When CR_C<0.7, the ASV will keep the current heading angle, otherwise it will change the heading angle according to Equation (18). To ensure that the ASV is able to escape from the local minima, a minimum heading angle change is set as 5^o. Figure 7 shows that the ASV successfully passes by the target ship and then recovers the heading angle to keep tracking the waypoints.

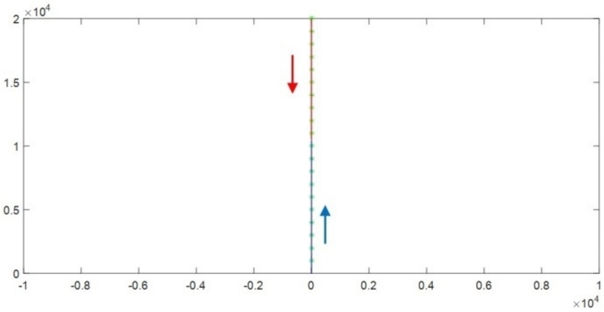


Fig. 6 — Local minima problem illustration.

Reasonable avoidance action for CRA based APF method

The other problem with the APF method is that the ASV navigated by APF may make an unreasonable decision when it encounters multiple objects, which is illustrated in Figure 8. Two target ships are used to indicate the problem, one is head-on ship and the other is overtaking ship. The ASV is moving from south to north, the head-on target ship is moving from north to south and the crossing ship is moving from east to west. The speed of ASV and the head-on target ship is 7 m/s and the speed of the crossing target ship is 8 m/s. The head-on target ship is offset to the trajectory of the ASV with 200 m.

