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A MODIFIED ARTIFICIAL POTENTIAL FIELD METHOD FOR RIVERINE OBSTACLES AVOIDANCE

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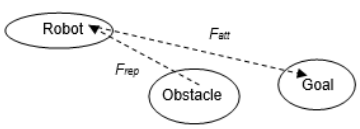
Graphical abstract



Abstract

This paper presents a modified artificial potential field (APF) based method for an Autonomous Surface Vessel (ASV) obstacles avoidance in a dynamic riverine environment. The APF method is combined with a balance control scheme to achieve river tracking and obstacles avoidance simultaneously. The APF method is further modified modification to comply with marine collision avoidance regulations (COLREGs). The overtaking and head-on scenarios are simulated in MATLAB platform. The simulation results are compared with other APF methods to prove that the proposed method is efficient for the ASV riverine navigation.

Keywords: Artificial potential field; autonomous surface vessel; obstacles avoidance; COLREGs

1.0 INTRODUCTION

Same as other unmanned systems, Autonomous Surface Vessels (ASVs) are used to accomplish tedious or dangerous tasks in environments that are not suitable for human. They are able to perform long time, wide area and low cost ocean engineering research, commercial and military work instead of people, such as remote sensing, ocean surveillance, ocean mapping, weather prediction, etc. The autonomy level of the ASV is determined by the navigation, guidance and control (NGC) system. Since the working environment of the ASV is generally with unknown or dynamic factors, obstacles detection and avoidance (ODA) system plays an indispensable role in the NGC system. Collision avoidance (CA) is the first priority requirement of the full autonomy ASV. It is reported that human error operations are the main reasons of the incidents, which were preventable. Thus the collision avoidance system is essential for both manned and unmanned surface vessels. On one hand, it is necessary for ASV to sense the environment and plan a collision free path; on the other hand, it is able to work as an aim or warning system to advise crew the potential collision.

Path planning methods can be divided into three classes, i.e. global path planning, local path planning and hybrid path planning. Global path planning refers to the prior known environment information, in which the path is planned offline to find an optimal or suboptimal path. Local path planning refers to the unknown or partially known environment information, which means that all the environmental information is obtained by onboard sensors. The path is planned online with a reactive way. The third class is hybrid methods, which refers to the rough known environment with dynamic or uncertain objects. The path is first planned offline based on the prior known information to guide the robot. Reactive obstacles avoidance methods will work when the robot encounters dynamic objects.

The local path planner is necessary for the unmanned system that works in a dynamic environment, which means that it is able to avoid both static and dynamic obstacles. Artificial potential field (APF) method, proposed by Khatib in1986 [1], is one of the most widely applied local path planning methods because of its simplicity and effectiveness. It uses the virtual repulsive and attractive potential field to achieve obstacles avoidance and goal tracking. To make this method applicable to the dynamic obstacles avoidance, Ge and Cui [2] took into account the relative velocities to perform dynamic obstacles avoidance and soft landing. Jaradat M A K et al. proposed a fuzzy logic expert system to realize the static and dynamic obstacles avoidance with only relative position information [3], which reduced the requirement of onboard sensors. This method also solved the local minima problem of APF. Yu et al. modified the APF method by using potential field intensity to replace force vector and they proposed an 'added potential field' to solve the local minima problem [4-6].

To improve the autonomy level of ASV, some scholars incorporated the marine traffic rules - The International Regulations for Preventing Collisions at Sea 1972 (COLREGs) into the NGC system. Naeem et al. Designed guidance system by line of sight coupled with a manual biasing scheme to generate COLREGs compliant routes [7]. This method is applied to a dynamic model of the ASV and the simulation results are compared with a DPSS algorithm in an environment with both static and dynamic obstacles. Benjamin et al. developed an interval programming based multiobjective optimization approach in a behaviour-based control framework to represent the COLREGs rules, and this method is implemented and verified with multiple ASVs [8].

The aim of this paper is to develop an obstacle avoidance algorithm that compliant with COLREGs for the riverine ASV system. The ASV is expected to track along the centerline of the river with the ability of obstacles avoidance, as illustrated in Figure 1. The riverbank lines are extracted with image processing approach and used to navigate the ASV by a balance control scheme to make it track along the centerline of the river, which were discussed in previous papers [9-11]. Dynamic obstacles avoidance is achieved by applying the method proposed by Ge and Cui [2]. Moreover, we modified Ge and Cui's method to integrate COLREGs into the path planner.

