A smart navigation and collision avoidance approach for Autonomous Surface Vehicle

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Marine traffic rules play an important role for all marine vessels to reduce the collision risk, thus The International Marine Organization (IMO) defined The International Regulations for Preventing Collisions at Sea (COLREGs) in 1972. All marine crafts including Autonomous Surface Vehicle (ASV) should follow COLREGs to avoid the collision when they encounter each other at sea or other water areas. However, the target ship may be located at the position which can cause collision if the ASV is forced to make a COLREGs compliant evasive manoeuvre. Thus, the navigation system of ASV is required to have the ability to identify the encounter situation and determine whether the ASV should obey the COLREGs or not when avoiding the target ship. To perform smart navigation and collision avoidance, the encounter situation division diagram is combined with Artificial Potential Field (APF) as the guidance system. The simulation results illustrate that the proposed guidance system successfully achieved the navigation of ASV at open sea and avoiding collision with moving target ship for different encounter situations.

[Keywords: COLREGs; Autonomous Surface Vehicle; encounter situation identification; Artificial Potential Field.]

Introduction

In recent decades, Autonomous Surface Vehicles (ASVs) are used more and more to detect the unknown water environment for ocean resources exploration, marine pollution, and lots of other applications in commercial business, science research, and military affairs. As unmanned vehicles, the ASVs are required to identify the surrounding water area by onboard sensors to perform the autonomous navigation without people. Thus, obstacles detection and avoidance are important for ASVs to achieve collision avoidance and fully autonomous navigation.

Many obstacles avoidance methods have been applied to mobile robot and other unmanned vehicles. Artificial Potential Field (APF) which is first proposed by Khatib, is utilized widely for obstacles avoidance due to its simplicity and effectiveness1. The APF method presents attractive and repulsive potential field as virtual forces to lead the robot to avoid obstacles and reach the goal. The resultant force which is formed by attractive and repulsive forces determines the heading angle and speed of the robot. Many improvements have been done by different researchers for better performance and special applications. To track the moving target and avoid dynamic obstacles, Ge and Cui took relative velocities between robot and objects into account2, and soft landing was realized. Jaradat et al. designed a fuzzy logic guidance system to calculate the attractive and repulsive potential forces3. Path planning and obstacle avoidance were accomplished in an environment with both static and dynamic obstacles.
To decrease the accidents at sea, The International Marine Organization (IMO) defined the marine traffic rules - The International Regulations for Preventing Collisions at Sea (COLREGs) in 1972. The COLREGs are meant to be followed by all marine vessels when they encounter each other at sea or other water area. Besides the autonomous navigation, the ASVs are expected to obey the marine traffic rules while encountering other vessels at the sea. Thus, some researchers combined the marine traffic rules into the navigation system of ASVs to avoid collision.

Tsou et al. adopted genetic algorithm and integrated COLREGs and the safety domain of ship to determine an optimal evasive manoeuvre for obstacles avoidance. An optimal turning angle, navigation restoration time and navigational restoration angle for evasive manoeuvre are computed by the proposed algorithm. Naeem et al. addressed a reactive path planning algorithm which was performed by waypoints guidance. They presented a manual biasing scheme and combined it with line of sight (LOS) strategy to comply with COLREGs.

Under-actuated characteristic is another problem to solve for both ASVs and Autonomous Underwater Vehicles (AUV) navigation. Xianbo Xiang and his partners performed a series of work on this problem. They proposed a control framework for both fully-actuated and under-actuated configurations, which adopted Lyapunov’s direct method and backstepping technique. This method achieved a smooth continuous transition between two configurations in a synthesized controller for Line-of-Sight guidance. To detect the subsea cable and its buried environment, they built a magnetic LOS guidance system to track the subsea cable and further guided the environmental protection. To solve the system uncertainty problem such as inaccuracy modeling parameters and time-varying environmental disturbances, they proposed a two-layered framework synthesizing the guidance and control 3D AUV path following. This method also reduced the design and implementation cost as compared with other existing methods.

The aim of this paper is to design a guidance system of ASV that is able to cruise at open sea with dynamic obstacles. The ASV is expected to track the predefined path at open sea and identify the encounter situations to make evasive manoeuvre when encountering other ships. The contribution of this paper is that the encounter situation division diagram is integrated with the artificial potential field to perform COLREGs compliant ASV navigation.

