A hybrid artificial potential field method for autonomous surface vessel path planning in dynamic riverine environment

Jian Hong Mei & M. R. Arshad
Underwater, Control and Robotics Research Group (UCRG), School of Electrical and Electronic Engineering, Engineering Campus, Universiti Sains Malaysia (USM), 14300 Nibong Tebal, Pulau Pinang, Malaysia.
[E-mail: meijianhong@gmail.com and rizal@eng.usm.my]

Received 9 July 2015; revised 4 December 2015

A hybrid Artificial Potential Field (APF) method is addressed in this paper for Autonomous Surface Vessel (ASV) cruising in the dynamic riverine environment. Firstly, a balance control scheme is proposed to replace the attractive potential function and perform the ASV tracking along the centerline of the river. Then, to simplify the repulsive potential function, the relative velocity between ASV and obstacle is derived from relative position, which reduces the requirement of on-board sensing. Finally, two challenging scenarios, head-on situation and overtaking situation, where ASV encounters another moving ship in a river are simulated. The simulation results illustrate that the proposed hybrid APF method is effective for simultaneous path planning and obstacle avoidance in the dynamic riverine environment.

[Keywords: Artificial Potential Field, Balance Control Scheme, Path Planning, Obstacles Avoidance]

Introduction

Path planning and obstacle avoidance are basic issues for autonomous vehicle navigation. Path planning methods can be divided into two categories, global path planning and local path planning, which refers to deliberate and reactive behavior, respectively. One of the advantages of global path planning is that it is able to generate an optimal or near optimal path for a robot with the lowest cost. However, global path planning is not efficient when the robot is travelling in an environment with unknown, uncertain or dynamic obstacles which always exist in real life and the natural environment.

Artificial potential field is widely used in local path planning and obstacle avoidance because of its simplicity and effectiveness. APF method was first proposed by Khatib for mobile robot obstacles avoidance\(^1\). It has been applied to many cases successfully and has proven sufficient performance, despite the drawbacks of local minima and goal non-reachable. Some researchers modified the APF method to overcome these two drawbacks. Lei Tang et al. proposed a steer angle tangent generated by a virtual gravity chain to guide the robot\(^2\). In this method the potential field force is not directly operated on the robot and the simulation results show that they solved the local minima and goal unreachable problems. Another solution is to modify the repulsive potential with a rotational potential force to generate a smoother trajectory around obstacles\(^3,4\). To solve the goal unreachable problem, Joe Sfeir et al. multiplied the obstacles’ potential by a positive quantity that was null when the robot’s position was closed to the goal\(^4\). Dong Hun Kim and Shin S. presented a multiplicative and additive composition APF between robot and goal, and between robot and obstacles, respectively\(^5\). They solved the two drawbacks and presented a set of analytical guidelines for designing potential functions.

Another problem of basic APF is that it is not suitable for avoiding obstacles in dynamic environment, because it is only based on position variable. Thus, the relative velocity is taken into account for moving obstacles. S.S. Ge and Y.J. Cui proposed new potential functions with respect to moving obstacles and moving target, by using relative positions and velocities\(^6\). The simulation and hardware experiment demonstrated that the modified APF method is effective for the mobile robot motion planning in a dynamic environment. Hybrid APF approach is one of the methods for path planning in dynamic environment, such as combined with artificial intelligence algorithms\(^7,10\). Jaradat M A K et al. proposed a fuzzy logic expert system to determine the attractive and repulsive potential forces\(^11\). They accomplished the path planning and obstacle avoidance in stationary and dynamic environments with relative positions to goals and obstacles.
respectively. Lee et al. proposed a fuzzy-APF hybrid algorithm to perform obstacles avoidance and trackkeeping\cite{12}, and this algorithm is able to handle static and dynamic environment. In addition, this research integrated the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) in the algorithm for the case where two moving ships encountered.

Furthermore, the APF method is extended to multi-robot formation control. Gazi and Passino built a kinematic swarm model and proposed a class of attractive and repulsive potential functions for stable swarm aggregations\cite{13}. After that, they extended the model for formation control and used sliding-mode control to force the motion of robots to obey the dynamic of the kinematic model\cite{14}. Zhang proposed a dynamic artificial potential field (DAPF) which was based on the local information to solve the problem of traditional APF\cite{15}. And they applied the DAPF method to formation control with effective simulation results.

