Fuzzy-based potential field collision avoidance technique for unmanned surface vehicles

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Abstract
Collision avoidance is a crucial part of the autonomous operation of an unmanned surface vehicle (USV), especially in a dynamic environment. This work presents a fuzzy-based potential field algorithm for collision prevention when a USV encounters an obstacle, either moving or static. Two types of repulsive potential functions are employed. The Gaussian repulsive potential is applied to repel the own ship (OS) away from the target ship (TS). On the other hand, the vortex potential function is used to smoothly deviate the heading of the OS towards the side that quickly resolves the collision. The fuzzy membership functions and rules are imposed to classify the encounter condition and apply the appropriate potential functions accordingly. Head-on and crossing encounter scenarios are simulated to demonstrate the performance of the proposed algorithm. The simulation results have shown that, when the collision is detected, the algorithm is effective in generating the vector field that directs the OS away from the collision path. Once the collision is resolved, the algorithm lets the OS continue the original course.

Keywords: Collision avoidance, USV, Fuzzy, Potential field, APF

1. Introduction
The development of collision avoidance systems not only can potentially help human navigators to react promptly and make a better judgement but also is a key component toward autonomous navigation of unmanned surface vehicles (USVs). An overview of the collision avoidance techniques for both manned and unmanned vessels has been presented by [1]. A potential roadmap to transform a manned ship into a fully autonomous ship was also discussed in this work.

In the literature, the collision avoidance can broadly be classified into global methods and local methods. The global methods seek for an optimal path that is collision-free and leads a USV from the start location to the desired destination [2,3,4]. The main drawback of this framework is that it needs complete knowledge of the environment. If anything changes, the global pathfinder needs to update the map and replan the path accordingly. Since an intensive computational power is required for updating the map and replanning the path, the global method may not be suitable for real-time collision avoidance, especially in a critical encounter scenario.

Artificial potential field (APF) is widely used for a local collision avoidance [5,6]. In this regard, the ship under our control is typically referred to as the own ship (OS); the other ship that the OS would
potentially make physical contact with at a certain time in the future is called the target ship (TS). The principle of the APF is to consider the OS as a particle under the influence of the artificial force field. The goal destination is virtually assigned with the long-range attractive potential that pulls the OS toward it, whereas the obstacle is assigned with the virtual short-range repulsive potential that repels the OS away. The collision-free path is then established by following the gradient of the resulting vector field. However, the APF approach does not guarantee a feasible solution because the gradient of the APF may lead the OS to the local trap instead of the destination [7]. A few methods to overcome the local trap of the APF were discussed in [8,9,10]. As an alternative to the traditional potential functions, [11] has suggested using a vortex function to evade the obstacle and a dipole function to make the OS converges to the desired path. A simulation study was presented to demonstrate the applicability of the concept.

Instead of blindly repelling the OS away from the TS, the velocity obstacle (VO) concept is adopted to evaluate the collision risk between the two vessels and execute the evasive action only when it is needed. In the VO concept, a collision is detected when the following conditions are met simultaneously: 1) the relative distance between the vehicles is smaller than a predefined threshold, and 2) the projection of the relative velocity vector from the OS intercepts with the safety circle of the TS. The collision can be resolved by changing speed and course of the OS so the relative velocity vector is pointing outside the collision cone [12, 13, 14].

Fuzzy logic is another framework that is employed by many researchers for developing marine collision avoidance algorithms [15, 16]. Mostly, the relative distance and bearing between the two ship are used to describe the encounter condition. However, more membership functions may be developed to accurately described the encounter condition (i.e., head-on, crossing, or overtaking) as well as the role of the OS (i.e., stand-on or give-way) [17, 18]. Then, the if-then rules are applied to interpret the linguistic variables and determine the deviation angle of the OS. The COLREGs rules [19] may be incorporated into the fuzzy inference system so the evasive action of the OS complies with the marine rules of the road.

This work presents a collision avoidance algorithm that combines the APF with the fuzzy logic. Section 2 explains the repulsive potential functions for collision prevention. The fuzzy membership functions and the inference system are developed in Section 3. This is followed by the simulation results in Section 4 and conclusion in Section 5.

2. Repulsive Potential Functions

Two repulsive potential functions are employed for collision avoidance. The first function is the Gaussian repulsive potential that repels the OS away from the TS. (This function is regarded as the STAY CLEAR action in Section 3.) The advantageous of this function is that its magnitude and range can be controlled more effectively when compared to the conventional FIRAS function [9]. The Gaussian repulsive potential and its derivative are as follows [10]:

$$U_g = c_g \exp \left(-\frac{||d||}{l_g}\right),$$  

$$\nabla U_g = -c_g \frac{d}{l_g} \exp \left(-\frac{||d||}{l_g}\right) \left[\frac{\partial d}{\partial x} \frac{\partial d}{\partial y}\right].$$

Here, the vector $d$ denotes the relative distance between the two vessels. The magnitude and effective range of the Gaussian potential function is defined by $c_g$ and $l_g$, respectively.