The organization of this paper is as follows. The problem statement is presented in the second section, and the proposed method is addressed in the third section. The fourth section addresses the simulation results and discussion. The last section addresses conclusion and future work.

**Problem statements**

In 1972, the International Maritime Organization (IMO) established the International Regulations for Preventing Collisions at Sea 1972 (COLREGs) as marine traffic rules to be followed by all marine vessels to prevent collisions. COLREGs include 5 parts and 38 rules.

Three most common scenarios, overtaking, head-on, and crossing encounter situations are regulated in Rules 13-15 respectively. The ASV is supposed to track the predefined waypoints when it is navigated at sea area. Since the objects that it encounters may not have the capability of collision avoidance, the ASV is required to evade other ships if it is in the collision risk range. According to the CORREGs, the ASV is supposed to bypass other ships from starboard (right) side when it is a give way vessel. Further, commonly the autonomously navigated ship is defined as Own-ship and the ship to be avoided as Target-ship.

To follow the predefined waypoints path and avoid objects, the APF method is utilized as navigation system of the own ASV. The APF approach is instructed in Figure 1. The robot is repulsed by the obstacle and attracted by the goal. The resultant force determines the orientation and speed of the robot. For the ASV, the way that it bypasses the objects depends on the relative location of the target. It may pass by the target ship from starboard (right) or port (left) side, but may not follow COLREGs. In some cases, the steer of ASV could be forced to right side to make the ASV follow COLREGs. However, this may increase the collision risk of the ASV in other cases as shown in Figure 2.

For the common head-on situation in Figure 2(a), the ASV is supposed to avoid collision by turning right to obey COLREGs when the target ship is in the straight ahead of the ASV. However, for the case that the target ship is located in the starboard bow of the ASV as shown in Figure 2(b), it may cause collision if the ASV turns right to bypass the target ship. This means that it is a conflict between safety and marine traffic rules when the ASV is moving in the sea or
riverine environment\textsuperscript{11,12}. Safety is always the first priority for all vehicles, much more important than traffic rules. Therefore, a smart navigation system is needed for the ASV to judge the encounter situation and make an intelligent decision to determine whether to follow the CORREGs when avoiding collision.

**Approach**

As presented above, three common encounter situations of marine vessels are regulated by COLREGs. However, the own and the target ships can meet each other from any location when they encounter. As shown in Figure 2, the ASV is supposed to obey COLREGs when it is able to avoid collision. It is also expected to be able to violate the marine traffic rules when the collision risk is high.

To achieve the smart collision avoidance, encounter situation identification is integrated with the ASV guidance system. For the problem described above, the ASV is expected to identify the relative location of target ship when they encounter each other. Thereafter, the ASV is required to be able to make a reasonable decision of follow COLREGs or not when it avoids collision.

As shown in Figure 3, division diagram for ship encounter situations is combined with APF method to guide the ASV. This division diagram is proposed by Zheng and Wu who divided the area around the ship into 6 sub-areas\textsuperscript{13}. The division principle is based on the COLREGs and survey of navigation habits of evasive manoeuvre. The surrounding area of ASV is allocated for the three encounter situations, head-on (F), crossing (A, B and E), and overtaking (C, D). The encounter situation could be judged from the location and speed of the target ship.

For overtaking and head-on case, the ASV will bypass the target ship from right side if the target ship is located in area F and E. The ASV should bypass the target ship from left side if the target ship is located in area A. Therefore, the ASV is able to violate marine traffic rules when the collision risk is high.

There are two ways to avoid target ship after identify the encounter situations. One is to change the heading only and the other is to change both the heading and speed. In this paper, only heading of ASV is changed to avoid collision.

To verify the proposed method, it is assumed that the target ship in this paper has no ability to avoid collision. So the ASV has to make the evasive manoeuvre when they encounter.

APF is used to change the heading of the ASV. The ASV is assumed to moving with a constant speed at open sea. The ASV tracks the predefined waypoints by LOS method when it does not encounter the target ship. It will change the heading to make an evasive manoeuvre when encountering the target ship.