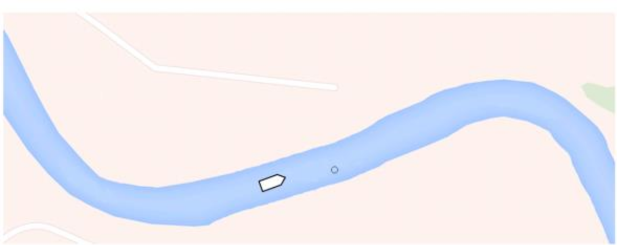


Figure1 View of Kerian River from Google Map

Organization of the paper is as follows. The COLREGs rules are introduced in the second section. The modified APF method for ASV navigation is presented in section 3. The simulation results and discussions are addressed in section 4. The final section presents conclusions and future work.

2.0 MARINE TRAFFIC RULES - COLREGS

The International Regulations for Preventing Collisions at Sea 1972 (COLREGs) is established by the International Maritime Organization (IMO) as navigation rules to be followed by ships and other vessels at sea to prevent collisions between two or more vessels [12]. Both the manned and unmanned ships should fulfill the marine traffic rules when travelling on the waterway.

The COLREGs consists of five parts and 38 rules. 'Part A: General' is the regulations on the application and responsibility. 'Part B: Steering and sailing' regulates the rules of marine crafts navigation. 'Part C: Lights and shapes' regulates the use of lighting signals. 'Part D' is Sound and light signals and 'Part E' is Exemption.

Rules 13-15 in Part B regulate three scenarios, i.e. overtaking, head-on and crossing, which are as follows [12].

Rule 13. Overtaking:

An overtaking vessel must keep out of the way of the vessel being overtaken.

Rule 14. Head-on situations:

When two power-driven vessels are meeting head-on both must alter course to starboard so that they pass on the port side of the other.

Rule 15. Crossing situations:

When two power-driven vessels are crossing, the vessel which has the other on the starboard side must give way and avoid crossing ahead of her.

Besides, Rule 9 regulates the narrow canal waterway, such as riverine environment.

Rule 9. Narrow channels:

A vessel proceeding along a narrow channel must keep to starboard.

Small vessels or sailing vessels must not impede (larger) vessels which can navigate only within a narrow channel.

Ships must not cross a channel if to do so would impede another vessel which can navigate only within that channel.

In summary, the ASV has to make an evasive manoeuvre and avoid the encountered obstacles from starboard side.

3.0 MODIFIED ARTIFICIAL POTENTIAL FIELD METHOD FOR ASV OBSTALCES AVOIDANCE

3.1 Artificial Potential Field

The artificial potential field method is illustrated in Figure 2.

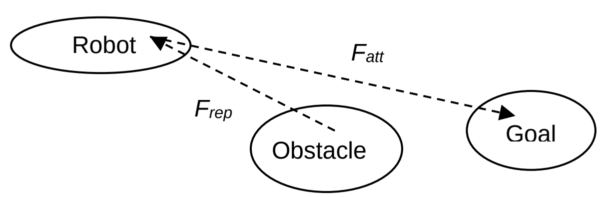


Figure 2 Artificial potential field illustration

The robot is attracted by the goal and repulsed by the obstacles. Equations representing the virtual attractive and repulsive force are as follows.

$$F_{rep}(X_R)=\begin{cases}K_r\times(\frac{1}{(d(X_R,X_o)-d_0)^2}-\frac{1}{(d_m-d_0)^2}) & d\le d_m\\ 0 & d>d_m\end{cases} \quad (1)$$

$$F_{att}(X_R)=K_a\times d(X_R,X_G) \quad (2)$$

where F_{rep} is repulsive force, $d(X_R,X_o)$ is distance from obstacle to robot, d_m is a distance threshold which only works when $d(X_R,X_o)\le d_m$, d_0 is the minimum safety distance to avoid collision, K_r is a repulsive potential field constant; F_{att} is attractive force, and K_a is attractive potential field constant, $d(X_R,X_G)$ is the distance from robot to the goal. Therefore the resultant force is

$$F_{res}=F_{rep}(X_R)+F_{att}(X_R) \quad (3)$$

Ge and Cui [2] proposed a modified APF method to implement dynamic obstacles avoidance, which involved relative velocity in the repulsive potential equation.