At moment t=1298 s, the ASV encounters the crossing target ship, the APF algorithm will lead the ASV turn right since the crossing target is on the left front of the ASV. However, this is an unreasonable decision since the crossing target ship has actually passed by as shown in Figure 8(a). The consequence of the avoidance manoeuvre is shown in Figure 8(b), where the ASV is turning right when it encounters the head-on target ship. Though the collision does not happen, the distance between the ASV and the head-on target ship is quite close when they pass by each other, which means that the collision risk is very high. It is obvious that the traditional APF avoidance action for multiple ships is unreasonable.

As a comparison, the same multiple ships encounter situation is used to test the CRA-based APF

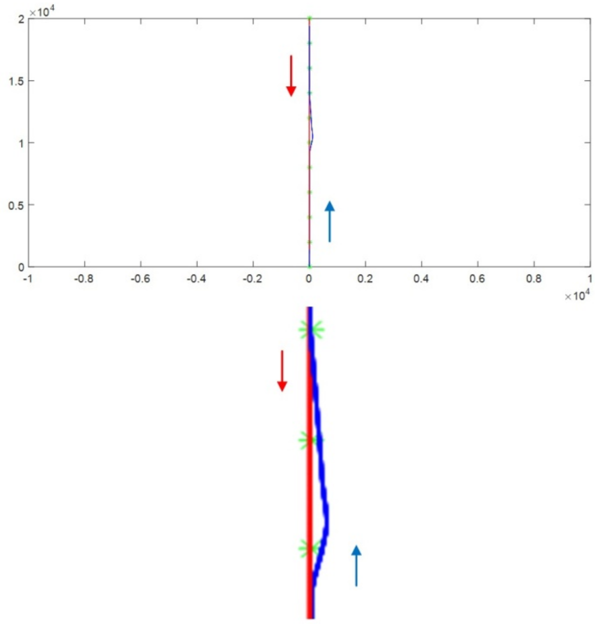
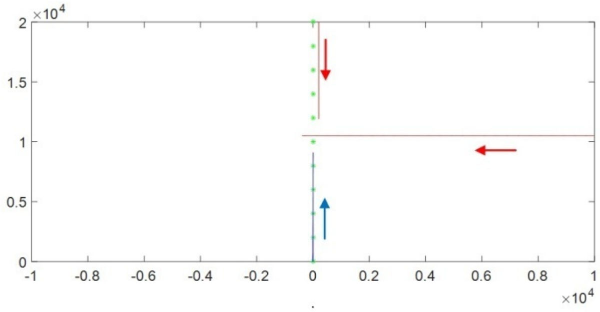
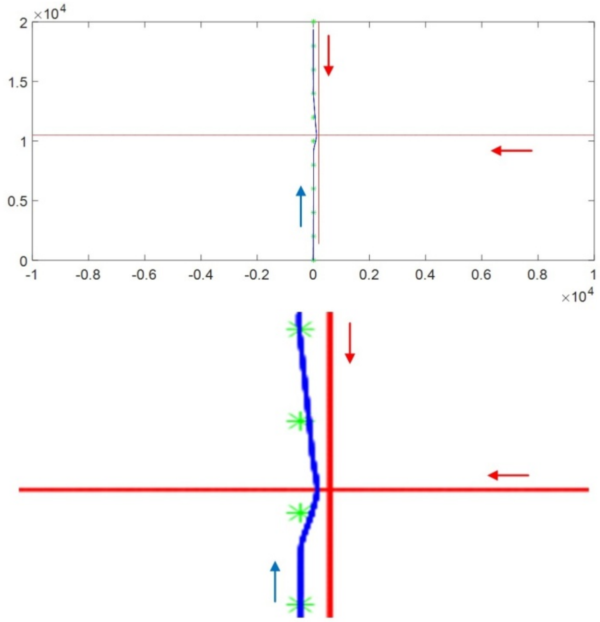