In this paper, we present an Autonomous Surface Vessel (ASV) which navigates in a riverine environment for bathymetry survey and environmental monitoring. The ASV is expected to cruise and keep in the center of the river, while being able to avoid stationary and dynamic obstacles. This work is challenging since there are lots of factors that will influence the navigation, such as water flow, wave, wind and moving ships in the river. Thus, we propose an improved Artificial Potential Field (APF) based method to solve the simultaneous track keeping and obstacles avoidance problems. Work in this paper is based on the previous research presented in\cite{16,18}. Firstly, lines of riverbanks are identified by a vision system to estimate both sides’ distances from the ASV to riverbanks, which is reported in\cite{16,17}. Then, a balance control scheme is proposed to perform ASV tracking along the river and keeping in the center of river\cite{18}. Study in this paper is to achieve a simultaneous track keeping and obstacle avoidance in a dynamic riverine environment by a balance-APF hybrid method. We propose new potential functions for the mission described above with only relative positions involved to avoid the moving obstacles (such as moving ships) in the river.

This paper is organized as follows: In section 2, we give a brief problem statement of ASV track keeping and obstacle avoidance. Section 3 presents the traditional APF and proposes a modified APF method. Simulation results and discussions are presented in Section 4. Finally, a conclusion is given in Section 5.

**Materials and Methods**

The developed ASV in this paper is designed to perform simultaneous track keeping and dynamic obstacles avoidance in the riverine environment. In the paper\cite{18}, we discussed the river track keeping problem with the balance control scheme, and it has been proved effective. However, it was based on the assumption that there were no obstacles in the river, which was only an ideal situation. Obstacles, such as moving ships, probably exist on the waterway of ASV.

The developed ASV platform is shown in Figure 1, which is mounted with integrated GPS+INS and vision system. These sensors are fused by Kalman filter to detect the obstacles. After measuring the position, velocity and size of obstacles, the ASV is navigated by path planner to determine the course.

There are several challenges in this problem. Firstly, not only the stationary and dynamic obstacles may fill the waterway, but also the workspace of ASV is limited by the riverbanks. Secondly, the simultaneous track keeping and obstacles avoidance is challenging since the track is not known, as the centerline of river is following with the river trend but the river is unknown. Finally, the speed of ASV is needed to keep constant speed; however, the speed is generally affected by the river current.

In this paper, the ASV is designed to cruise in the river with a constant speed, where the relative velocities to the obstacles and riverbanks are not measured. Therefore, the problem becomes how to control the ASV to perform simultaneous track keeping and dynamic obstacles avoidance by only heading control, and with only relative position involved.

For the problem of obstacles avoidance in dynamic environment, Ge and Cui proposed a method based on the sensing of relative position and velocity of target and obstacles, respectively\cite{6}. They gave a new attractive and repulsive function which includes relative velocities of moving target and obstacles information. However, for the specific problem in this paper, the ASV is not tracking a moving target, but an unknown centerline of river; meanwhile it has to avoid stationary and dynamic obstacles with only relative position known.
The ASV navigating in a riverine environment described above, can be decomposed to two individual tasks, track keeping and obstacle avoidance. According to the concept of Artificial Potential Field, the track keeping can be expressed as the attractive potential, while obstacles avoidance as the repulsive potential. Then the total potential of attractive and repulsive potential realizes the complete navigation of ASV in the river. Thus we combine the balance control scheme which has been presented in 18 and the APF function proposed in 6, to construct a hybrid navigation method, which is shown in Figure 2. The basic principles of this method are as follows.

When ASV is cruising out of the obstacles influence range, it is navigated by the balance control scheme and attracted to track along the centerline of river. When ASV moves into the influence range of obstacles, the repulsive forces start to affect on the ASV and make it move away from the obstacles. The total force of attractive force and repulsive force conducts the ASV with an appropriate heading angle.

This heading controller in Figure 2 is a PD controller which receives the heading angle from hybrid APF path planning. Then heading controller outputs the signal to a differential thruster to control the motion of ASV.