$$F_{rep}(p,v)= \quad (4)$$

$$\begin{cases}F_{rep1}+F_{rep2}, & 0<\rho(p,p_{obs})-\rho_m(v_{RO})<\rho_o \text{ and } v_{RO}>0\\ \text{not defined}, & v_{RO}>0 \text{ and } \rho_s(p,p_{obs})<\rho_m(v_{RO})\end{cases}$$

where

$$F_{rep1}=\frac{-\eta}{(\rho_s(p,p_{obs})-\rho_m(v_{RO}))^2}(1+\frac{v_{RO}}{a_{max}})n_{RO} \quad (5)$$

$$F_{rep2}=\frac{\eta v_{RO}v_{RO\perp}}{\rho_s(p,p_{obs})a_{max}(\rho_s(p,p_{obs})-\rho_m(v_{RO}))^2}n_{RO\perp} \quad (6)$$

where P denotes the position, V denotes the velocity, ρ denotes the obstacle influence range, and η denotes a constant parameter.

3.2 Balance-APF Hybrid Method

For the case in this paper, there is no goal for ASV to track and the ASV is expected to track along the centerline of the river. The ASV should be attracted by the centerline of the river. However, the centerline of the river is virtual and cannot be detected by ASV. Therefore, the balance control scheme is employed to replace the attractive potential in Equation (2) to perform river tracking. The principle of the balance control scheme is denoted in Equation (7), which uses a comparison of distances from left and right side riverbanks to make sure that the ASV track along the centerline of the river.

$$\begin{cases}\text{turnleft}, & (D_L-D_R)>0\\ \text{turnright}, & (D_L-D_R)<0\\ \text{keepcourse}, & (D_L-D_R)=0\end{cases} \quad (7)$$

where D_L is distance from ASV to left riverbank, and D_R is the distance from ASV to right riverbank, K_{att} is a distance coefficient. Equation (7) shows that, if ASV is on the centerline of the river ($(D_L-D_R)=0$), it will keep the course; if the ASV is closer to the left side of riverbank ($(D_L-D_R)>0$), it will turn left; if the ASV is closer to the right side of the riverbank, it will turn right.

The ASV in this paper is moving with a constant speed of 2m/s, which means that the speed of ASV is not controlled by the repulsive and attractive force. The river tracking and obstacles avoidance are performed by changing the heading of the ASV. Therefore the direction of repulsive force and attractive force is extracted to control the heading of ASV, while the magnitudes of the forces are abandoned.

As presented above, the river centerline tracking is achieved by the balance control scheme. The heading control law is expressed in Equation (8), which can be used to replace the Equation (2) to perform river tracking and obstacles avoidance task. In this way, the resultant heading of ASV is determined by the direction of the resultant force of Equation (3).

$$\theta_{att}=K_{att}\times(D_L-D_R) \quad (8)$$

3.3 COLREGs Compliant Path Planning

Since the ASV is travelling with a constant speed, only the heading angle is affected by repulsive force. The Equation (1) and Equation (7) are combined to guide the ASV in the river.

$$heading=\begin{cases}K_{att}\times(D_L-D_R)-angle(F_{rep}(X_R)) & d\le d_m\\ K_{att}\times(D_L-D_R) & d>d_m\end{cases} \quad (9)$$

where $angle(F_{rep}(X_R))$ is the direction extracted from the repulsive potential; d is the distance from ASV to the obstacle; d_m is an influence range of obstacle, which means that the obstacles will repulse the ASV away if and only if the distance $d\le d_m$. Otherwise, the obstacles will not affect the ASV.

It can be seen from Equation (9) that when ASV is out of the influence range of obstacles, it is navigated by the balance control scheme. When ASV enters the influence range of obstacles, heading angle of ASV is the resultant of balance control and repulsive function.

The direction angle extracted from Equation (1) can be negative or positive depending on the location of the obstacle. When the repulsive direction angle is positive, the ASV will pass by the obstacle from port side; when the repulsive direction angle is negative, the ASV will pass by the obstacle from starboard side. Thus we can force the repulsive direction angle to be negative, then the ASV will turn starboard side when enters influence range of obstacle, which is indicated in Equation (10).

$$heading=\begin{cases}K_{att}\times(D_L-D_R)-abs(angle(F_{rep}(X_R))) & d\le d_m\\ K_{att}\times(D_L-D_R) & d>d_m\end{cases} \quad (10)$$

where *abs* is the absolute value of $angle(F_{rep}(X_R))$. In addition, Equation (10) is an iterative process to generate an evasive maneuver action until satisfied COLREGs.