Fig. 7 — ASV escapes from the local minima.



(a) — t=1298 s



(b)—Complete navigation

Fig. 8 — ASV avoid head-on and crossing target by traditional APF method.

avoidance. In this approach, the avoidance manoeuvre is determined by the collision risk. The ASV will make an avoidance action when the collision risk is greater than 0.7, otherwise it will keep the heading angle. For multiple objects situation, the ASV will assess all the ships' collision risk simultaneously and select the highest risk ship as the target ship. The ASV will avoid the target ship by the proposed CRA-based APF method. During the avoidance action, the ASV may select any other ship as the target ship if the collision risk of this ship is the greatest. This is a safety first avoidance since the ASV is always avoiding the most dangerous target.

As shown in Figure 8(a), the ASV encounters the crossing ship at t=1298 s. However, it does not make an avoidance manoeuvre because the crossing ship has been passed by and the collision risk is less than 0.7. Thus the ASV is still moving toward north until it encounters the head-on ship. Then the ASV turns left to avoid the collision since the head-on ship is on the right front of the ASV. The complete navigation result is illustrated in Figure 9. It can be seen that the proposed method makes a reasonable avoidance action for the multiple ship avoidance.

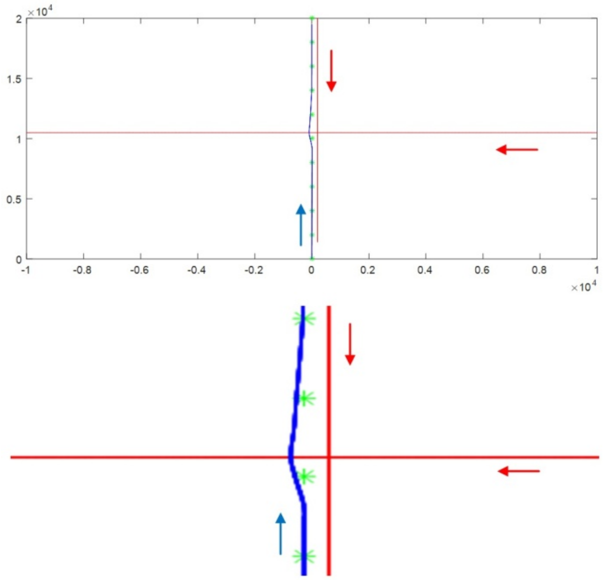
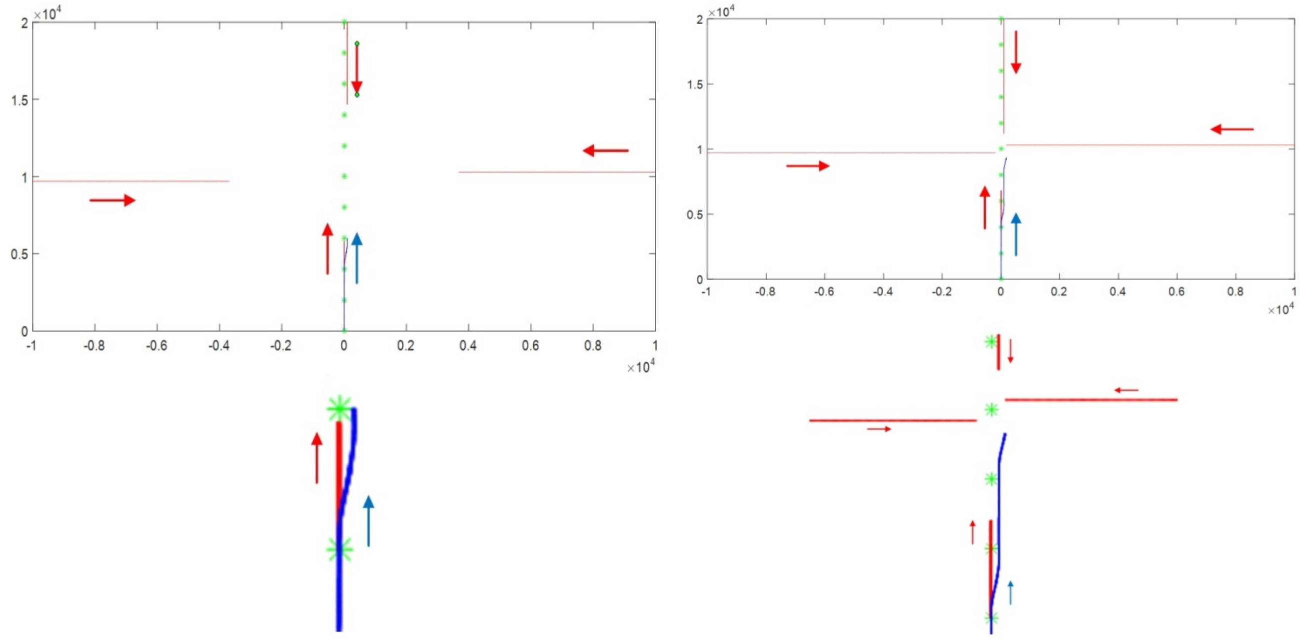


Fig. 9 — ASV avoid head-on and crossing target by CRA-based APF method.