**Attractive Potential Function**

Generally, the attractive potential is defined as a function of relative distance between the robot and the stationary target, or a function of the relative distance and relative velocity between the robot and the moving target\(^6\).

\[
U_{attract}(p,v) = \alpha_p \|p_{tar}(t) - p(t)\|^2 + \alpha_v \|v_{tar}(t) - v(t)\|^2
\]

(1)

where \(p(t)\) and \(p_{tar}(t)\) denote the positions of robot and target respectively; \(\|p_{tar}(t) - p(t)\|\) is the distance between the robot and target; \(v_{tar}(t)\) and \(v(t)\) are the velocities of robot and the target; \(\|v_{tar}(t) - v(t)\|\) is the magnitude of the relative velocity between the target and the robot; \(\alpha_p\) and \(\alpha_v\) are scalar parameters; \(m\) and \(n\) are positive constants.

---

**Fig. 1—Integrated GPS/INS/Vision navigation ASV platform.**

**Fig. 2—Block diagram of ASV path planning.**

However, in this paper we don’t have a specific target that the ASV is following. The ASV is developed to track the centerline of river with a designed speed. As mentioned in paper 18, the balance control scheme can be used as attractive potential function to perform the track keeping task. The heading angle is as follow,

\[
F_{attractor} = K_{attractor} \times (D_G - D_H)
\]

(2)
where $D_L$ and $D_R$ denote the distances from left and right side riverbanks to the ASV; $F_{att}$ denotes the attractive force operated on the ASV; $K_{att}$ is scalar parameter.

Equation (2) means that the ASV is navigated by comparing the distances from ASV to the left and right side of riverbanks. Putting Equation (2) into the feedback system of Figure 1, the control law is as follows to make sure that the ASV track along the centerline of river.

$$\begin{cases} \text{if } (D_L - D_R) > 0 & \text{turn left} \\ \text{if } (D_L - D_R) < 0 & \text{turn right} \\ \text{else } & \text{keep course} \end{cases}$$

(3)

When $D_L > D_R$, which means that the ASV is nearer to the right side riverbank, the ASV will control the rudder to turn left. When $D_L < D_R$, which means that the ASV is nearer to the left side riverbank, the ASV will control the rudder to turn right. When $D_L = D_R$, which means that the ASV is in the center of river, the ASV will keep the current heading angle.

Repulsive Potential Function

The traditional repulsive potential can be defined as follows

$$U_{rep} = \begin{cases} \frac{1}{2} \left( \frac{1}{\rho} - \frac{1}{\rho_o} \right), & \rho \leq \rho_o \\ 0, & \rho > \rho_o \end{cases}$$

(4)

where $\rho$ is the distance from robot to obstacle; and $\rho_o$ is the influence range of obstacle; $\eta$ is the scalar parameter. The traditional repulsive potential function is used to accomplish stationary obstacles avoidance, but not sufficient for dynamic obstacles avoidance.

To solve moving obstacles avoidance, Ge and Cui proposed a new repulsive potential function which used both the relative position and relative velocity between the robot and obstacles,

$$F_{rep} = \frac{-\eta}{(\rho_s(p, p_{obs}) - \rho_o(v_{obs}))} \left(1 + \frac{v_{obs}}{a_{max}}\right) n_{RO}$$

(6)

$$F_{rep2} = \frac{\eta v_{obs} v_{RO}}{(\rho_s(p, p_{obs}) - \rho_o(v_{obs}))} n_{RO}$$

(7)

where $P$ denotes the position, $V$ denotes the velocity, $\rho$ denotes the obstacle influence range, and $\eta$ denotes a constant parameter.

Equations (5)-(7) involve two vectors that should be measured, one is relative position and the other is relative velocity which are corresponding to $F_{rep1}$ and $F_{rep2}$, respectively. Both of the $F_{rep1}$ and $F_{rep2}$ repulse the robot away from obstacles, but with different force and steering angle.

The magnitude of relative position is the Euclidean distance from the obstacle to the robot, and the direction is also from the obstacle to the robot. The relative velocity between the robot and the obstacle is defined as

$$v_{RO} = [v - v_{obs}] n_{RO}$$

(8)

where $n_{RO}$ is a unit vector pointing from the robot to the obstacle. If $v_{RO} > 0$, i.e. the robot is moving toward the obstacle, thus the robot has to be operated to avoid the obstacle. If $v_{RO} \leq 0$, i.e. the robot is moving away from the obstacle, no avoidance is needed.