4.0 RESULTS AND DISCUSSIONS

The proposed modified COLREGs compliant APF method is implemented in MATLAB environment and Marine System Simulator GNC toolbox which is developed by Fossen and Perez [13]. Two scenarios of head-on and overtaking are performed for ASV path planning in a riverine environment with both static and dynamic obstacles. In addition, the new proposed method is compared with the existing method (Ge and Cui) [2] to verify the performance of the proposed method.

As discussed above, (Ge and Cui) [2] proposed a modified APF method which took into account the relative velocities between robot and obstacles and goal. The results showed that this method was suitable for obstacles avoidance in a dynamic environment. However, the direction of evasive manoeuvre is uncertain when the robot avoids the obstacles, which does not fulfil the marine traffic rules. Thus we modify the method to make it compliant with marine traffic of COLREGs.

Figures 3 to 6 present the comparison of the simulation results of Ge and Cui's method and the proposed method in this paper. In general, the three primary rules in COLREGs must be integrated in NGC system are *Rule 13: overtaking, Rule 14, Head-on and Rule 15 Crossing*. However, the *Rule 9* regulates a situation that '*Ships must not cross a channel if to do so would impede another vessel which can navigate only within that channel*,' which is exactly a regulation for narrow channel waterway, such as a river. Thus, only two scenarios, head-on and overtaking scenarios are discussed in this paper.

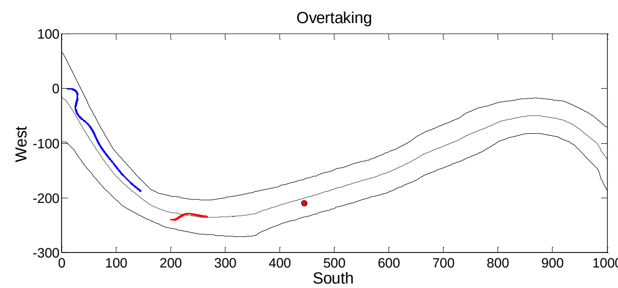
To make the simulation more practical, we choose a part of a real river map as the riverine environment. This river is located in Nibong Tebal, Penang, Malaysia. It is near to Engineering Campus, Universiti Sains Malaysia, with the name of Sungai Kerian. The length of this part of the river is 1000m, with the maximum width of 166m and minimum width of 56m.

View of the river is obtained from Google map and the riverbank lines are extracted by image processing approach. The ASV is expected to be navigated by the proposed path planning method with capability of keeping in the center of the river and obstacles avoidance. The simulation sampling time is 0.1s. The ASV is designed with constant speed of 2.5m/s, thus only heading angle is changed by the proposed path planner. The ASV platform and model has been discussed in previous paper [11].

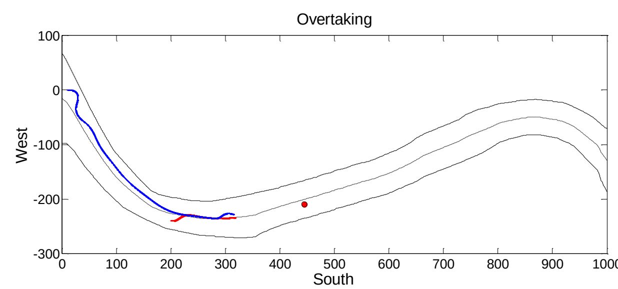
4.1 Comparision of Overtaking Scenario

Figures 3(a) to (c) show the overtaking scenario of ASV navigation process in the river by Ge and Cui's method. There are one static obstacle and one dynamic target ship in the river, which the ASV needs to avoid them. The blue line in Figure 3 is the trajectory of ASV, and the red circle is static obstacle, and the red line is the trajectory of target ship. The static obstacle is circle shape with a diameter of 10m and located on (440, -215). The target ship has the same size with the ASV starts from (200, -240) and it moves with a constant speed of 0.7m/s. Both the ASV and the target ship are guided by balance control scheme to track along the centerline of the river from west to east, but the ASV is able to avoid encountered obstacles while the target ship is not.