As illustrated in Figure 1, the attractive force is provided by the waypoints, 
\[
F_{\text{att}} = m \times \alpha \times \| P_{\text{wp}(t)} - P_{\text{tr}} \| \tag{1}
\]
where \( P(t) \) and \( P_{\text{wp}(t)} \) is the current position of ASV and next waypoint position respectively; \( m \) is constant and \( \alpha_p \) is a scaling parameter; \( F_{\text{att}} \) is the attractive force of APF method.

The waypoints are expressed by Cartesian coordinates, waypoints \((x_i, y_i)\) for \( i=1,\ldots,n \). These waypoints can be predefined by human or generated by onboard computer and stored as a database that consists of:

\[
\text{wpt.pos}=\{(x_0, y_0), (x_1, y_1), \ldots, (x_n, y_n)\}
\]  

(2)

The target ship provided a virtual repulsive force which is expressed as \(^2\),

\[
F_{\text{rep}}(p,v) = \begin{cases} 
F_{\text{rep}1} + F_{\text{rep}2}, & 0 < \rho(p,p_{\text{obs}}) - \rho_o(v_{\text{RO}}) < \rho_s \quad \text{and} \quad v_{\text{RO}} > 0 \\
\text{not defined}, & v_{\text{RO}} > 0 \quad \text{and} \quad \rho(p,p_{\text{obs}}) < \rho_o(v_{\text{RO}})
\end{cases}
\]  

where

\[
F_{\text{rep}1} = \frac{-\eta}{(\rho_s(p,p_{\text{obs}}) - \rho_o(v_{\text{RO}}))^2} (1 + \frac{v_{\text{RO}}}{a_{\text{max}}}) \eta_{\text{RO}}
\]  

(3)

\[
F_{\text{rep}2} = \frac{\eta_{\text{RO}} v_{\text{RO}}}{\rho_s(p,p_{\text{obs}}) a_{\text{max}} (\rho_s(p,p_{\text{obs}}) - \rho_o(v_{\text{RO}}))^2} \eta_{\text{RO}}
\]  

(5)

where \( \eta_{\text{RO}} \) is a unit vector pointing from the ASV to the obstacle; \( a_{\text{max}} \) is a maximum deceleration of magnitude of the ASV; \( p \) is the position, \( v \) is the velocity, \( \rho_s \) is the obstacle influence range, and \( \eta \) is a constant parameter. \( \rho_o \) determines the distance range that the obstacle generates repulsive force to the robot. The repulsive force will be zero when the distance between ASV and target ship \( \rho_s > \rho_o \).

Thus, the resultant force is,

\[
F_{\text{rs}} = F_{\text{att}} - F_{\text{rep}}
\]  

(6)

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

The flow chart of navigation and collision avoidance is illustrated in Figure 4. When the ASV is far from the target ship \( (\rho_s > \rho_o) \), the ASV is guided by the predefined waypoints. When the ASV detects the target ship, it identifies the encounter situation which is shown in Figure 3 to make a decision to follow COLREGs or not. Therefore the ASV is capable of performing simultaneous path tracking and collision avoidance.

The encounter situation identification in Figure 4 is determined by division diagram combined with APF method. If the target enters the surrounding area of the own ASV \( (\rho_s(\rho_o)) \), the relative position between the own ASV and the target will be calculated to confirm the encounter situation, such as head-on, overtaking etc.. The own ASV will judge the encounter situation and make an evasive manoeuvre action to avoid the collision. Thus, both of the magnitudes of the potential attractive and repulsive force will not be changed while the direction of the potential force might be changed to make the ASV move safely. Based on this approach, the own ASV has the ability to determine whether it should follow or violate the COLREGs, which makes it travel in a smart way.

**Simulation results and discussion**

The simulation of ASV navigation at open sea is achieved in MATLAB environment and Marine System Simulator GNC toolbox which is developed by Fossen and Perez\(^1\). Three encounter situations of head-on, overtaking and crossing are discussed in this section. The own ASV is defined as the ship that is able to avoid the obstacles while the target ship cannot.