However, sometimes the relative velocity is not easy to be obtained by online sensing. Therefore we propose a new definition of relative velocity between ASV and obstacles. Assume that the relative position between ASV and obstacle is known, and then relative velocity can be defined as the derivative of relative position,

$$v_{RO} = \frac{d\rho_s(p, p_{obs})}{dt}$$

(9)

In practice, the magnitude of relative velocity can be computed by

$$v_{RO} = \rho_s(p, p_{obs})(t) - \rho_s(p, p_{obs})(t-1)$$

(10)

where $\rho_s(p, p_{obs})(t)$ and $\rho_s(p, p_{obs})(t-1)$ are relative position at time $t$ and $(t-1)$. Same as the definition of Equation (9), if $v_{RO} > 0$, it means that the ASV is moving closer to the obstacle while
\( v_{BO} \leq 0 \) means that the ASV is moving away from the obstacle. Thus we modified Equation (7) to

\[
F_{\text{rep}2} = K_v (p, p_{obs})(t) - \rho_v (p, p_{obs})(t - 1)
\]

(11)

where \( K_v \) is a scalar parameter.

For the case that multiple obstacles (including stationary and dynamic) exist in the environment, the repulsive force is

\[
F_{\text{rep}} = \sum n_{\text{obs}} F_{\text{rep}i}
\]

(12)

where \( n_{\text{obs}} \) is the number of obstacles, and \( F_{\text{rep}i} \) is repulsive force of the \( i \)th obstacles.

Thus, the total virtual force is

\[
F_{\text{total}} = F_{\text{att}} + F_{\text{rep}}
\]

(13)

where \( F_{\text{att}} \) and \( F_{\text{rep}} \) can be computed through Equations (2) and (12).

Since the traveling speed of ASV is constant in this paper, the motion planning only refers to the heading angle. \( F_{\text{total}} \) is used to steer the ASV cruise in the river with simultaneous track keeping and obstacles avoidance.

**Model of ASV with differential thruster**

Assume that the ASV is moving in the horizontal plane of water surface, as shown in Figure 3. With the assumption that,

(1). The hull is symmetrical on \( O_x Y_b Z_b \) planar.

(2). The environment disturbances are considered to be slowly time-varied process.

Then 3 degrees of freedom ASV model can be expressed as

\[
\dot{\eta} = J(\eta)\nu
\]

\[
M\nu + C(\nu)\nu + D(\nu)\nu = \tau + \tau_E
\]

(14)

where matrices \( J(\eta) \) is the transformation matrix for converting from body-fixed frame to earth-fixed frame; \( M \) is a mass matrix; \( C(\nu) \) is a Coriolis matrix; and \( D(\nu) \) is the summation of linear and nonlinear drag matrices; \( \tau \) is the sum of all forces and moments acting on the ASV\(^{10}\).

Where matrices \( J(\eta), M, C(\nu), D(\nu) = D + D_n(\nu) \) are expressed as,

\[
J(\eta) = \begin{bmatrix}
\cos(\nu) & -\sin(\nu) & 0 \\
\sin(\nu) & \cos(\nu) & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

(15)

\[
M = \begin{bmatrix}
m - X & 0 & 0 \\
0 & m - Y & -Y_r \\
0 & Y_r & I_z - N_r
\end{bmatrix}
\]

(16)

\[
C(\nu) = \begin{bmatrix}
0 & 0 & -m_Y \nu + Y_r \nu \\
0 & 0 & m_u - X_u \nu \\
m_Y \nu - Y_r \nu + m_u - X_u \nu \\
\end{bmatrix}
\]

(17)

\[
D = \begin{bmatrix}
X_u & 0 & 0 \\
0 & Y_v & Y_r \\
0 & N_v & N_r
\end{bmatrix}
\]

(18)

\[
D_n(\nu) = \begin{bmatrix}
X_{\|h} & 0 & 0 \\
0 & Y_{\|l} + Y_{\|r} & Y_{\|l} \\
0 & N_{\|l} + N_{\|r} & N_{\|l} + N_{\|r}
\end{bmatrix}
\]