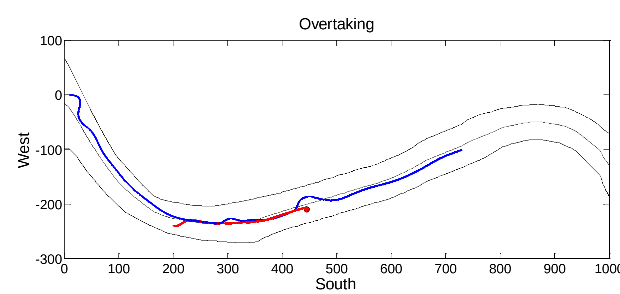
The ASV starts from the position of (0, 10) and its initial heading angle is 0°. At the beginning, the ASV is far from the static obstacle and target ship, thus its heading angle is determined by the balance control. Figure 3 (a) shows the navigation state when t=10s. We can see that the ASV is tracking along the centerline of the river and not affected by the static obstacle and target ship. At time t=17.5s, the ASV encounters the target ship and needs to overtake the target ship. As discussed above, the evasive manoeuvre is not certain to make the decision that the ASV should bypass the obstacle on port or starboard side. The evasive manoeuvre depends on the position of the obstacle. In this case, the ASV overtakes the target ship on port side. However, this does not obey the marine traffic rules of COLREGs. After overtaking the target ship, the ASV moves on until it encounters the static obstacle. Same with the case that the ASV encounters the target ship, the ASV also bypasses the static obstacle on the port side and then moves on. As shown in Figure 3(c), the static obstacle is on the path of ASV and target ship, however, the target ship has no ability of obstacles avoidance. This causes a collision when the target ship encounters the static obstacle.



(a) t=10s



(b) t=17.5s

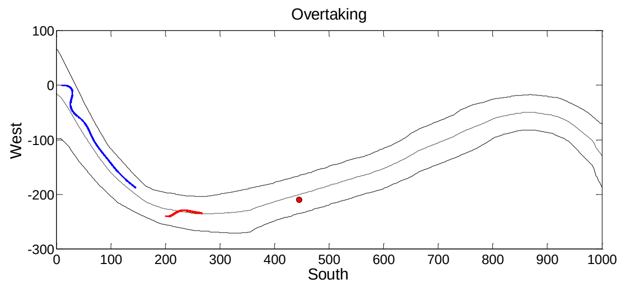


(c) Complete navigation
(d)

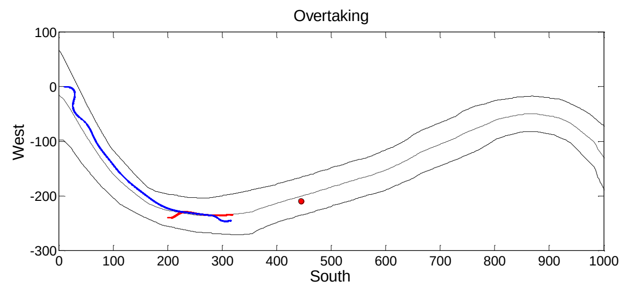
Figure 3 Overtaking scenario of ASV navigating in river with method in [2]

Figure 4 shows the simulation results of the proposed APF method which is compliant with COLREGs. All the parameters and condition are same with the results of Figure 3 but the evasive manoeuvre is forced to be certain to turn starboard side when ASV encounters obstacles, which is determined by Equation (10).

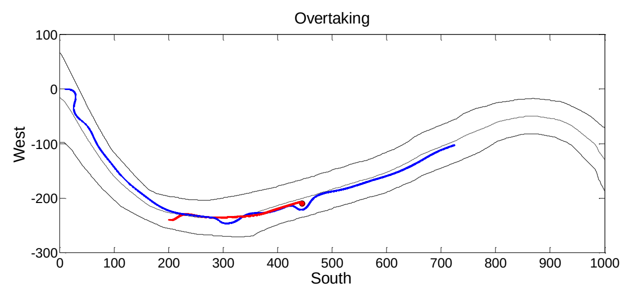
The initial states of Figure 4 are exactly same with Figure 3, which can be seen in Figure 4(a). As shown in Figure 4(b), at time t= 17.5s, the ASV encounters the target ship. Since the marine traffic rules of COLREGs are incorporated in the path planner, the ASV overtakes the target ship on starboard side. After overtaking the target ship, the ASV moves on and also bypasses the static obstacle on the starboard side, which is shown in Figure 4(c). Same with Figure 3, the simulation stops when the target ship collides with the static obstacle.