The second function is the vortex repulsive potential. Depending on the encounter condition, the vortex function generates either clockwise or counter-clockwise spinning force field that deviates the heading of the OS away from the collision path. (This function is regarded as the VORTEX_CW and VORTEX_CCW actions in Section 3.) The vortex potential function and its derivative are modified from [11,20] as presented below:
\[ U_v = c_v \exp \left( \frac{-|d|}{l_v} \right), \]  
\[ \nabla U_v = -\tau c_v \frac{l_v}{l_v} \exp \left( \frac{-|d|}{l_v} \right) \left[ -\frac{\partial d}{\partial y}, \frac{\partial d}{\partial x} \right]^T, \]

where \( c_v \) and \( l_v \) are used for controlling the strength and the effective range of the vortex function. The parameter \( \tau \) is set to either \(-1\) for a clockwise vortex or \(1\) for a counter-clockwise vortex.

3. Fuzzy logic decision-making
The fuzzy logic framework helps to design which potential function should be used when the collision is detected in different encounter conditions; otherwise, it lets the OS keep course and speed when the path is collision-free. To this end, the encounter situation between the two vessels is characterised by two membership functions: 1) relative distance and 2) encounter angle. (As illustrated in Figure 1.)

![Figure 1](image_url)

**Figure 1.** Illustration of the relative distance and the encounter angle for describing the encounter condition between the two vessels

3.1 Relative distance membership function
Two concentric circles are located over the OS and divide the space into three zones. The safe zone (i.e., \( d > d_{wr} \)) represents the condition where there is plenty of space between the two vessels; hence, the collision is not a concern. The TS could potentially be a thread if it is inside the warning zone (i.e., \( d_{wr} \geq d > d_{cr} \)), and the avoidance action may be triggered depending on the encounter condition. However, if the TS is inside the critical zone (i.e., \( d_{cr} \geq d \)), the OS would try its best to stay clear and maintain a safe distance between the two vessels. These zones can be defined as a fuzzy membership function as shown in Figure 2.
3.2 Encounter angle membership function

The collision cone and the relative velocity vector are used for classifying the likelihood of the collision. In this regard, the cone is defined to have its apex at the TS and with the two sides of the cone tangential to the boundary of the critical zone of the OS [12], as illustrated in Figure 1. The half-apex angle of the collision cone is: \( \alpha = \sin^{-1}(d_{cr}/d) \). For the relative velocity between the two vessels, it is denoted by \( V_{TO} = V_{TS} - V_{OS} \), where \( V_{TS} \) and \( V_{OS} \) are the velocity vectors of the TS and the OS, respectively. The likelihood of the collision is determined according to the encounter angle, \( \theta \), which is the angle that \( V_{TO} \) makes to the centreline of the collision cone. The collision is identified as likely positive (LIKELY_P) when \( \alpha \geq \theta \geq 0 \). Likewise, it is said to be likely negative (LIKELY_N) when \( 0 > \theta \geq -\alpha \). These two likelihood sets help to decide which side the OS should deviate to quickly resolve the collision. Otherwise, the collision is recognised as unlikely for \( \theta \) that is not contained inside the collision cone. The fuzzy membership function that represents the collision likelihood w.r.t. the collision angle is given in Figure 3.

3.3 Determining avoidance action

The two fuzzy membership functions described above are used to identify the encounter condition. Then, the if-then rules are developed here to determine the appropriate avoidance actions accordingly. For example, if the distance is SAFE, then there is nothing to worry about, i.e., the ship would keep going on the desired track with the TRACK-KEEPING action. The same thing applies when the distance is WARNING but the collision is UNLIKELY. However, if the distance is WARNING and the collision is either LIKELY_P or LIKELY_N, then the appropriate VORTEX is triggered to steer the OS away on the side that quickly resolves the collision with the TS. Lastly, When the distance is CRITICAL, the rules trigger the STAY CLEAR action, or even discard the TRACK-KEEPING action in order to prioritise the safety over the progress on the path following. These if-then rules are summarised in Table 1. The total potential gradient that affects the OS is computed from the rules as follows:
\[ \nabla U = K_a \nabla U_a + K_g \nabla U_g + K_{v,CCW} \nabla U_{v,CCW} + K_{v,CW} \nabla U_{v,CW} \]  

(5)

where

\[ K_a = R_1 + R_2 + R_3 + R_4 + R_5 \]  

(6)

\[ K_g = R_5 + R_6 + R_7 \]  

(7)

\[ K_{v,CCW} = R_3 + R_6 \]  

(8)

\[ K_{v,CW} = R_4 + R_7 \]  

(9)

As can be noted, the vector \( \nabla U_a \) is the gradient of the attractive potential that guides the OS to the desired heading and speed. This vector is assumed a constant during the simulation.