(19)

If neglect the influence of nonlinear damping and uncertainty, the simplified ASV model on horizontal planar is
The ASV in this paper is differentially propelled, which means that both of the steer angle and the speed are controlled by two differential thrusters.

\[ r = \begin{bmatrix} F_l + F_r \\ 0 \\ (F_l - F_r) \times d \end{bmatrix} \]

where \( F_l \) and \( F_r \) are the port and starboard forces respectively, which are provided by differential thrust. \( d \) is the side hull separation (from hull centerline to ASV centerline).\(^{20}\)

For the case in this paper, the ASV maintains a constant speed, thus the force \( F_l \) and \( F_r \) can be expressed as

\[ F_l = F + \Delta F/2 \]
\[ F_r = F - \Delta F/2 \]

where \( F \) and \( \Delta F \) are magnitudes of the collective thrust differential thrust respectively. In this case, \( F \) is to control speed and \( \Delta F \) is to control the heading.

In addition, the heading controller in Figure 2 is PD controller,

\[ \delta = K_p \times (\theta - \theta_{\text{ref}}) + T_d \times r \]

where \( \delta \) is angle input for heading control; \( K_p \) is proportional gain and \( T_d \) is differential gain of heading controller; \( \theta \) and \( \theta_{\text{ref}} \) are current heading angle and desired reference heading angle respectively. \( r \) is yaw rate of ASV.

In this paper the ASV is traversing with a constant speed, thus the total virtual force is only used to steer the heading angle of ASV

\[ \theta_{\text{ref}} = \theta_{\text{att}} + \theta_{\text{rep}} \]

Where

\[ \theta_{\text{att}} = K_{\text{att}} \times (D_l - D_r) \]
\[ \theta_{\text{rep}} = K_{\text{rep}} \times F_{\text{rep}} \]

Results and Discussion

To verify the effectiveness of the proposed hybrid APF method, simulation is carried out under Matlab™ environment. The ASV in this paper is with length=1.5m, width=1m, height=0.5, weight=50kg (with batteries). The ASV model and path planning simulation is implemented in Marine System Simulator GNC toolbox which is developed by Fossen and Perez.\(^{21}\)

Figure 4 shows a part of a river from google map which is located in Nibong Tebal, Penang, Malaysia. This river 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. It is assumed that,

1. No shallow water
2. No rapids disturbance
3. Speed of water flow is from west to east (from left to right in Figure 4) with speed of 0.5m/s.

To construct the riverine environment for simulation, riverbank lines are extracted from Figure 4. The interval points of riverbank lines are interpolated from 1m to 0.1m for more accurate simulation results, and the sampling interval of simulation is 0.1s.

The ASV is expected to cruise in the center of this river, meanwhile avoiding all the stationary and dynamic obstacles in the river.

Two challenging scenarios with stationary and dynamic obstacles are conducted to check the
performance of the proposed hybrid APF path planning method. One is head-on situation and the other is overtaking. Thus we set a stationary and a moving ship in the river for simulation of these two situations.

**Simulation of head-on situation**

Figure 5 shows the simulation results of the head-on situation. There are one stationary obstacle and one moving ship in this scenario which are shown in red color. The stationary obstacle is located at (100, -150) with a diameter of 10m. The moving ship is the same size of ASV and the initial position is (1000, -130). The ASV is blue color which starts from point (10, 0). The dash line is the centerline of the river. Assume that both of the ASV and the moving ship are cruising in the center of the river, and the ASV is moving from west to east while moving ship from east to west. If without obstacle avoidance capability, the ASV and moving ship are supposed to encounter and collide because they are tracking along the same centerline of the river. Both the speed of the ASV and the moving ship are set at 2m/s. However, the ASV is following the river current (with speed of 0.5m/s) while moving ship is moving against the river current. The final speed of ASV is 2+0.5=2.5m/s, while the final speed of moving ship is 2-0.5=1.5m/s.

The relative position between the ASV and the obstacles are generally measured by on-board sensors, which may be inaccurate due to the noises and measurement errors. Thus we set the influence range of obstacles $\rho_o = 30m$, and take the size of ASV into account for the minimum feasible distances between the ASV and the obstacles.