Multiple ships avoidance

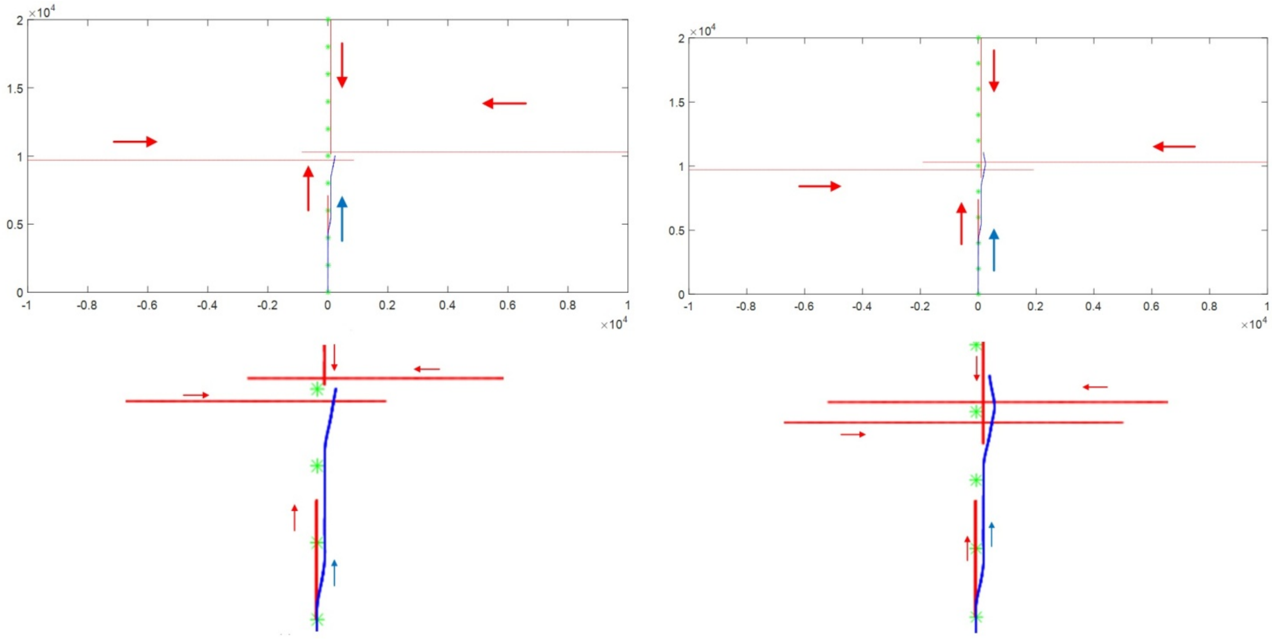
To test the CRA-based APF method further, a challenging multiple ships encounter situation is presented here, which includes four target ships. As shown in Figure 10, the ASV is moving from south to north with the predefined waypoints. The head-on, privileged crossing (from east to west), and burdened crossing (from west to east) ships are moving with a constant speed of 7 m/s; the overtaking ship is moving with speed of 2 m/s. The trajectory of the head-on ship is offset by the ASV's trajectory with 100 m. The distance between the trajectories of privileged crossing ship and the burdened crossing is 600 m. The avoidance strategy is the same as given above which is safety first, means that the ASV will avoid the greatest risk ship if it is more than 0.7. For the multiple ship situation, both the heading angle and the speed need to be changed if the collision risk is greater than 0.9. To reduce the collision risk, the speed of the ASV will decrease to half of the current speed besides the heading angle change.

As shown in Figure 10(a), the ASV encounters the overtaking ship first and makes an avoidance manoeuvre at t=900 s. It returns to the predefined trajectory after passing by the overtaking ship. At t=1400 s, the ASV encounters the burdened crossing ship which is supposed to give way. However, the burdened crossing ship is keeping the heading angle so the ASV has to make an avoidance action. The ASV turns right since the burdened crossing ship is on the left front of the ASV. The collision risk is increasing since both the burdened crossing ship and the ASV are moving to the right side. When the collision risk is greater than 0.9, the speed of the ASV is reduced to 3.5 m/s, which is shown in Figure 10(b). The burdened crossing ship passes by without collision because the ASV becomes slow. At t=1550 s, the ASV