Table 1. If-then rules for the fuzzy inference system.

| Rule | if     | Distance is | and | Collision is | then do        | Action 1       | and | Action 2 |
|------|--------|-------------|-----|--------------|----------------|----------------|-----|----------|
| R1   | if     | SAFE        | -   | -            | then do TRACK-KEEPING | -              | -   | -        |
| R2   | if     | WARNING     | and | UNLIKELY     | then do TRACK-KEEPING | -              | -   | -        |
| R3   | if     | WARNING     | and | LIKELY_P     | then do TRACK-KEEPING | and VORTEX CCW |     |          |
| R4   | if     | WARNING     | and | LIKELY_N     | then do TRACK-KEEPING | and VORTEX CW  |     |          |
| R5   | if     | CRITICAL    | and | UNLIKELY     | then do TRACK-KEEPING | and STAY CLEAR |     |          |
| R6   | if     | CRITICAL    | and | LIKELY_P     | then do STAY CLEAR | and VORTEX CCW |     |          |
| R7   | if     | CRITICAL    | and | LIKELY_N     | then do STAY CLEAR | and VORTEX CW  |     |          |

4. Results and discussion

Two cases of the simulation studies were implemented in MatLab to evaluate the resulting potential field that was generated by the proposed fuzzy-based collision avoidance framework. In the first case, the TS was set to travel north at the speed of 1 m/s whereas the OS travelled south at the speed of 2 m/s. Zone #1 in Figure 4 represents the situation where the two vessels encounter head-on, as well as where the OS encounters a static obstacle. When the TS was outside the critical zone, the vector field smoothly deviated the OS heading aside so the relative velocity vector pointed outside the collision cone and the OS smoothly circumvented the TS.

However, the vector field was stronger if the TS was inside the critical zone. In this case, the resulting vector field not only deviated the OS heading but also repelled it from the TS to ensure the safe distance between the two vessels. The OS did not need to worry about the collision if it was abaft of the TS because the two vessels were going apart (see zone #2 in Figure 4); in this regard, the vector field let the OS continue going south at the desired speed.
Figure 4. Vector field of the first scenario for a different state of the OS whereas the TS is fixed at the centre (the OS speed = 2 m/s, heading south; the TS speed = 1 m/s, heading north).

The second scenario represented the situation where the two vessels were crossing. Both vessels were set to travel at the speed of 2 m/s, but the OS was set to go east whereas the TS was set to go north. The diagonal dashed line in Figure 5 indicates the condition where the relative velocity vector directly led the OS to collide with the TS. Below the dashed line, zone #1 in Figure 5, the collision likelihood is identified as LIKELY_P. In this case, the CCW vortex potential was applied, inducing the OS to pass the TS from behind. Furthermore, if the OS got too close to the TS, the Gaussian repulsive potential component kicked in to also keep the clear distance between the two vehicles.

Zone #2 in Figure 5 was where the collision likelihood was recognised as LIKELY_N, so the OS was induced to speed up and pass in front of the TS because this is the quickest way to get the relative velocity vector outside the collision cone. However, one can argue that this may increase the risk of collision, especially when the OS cut in front of the TS at the close distance. More membership functions and fuzzy rules should be added to deal with this situation more delicately. Once the collision risk has relieved, the strength of the repulsive potential decayed so the OS can continue the original course and speed.

Figure 5. Vector field of the first scenario for a different state of the OS whereas the TS is fixed at the centre (the OS speed = 2 m/s, heading east; the TS speed = 2 m/s, heading north).
5. Conclusion
This work developed a fuzzy-based potential field collision avoidance framework for preventing an unmanned surface vehicle from crashing into another vessel or an obstacle. The basic idea is to use two fuzzy membership functions to classify the encounter condition between the two vessels. In addition, the fuzzy rules are developed to appropriately apply the potential functions in order to guide the own ship away from the collision path. The proposed framework has been demonstrated by the simulation to be effective for collision prevention. Once the collision has been resolved, the algorithm then lets the vehicle continue its original course and speed.

In the current state of this research, it is assumed that the state of the other vessel does not change, and the owner is the one that is entirely responsible for collision prevention. The future work will be focusing on developing membership functions and adding more fuzzy rules to make the algorithm COLLEGs compliance and be able to handle more complex encounter situations.

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