(a) t=10s



(b) t=17.5s



(c) Complete navigation

(d)

Figure 4 Overtaking scenario of ASV navigating in river with proposed method

4.2 Comparision of Head-on Scenario

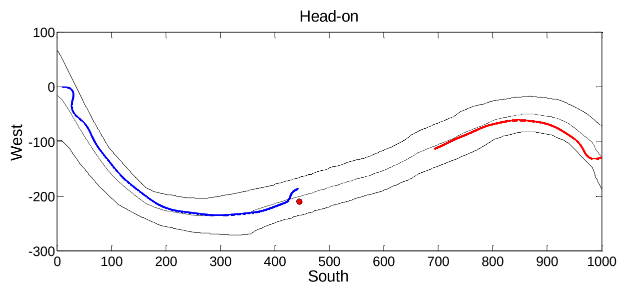
Figures 5 to 6 show the comparison of the simulation results of head-on scenario with Ge and Cui's method and the proposed method in this paper, respectively. The static obstacle locates on (440, -215). The target ship starts from the location of (1000, -130) and tracks along the centerline of the river from east to west with a constant speed of 1.5m/s. The initial pose of ASV is still in the position of (0, 10) and heading angle of 0°. The ASV tracks along the centerline of river from west to east with constant speed of 2.5m/s.

Since the ASV and the target ship track along the centerline of the river with opposite direction, the paths of the ASV and the target ship are symmetrical about the centerline of the river. The heading controller in this paper is a PD controller, thus the ASV and the target ship are roughly tracking along the centerline of the river, and the trajectories of the ASV and target ship are not overlapped. For this reason, the target ship is on the port side the ASV when they encounters. The ASV will automatically make the evasive manoeuvre from starboard side. To make a more obvious comparison, we changed both of the trajectories of ASV and target ship. The path of the ASV is moved above with 3 meters and the path of the target ship is moved below with 20 meters to create a more challenging situation. In such way, the target ship will be on the exact opposite direction when they encountered. Besides, the trajectories of the ASV and target ship are partially overlapped.

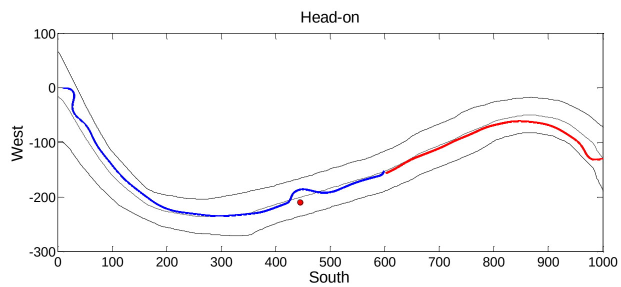
As shown in Figure 5(a), at time t=23s, the ASV first encounters the static obstacle and bypasses the static obstacle from port side. At t=29.7s, the ASV encounters the target ship, and the ASV bypasses the target ship from port side due to the relative location. From Figure 5(c) we can see that the evasive manoeuvre of ASV appears overshoot when ASV avoids the target ship. This is because the relative velocity of head-on scenario is greater than the relative velocity of overtaking. Therefore the second item of Equation (4) is greater, which causes a bigger evasive manoeuvre. The static obstacle is on the path of the target ship, thus the simulation stops when the target ship collides with the static obstacle.

Figure 6 presents the simulation results to compare with Figure 5. Same as stated above, the ASV makes a starboard evasive manoeuvre when it encounters the static obstacle at t=23s, which is shown in Figure 6(a). At time t= 30s, the ASV encounters the target ship and bypasses it from starboard side. The simulation also stops when the target ship collides with the static obstacle.

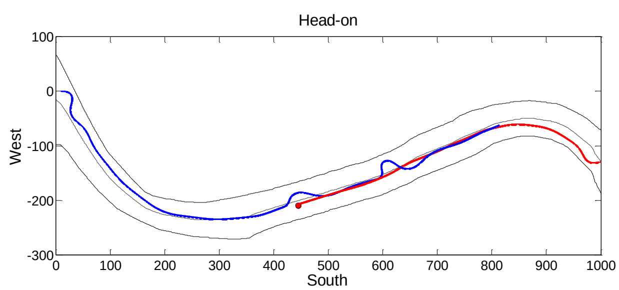
Comparison of the simulation results in overtaking and head-on scenarios shows that the proposed APF method integrates the marine traffic rule-COLREGs in the path planner. This path planner guarantees that the ASV is able to avoid both of the static and dynamic obstacles.