At first, the ASV starts from the initial position and track along the centerline of river with a speed of 2m/s before it enters the influence range of the obstacles. At this time it is only steered by the attractive force which is generated by Equation (26). At time $t=6.5s$, the ASV enters the influence range of the stationary obstacle, and this obstacle generates a repulsive force to make ASV bypass for collision avoidance. At time $t=10s$, the ASV achieves the obstacle avoidance with a smooth path, and keeps going along the centerline of river. Then the ASV alters the course and keeps out of the waterway of the moving ship, while the moving ship still tracks along the centerline of river. After the ASV passing through the stationary obstacle and the moving ship, it is only affected by the attractive force again and keeps the original track. The complete path of the ASV from the start point to the final point is shown in Figure 5(c).

Figure 6(a) to Figure 6(d) show the navigation states of yaw rate, speed, yaw angle and input angle of differential thrusters, respectively. From Figure 6 we can see that there are three dramatic changes of the navigation states. These three navigation states changes are corresponding to three phases, i.e.
transient process, stationary obstacle avoidance and moving ship avoidance. The transient process is from 
\(t=0s\) to \(t=3.5s\), with the initial position \((10, 0)\) and speed \((0m/s)\) of the ASV. Another two navigation 
states changes are due to stationary and moving ship 
avoidance, which are from \(t=6.5s\) to \(t=11s\) and from 
\(t=30s\) to \(t=33s\), respectively. In particular, the speed 
of ASV is set a constant speed of \(2m/s\), the speed 
changes in Figure 6(b) is due to the dynamic model of 
ASV. In other phases, the ASV moves along the 
centerline of river, with a speed of \(2.5m/s\), and the 
yaw rate changes slightly to steer a smooth path of 
track keeping.

**Simulation of overtaking**

Figure 7 shows the simulation results of the 
overtaking situation. Same as the head-on situation, 
one stationary obstacle and one moving ship are set in 
this scenario. The stationary obstacle is still located at 
the position of \((100, -150)\) while the moving ship 
starts from \((200, -240)\). Both of the ASV and moving 
ship are cruising in the center of river, and following 
the river current with speed of \(2m/s\) and \(0.2m/s\) 
respectively. Taking the water flow speed into 
account, the final speeds of the ASV and the moving 
ship are \(2+0.5=2.5m/s\) and \(0.2+0.5=0.7m/s\) 
respectively. As shown in Figure 7, they may 
counter since the paths of the ASV and the moving 
ship are exactly the same. Thus the ASV is expected 
to overtake the moving ship and after that, it is 
supposed to keep the track until completion of the 
navigation.

Figure 7(a) shows the path of overtaking at \(t=10s\), 
where the ASV has successfully avoid the stationary 
obstacle, and the moving ship is moving along the 
centerline of the river. Figure 7(b) shows the process 
where ASV is overtaking the moving ship at \(t=20s\). 
We can see that the ASV alters the course and keep 
out of the waterway to overtake the moving ship. 
After that, the ASV turns back to the path of the 
centerline of the river and keeps going until
completing the path, which is shown in Figure 7(c). Since the model and controller are totally the same as the ASV and the moving ship, some part of the paths of the ASV and the moving ship is overlapped in Figure 7(c).

Figures 8(a) to Figure 8(d) show the navigation states of the overtaking situation. Same as the head-on situation, there are three dramatic changes when ASV is on the transient process, avoiding the stationary obstacle and the moving ship.

The transient process and stationary obstacle avoidance are the same in Figure 6 and Figure 8. However, the navigation states are different when
ASV avoids the moving ship. All of the navigation states change more dramatically in Figure 6 than in Figure 8. The reason is that the relative velocities are different in head-on and overtaking situations. Thus the performance of obstacle avoidance with different relative velocity will be discussed in the next section.

**Comparison of simulation results and discussion**

The original artificial potential field method is mostly applied in non-confined environment, such as the open sea. Thus the main contribution of this paper is to modify APF to make it suitable for the riverine environment, which has been discussed in previous sections. The proposed method is much different from other APF methods since the attractive force is replaced by the balance control scheme, and it is only suitable for corridor passage, such as the river waterway. The comparison of proposed method and other APF methods is not significant because they are applied to different situations.