(a)—t=900 s

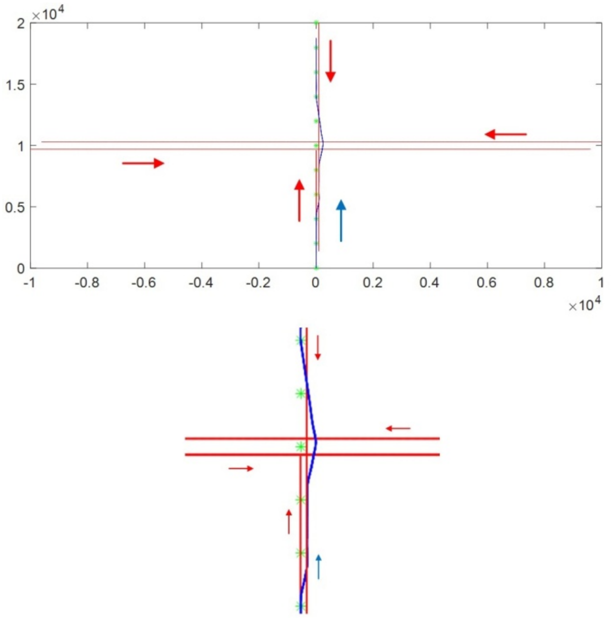
(b)—t=1400 s



(c)—t=1550 s

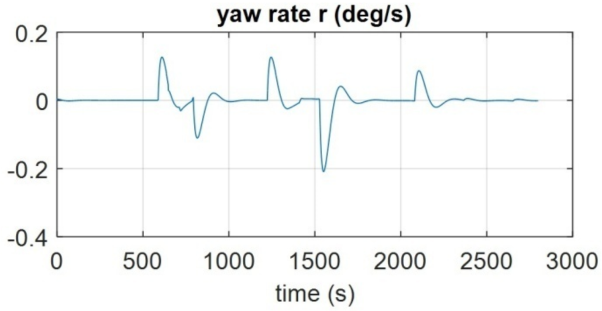
(d)—t=1700 s

Fig. 10 (*Contd.*)



(e)—Complete navigation

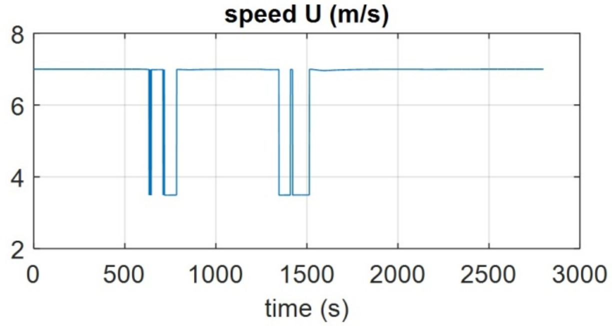
Fig. 10 — Multiple objects avoidance.



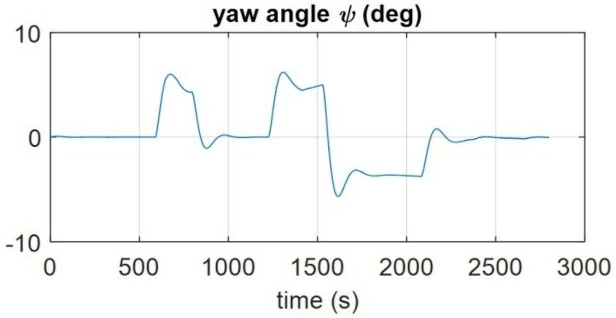
(a)

Fig. 11 (*Contd.*)

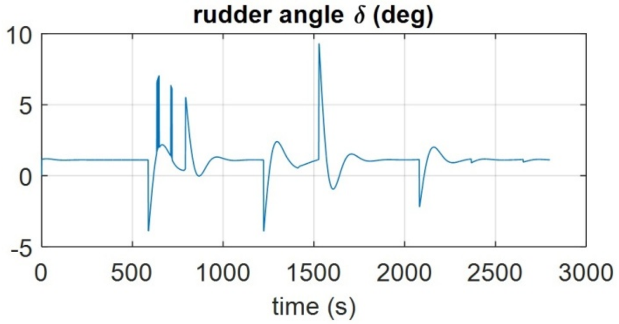
encounters the privileged crossing ship and the head-on ship at the same time. The head-on ship is with greater collision risk and thus the ASV selects the head-on ship as the target ship to avoid. The ASV turns right to avoid the head-on ship because it has not returned to the predefined trajectory and it locates on the right side of the head-on ship. At t=1700 s, the ASV completes all the avoidance action for all the four ships, then it goes back to follow the waypoints. The complete navigation result is indicated in Figure 10(e). The detailed motion states and the collision risk for all the four target ships are shown in Figures 11 and 12, respectively.