(a) t=23s

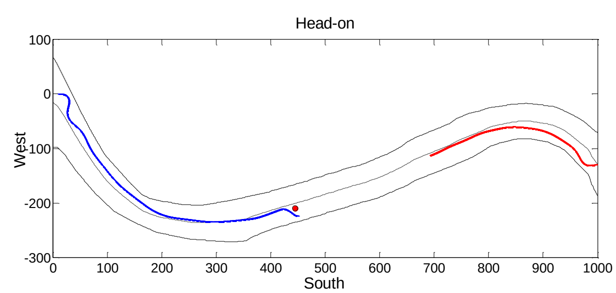


(b) t=29.7s

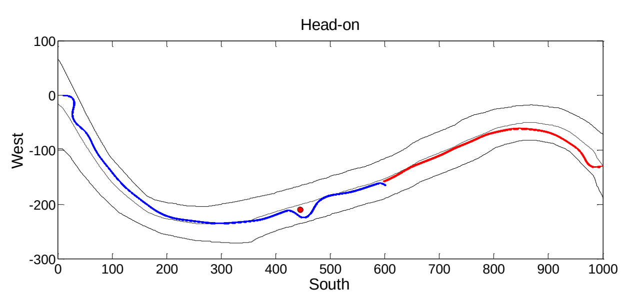


(c) Complete navigation

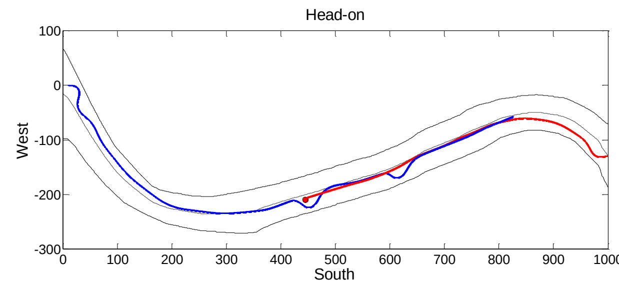
Figure 5 Head-on scenario of ASV navigating in river with method in [2]



(a) t=23s



(b) t=30s



(c) Complete navigation

Figure 6 Head-on scenario of ASV navigating in river with proposed method

4.3 Discussions

The proposed method in this paper is to realize simultaneous river centerline tracking and obstacles avoidance that complies with COLREGs. This strategy is different from other path following and obstacles avoidance methods. The reported paths following methods, such as in paper [7], are based on the GPS and other global information to track a planned path. However, in this paper the path that the ASV needs to follow is unknown, and only the local distances from riverbanks are used to perform river tracking.

The existing reported COLREGs compliant obstacles avoidance methods are applied in the open sea environment. These methods are not suitable for the riverine or the other corridor environment. The proposed approach in this paper, the balance control combined with APF method, is firstly presented in riverine environment to achieve simultaneous river tracking and obstacles avoidance. In addition, this method can also be applied to the other corridor type environment.

From the results we can see that, the accuracy of the river tracking is different in different parts. From the simulation results we cans see that the accuracy of river tracking depends on the trend of the river. For example, the accuracy of tracking is poor in the parts (0-400m) and (800-1000m). This is because that the river is more curved in these two parts. In contrast, the accuracy of tracking is much better in part (400m-800m) since the river is kind of straight in this part. Thus, the accuracy of tracking depends on the river environment.

In addition, the marine traffic rules-COLREGs is regulated for navigation safety but not compulsory. The navigator of ships should judge the situation to make sure that collisions can never occur, even when it has to breach the COLREGs rules [14].

5.0 CONCLUSION

This paper presents a COLREGs compliant path planning method based on the artificial potential field for an ASV navigating in the dynamic riverine environment. The APF method is combined with a balance control scheme to perform river tracking. The marine collision regulations COLREGs are incorporated as well in the NGC system. Two scenarios of overtaking and head-on are simulated in MATLAB. Simulation results are compared with other existing APF method and it proves that the proposed method has a better performance.

Future work will focus on path planning in the riverine environment with multi dynamic obstacles and the experimental implementation.

Acknowledgement

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