To verify the effectiveness of the proposed method, the results are compared between the APF with and without relative velocity for both head-on and overtaking situations.

Figure 9 and Figure 11 show the simulation results of head-on and overtaking avoidance respectively, where relative velocity is not included. The results indicate that both of the APF methods (with and without relative velocity) are capable of avoiding collision, however, the collision avoidance performance is different. Figure 10 and Figure 12 are the corresponding navigation states.
To compare the collision avoidance performance, the maximal yaw rate change and closest distance between the obstacles and the ASV are listed in Table 1.

For the static obstacle, the head-on and the overtaking situations have the same performance. When relative velocity is included, the maximal yaw rate change is 27.8 deg/s, which changes from -13.4 deg/s to 14.4 deg/s, and the closest distance from the ASV to the static obstacle in avoidance process is 9.48m. Meanwhile, when relative velocity is not involved, the maximal yaw rate change is 19.9 deg/s (changes from -5.6 deg/s to 14.3 deg/s), and the closest distance from the ASV to the obstacle is 7.3m. The comparison shows that the original APF method has better avoidance performance for static obstacles, and the path in Figure 5(a) is smoother than path in Figure 9(a).
For moving ship collision avoidance, we can see that the ASV in Figure 5 makes a greater evasive maneuver than in Figure 9. The maximal yaw rate change in Figure 6(a) and Figure 10(a) are 23.6 deg/s and 7.14 deg/s, respectively. And the closest distance from the ASV to the moving ship is 14.9m and 9.6m respectively. For the overtaking situation, the comparison can be seen in Figure 7 and Figure 11. In Figure 11(b) we can see that the ASV is very close to the moving ship at t=18.4s, and the distance at this moment is only 2.2m which means that the collision risk is quite high. Collision is very possible to happen for this case due to measurement errors or other factors. Because the distance is very short, the repulsive force from the moving ship becomes very large and it makes the ASV bypass the moving ship with a quite big maneuver. Besides, the path of avoidance appears overshoot.

From the comparison we can see that, the original APF method is suitable for static obstacle avoidance, however, collision may happen with moving obstacles in some case. While the modified APF method, which includes relative velocity in the formula, is suitable for dynamic obstacles avoidance.
Obstacles avoidance performance with different relative velocities

From Equation (2) we can see that the ASV is always affected by the attractive force to keep it in the center of the river, which is related to the distances from the ASV to the left and right side of the riverbanks. As illustrated in Equation (5), the repulsive force includes two parts of relative position and relative velocity and it determines the obstacle avoidance performance.

For head-on and overtaking situation, the relative velocities between the ASV and the stationary obstacle are both 2.5m/s which equal to the real speed of the ASV, so the navigation states are the same when the ASV avoids the stationary obstacle. However, the relative velocities are different when ASV avoids the moving ship in head-on and overtaking situations. In head-on situation, the relative velocity between the ASV and the moving ship is the sum of the ASV speed and the moving ship speed, which equals to 2.5+1.5=4m/s. While in overtaking situation, the relative velocity is the result of moving ship speed subtracted from ASV speed, which equals to 2.5-0.7=1.8m/s. The relative velocity between the ASV and the moving ship in head-on situation is greater than the relative velocity in overtaking situation, this is the reason why the navigation states in Figure 6 change more dramatically than in Figure 8.

To verify the obstacle avoidance performance with different relative speeds, the comparison is listed in Table 2 for head-on and overtaking situations respectively. The speed of ASV is set to 2m/s, while the speed of moving ship varies from 1.6m/s to 2m/s for head-on situation, and varies from 0.2m/s to 0.6m/s for overtaking situation. Taking the water flow speed (0.5m/s) into account, the relative speed between the ASV and the moving ship varies from 3.6m/s to 4m/s for head-on situation, and varies from 1.8m/s to 1.4m/s.

Besides the four navigation states that illustrated in Figure 6 and Figure 8, the nearest distance from the ASV to the moving ship is also listed. The nearest distance from the ASV to the moving ship denotes how much the ASV needs to deviate from the original path when ASV passes through the moving ship, and so as the variation ranges of other four navigation states. All the five parameters are extracted only when ASV avoids the moving ship.