11 (b)



11 (c)



11 (d)

Fig. 11 — Motion States of ASV.

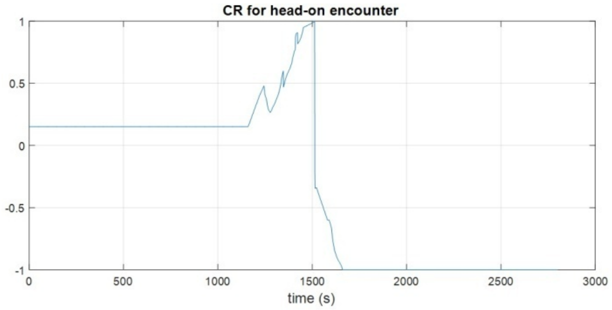


Fig. 12(a) — Collision risk for head-on target ship.

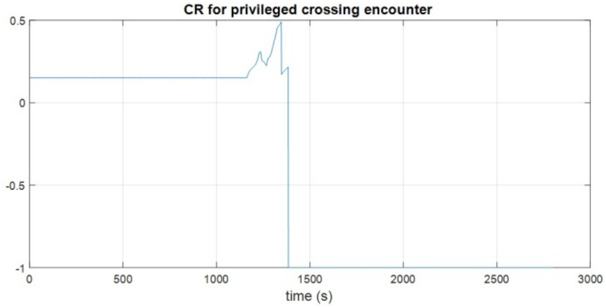


Fig. 12(b) — Collision risk for privileged crossing target ship.

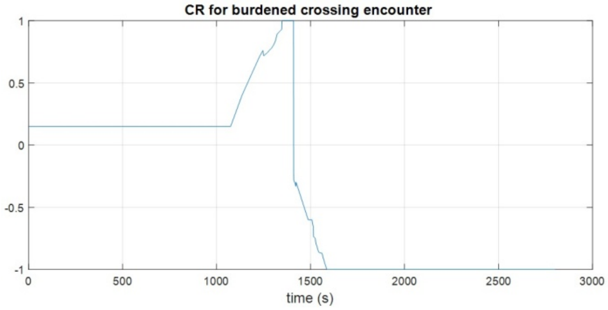


Fig. 12(c) — Collision risk for burdened crossing target ship.

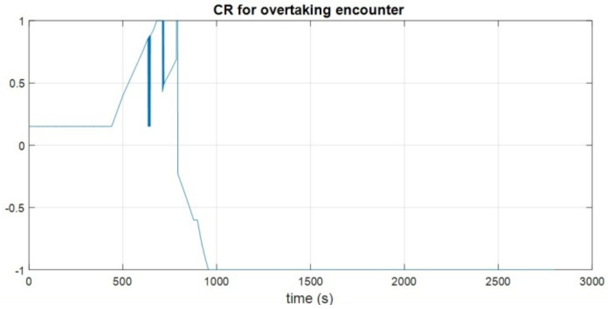


Fig. 12(d) — Collision risk for overtaking target ship.

Fig. 12 — Collision risks for the 4 target ships.

Conclusion

The CRA-based APF method is proposed to improve the performance of traditional APF method for multiple ship encounter. Different from the traditional APF method which uses distance and velocity as the avoidance criteria, the proposed method uses the collision risk assessment to determine the collision avoidance action. The results show that this CRA-based APF approach successfully solved the local minima problem. Besides, the comparison of the multiple ship encounter results is performed and it shows that the CRA-based APF method is able to make a more reasonable avoidance action for the multiple ship encounter situation. Finally, a challenging multiple ships encounter including four ship is used to test the proposed CRA-based APF method. The results show that the ASV is able to avoid the collision under critical encounter situation.

Acknowledgment

The authors would like to express sincere thanks for the support given to this research by Hebei University, China, and Universiti Sains Malaysia (USM). This research is supported by the Opening Foundation of Machine Vision Engineering Research Center of Hebei Province under grants 2018HBMV03 and 2018HBMV04.

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