The open sea environment and ASV model are integrated into Marine System Simulator GNC toolbox which is developed by Fossen and Perez\(^1\), where the length of the own ASV is 160.93m. To verify the proposed navigation algorithm, the own ASV and target ship are the same size, which is in blue and red color respectively in simulation results. The motion area of ASV is 20000 m × 20000 m. The ASV and target ship are following the predefined waypoints and the distance interval is 1000m.

The comparison of head-on situation is illustrated in Figure 5. The planned paths of own and target ASVs are two parallel straight lines, where the distance between them is 200m. The own ASV is moving from south to north while the target ASV is from north to south. Both of the ASVs’ speeds are 7m/s.

Figure 5(a) shows that the own ASV turns right when it encounters target ASV to fulfill the COLREGs. Since the target ASV is located at starboard bow (front right) of the own ASV, the collision happens when they encounter. This is the situation that the own ASV is forced to turn starboard (right) side when it bypasses the obstacles to follow the marine traffic rules.

**Head-on situation in open sea**

Figure 5(b) shows the navigation of own ASV integrated with the division diagram for ship encounter situations which is denoted in Figure 3. The own ASV turns portside (left) when the target ASV is located at the starboard bow of the own ASV.
The collision is avoided due to the encounter situations judgment before the own ASV makes the avoidance decision.

**Overtaking situation in open sea**

The comparison of overtaking situation is illustrated in Figure 6. Both of the own and target ASVs are moving from south to north. The own ASV starts from (0, 0) and is moving with speed of 10m/s; the target ASV starts from (0, 4000) and is moving with speed of 3m/s. Same as head-on situation, the distance between planned paths of own ASV and target ASV is 200m.

The trajectory of own ASV shows oscillation when it avoids the target ASV. The reason is that the target ASV is close to the waypoints which attract and navigates the own ASV. According to the APF theory, the ASV is attracted by the goal (waypoints) and repulsed by the obstacles (target ASV). This oscillation is called goal nonreachable with obstacles nearby (GNRON)\(^1\). To lead the ASV escape from the oscillation, the ASV is navigated to next waypoint when it is during the process of avoiding obstacles.

![Flowchart of the ASV collision avoidance strategy](image)

**Figure 4.** Collision avoidance strategy of the ASV.

In Figure 6(a), the own ASV is trying to overtake the target ASV from right side while the target ASV is located at the starboard bow of own ASV. Thus the collision happens when they encounter. The

![Graph showing head-on encounter](image)

**Figure 5(a).** Head-on encounter situation in open sea.

Figure 6(b) shows the avoidance of target ASV by the proposed method. The own ASV successfully
avoid the collision when it is overtaking the target ASV with the same location of Figure 6(a). The oscillation still exists but is not distinct since the waypoints of the own ASV is at the left side of the target ASV and the own ASV is also bypassing the target ASV from left side.

As shown in Figures 7 and 8, there are two different crossing encounter situations. One is privileged crossing in which the target ASV is moving from east to west, as shown in Figure 7; the other is burdened crossing in which the target ASV is moving from west to east, as shown in Figure 8. According to COLREGs, the own ASV is supposed to turn right to avoid collision in Figure 7 thus the collision does not happen. For the case of Figure 8(a), the own ASV turns right when the target ASV is moving from left to right, therefore the collision happens. The proposed method for navigation which integrates the encounter division diagram is illustrated in Figure 8(b). The own ASV bypasses the target ASV successfully from left side.

**Conclusion**

A smart navigation and collision avoidance system for ASV is presented in this paper. To solve the conflict between high collision risk and following marine traffic rules, the encounter situation identification is integrated with the Artificial Potential Field as the guidance system. The surrounding of the ASV is divided into 6 sub-areas to identify the encounter situation which is based on the encounter situation division diagram. The ASV will pass by the target ship from starboard (right) side if the target ship is located in the straight ahead or port bow area of ASV, which follows COLREGs; the ASV will take the safety as the first priority and pass by the target ship from port (left) side if the target
ship is located in the starboard bow area of ASV. The proposed method is verified by simulation at open sea environment and the results show that it successfully navigates the ASV for three encounter situations, head-on, overtaking and crossing. Besides, the proposed approach can work as not only autopilot but also the navigation aided system for human to avoid collision.

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