From the comparison of Table 2 and Table 3 we can see that the nearest distance, variation range of yaw rate, variation range of yaw angle and variation range of input angle for head-on situation are greater than that of the overtaking one. While the minimum speed of ASV for head-on is less than overtaking. As discussed above, this is because that the relative velocity is different for head-on and overtaking situations. This means that the ASV needs to deviate more from the original path to pass through the moving ship if the relative velocity is greater. However, the minimum speed of ASV is approximately close to the desired speed of the two scenarios, which means that ASV basically maintains a constant speed when avoiding the moving ship. This way of steering makes the ASV pass through the moving ship fast and keep a smooth path.

<table>
<thead>
<tr>
<th>Speed of moving ship (m/s)</th>
<th>Relative speed (m/s)</th>
<th>Nearest distance (m)</th>
<th>Variation range of yaw rate (degree/s)</th>
<th>Minimum Speed (m/s)</th>
<th>Variation range of yaw angle (degree)</th>
<th>Variation range of Input angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>3.6</td>
<td>16.68</td>
<td>20.8</td>
<td>2.35</td>
<td>53.97</td>
<td>28.48</td>
</tr>
<tr>
<td>1.7</td>
<td>3.7</td>
<td>18.64</td>
<td>19.61</td>
<td>2.37</td>
<td>53.27</td>
<td>26.59</td>
</tr>
<tr>
<td>1.8</td>
<td>3.8</td>
<td>17.71</td>
<td>20.47</td>
<td>2.35</td>
<td>65.32</td>
<td>27.79</td>
</tr>
<tr>
<td>1.9</td>
<td>3.9</td>
<td>16.38</td>
<td>21.61</td>
<td>2.33</td>
<td>72.93</td>
<td>29.43</td>
</tr>
<tr>
<td>2.0</td>
<td>4</td>
<td>14.89</td>
<td>22.84</td>
<td>2.3</td>
<td>80.66</td>
<td>31.32</td>
</tr>
</tbody>
</table>
Table 3—Navigation states of ASV with different relative speed for overtaking situation

<table>
<thead>
<tr>
<th>Speed of moving ship (m/s)</th>
<th>Relative speed (m/s)</th>
<th>Nearest distance (m)</th>
<th>Variation range of yaw rate (degree/s)</th>
<th>Minimum Speed (m/s)</th>
<th>Variation range of yaw angle (degree)</th>
<th>Variation range of Input angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1.8</td>
<td>7.28</td>
<td>17.46</td>
<td>2.4</td>
<td>67.25</td>
<td>24.18</td>
</tr>
<tr>
<td>0.3</td>
<td>1.7</td>
<td>5.97</td>
<td>15.6</td>
<td>2.42</td>
<td>72.3</td>
<td>22.2</td>
</tr>
<tr>
<td>0.4</td>
<td>1.6</td>
<td>5.13</td>
<td>14.88</td>
<td>2.43</td>
<td>65.56</td>
<td>20.81</td>
</tr>
<tr>
<td>0.5</td>
<td>1.5</td>
<td>4.35</td>
<td>10.97</td>
<td>2.44</td>
<td>49.28</td>
<td>15.38</td>
</tr>
<tr>
<td>0.6</td>
<td>1.4</td>
<td>3.09</td>
<td>11.15</td>
<td>2.42</td>
<td>53.34</td>
<td>13.85</td>
</tr>
</tbody>
</table>

**Conclusion**

In this paper, a hybrid artificial potential field method is proposed for the ASV path planning in the riverine environment with stationary and dynamic obstacles. To achieve the simultaneous riverine cruise and obstacles avoidance, a balance control scheme is used as the attractive potential and combined with artificial potential field. Instead of onboard sensing, the relative velocity between the ASV and the moving obstacle is derived from relative position, which simplifies the sensing system and is easier for implementation. The simulation results of head-on situation and overtaking situation demonstrate that the proposed method is effective for riverine path planning and obstacles avoidance. The obstacle avoidance performance with different relative velocities is also discussed and this article also illustrates the steering performance when ASV passes through the moving ship with different speeds.

**Acknowledgment**

Authors would like to express sincere thanks for the support given to this research by Hebei University, China and Universiti Sains Malaysia (USM).

**References**


