A COLREG-compliant Local Path Planning for Unmanned Surface Vehicle

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***Abstract*—This paper proposes a COLREG-compliant Artificial Potential Field (C-APF), a path planning method for Unmanned Surface Vehicles (USVs) that simultaneously ensures compliance with Convention on the International Regulations for Preventing Collisions at Sea (COLREG). The proposed method consists of COLREG-compliant local path planning using a Dynamic Potential Field mathematically modeled based on COLREG to generate collision avoidance paths in encounter scenarios such as Head-on and Crossing situations. The potential fields generated in the local planning stage are then integrated into a single unified potential field, enabling path planning that ensures collision avoidance safety.**

***Index Terms*—Unmanned Surface Vehicle, Path Planning, COLREG, Artificial Potential Field, Collision Avoidance.**

I. Introduction

Unmanned Surface Vehicles (USVs) have become increasingly important in maritime domains such as transportation, oceanographic surveys, surveillance, and search and rescue. As their roles continue to expand, ensuring the reliability, safety, and efficiency of autonomous navigation has emerged as a key research focus [1].

In real-world operations, USVs must navigate complex and dynamic marine environments characterized by waves, currents, winds, and moving obstacles. To operate safely and efficiently under such conditions, they require a real-time path planning system that balances energy consumption with collision avoidance [2].

A critical element of safe maritime navigation is compliance with the COLREG [3], which defines maneuvering rules for scenarios such as head-on encounters, crossings, and overtaking. However, many existing collision avoidance approaches struggle to quantitatively embed these rules into planning algorithms, limiting their reliability in actual deployments. Consequently, there is a growing demand for planning methods that account for both COLREG compliance and dynamic obstacle avoidance.

Various path planning techniques have been developed to address this need, ranging from rule-based to learning-based approaches. Among rule-based methods, the Velocity Obstacle (VO) [4], Dynamic Window Approach (DWA) [5], and Artificial Potential Field (APF) [6] are widely used. VO determines safe velocity vectors by avoiding predicted collisions, but it may introduce new conflicts when multiple obstacles are present. DWA generates paths through velocity sampling but tends to produce overly conservative trajectories in dense environments. APF generates intuitive paths by combining attractive and repulsive forces but is prone to local minima that can trap the vehicle or cause instability.

To overcome these limitations, Deep Reinforcement Learning (DRL) has attracted attention for its ability to learn adaptive avoidance strategies through simulation. DRL considers long-term safety and performs well in nonlinear, uncertain environments. However, such models often lack interpretability, and their robustness under untrained or unexpected scenarios remains difficult to guarantee, especially in real-time maritime operations.

Building upon this motivation, we propose C-APF method. This approach extends the traditional APF framework, which offers computational efficiency and modularity suitable for

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onboard implementation. The C-APF introduces rule-based collision avoidance by incorporating the following novel potential functions:

- COLREG-Compliant Potential (CCP): Ensures safe navigation by mathematically modeling the encounter rules defined in COLREG.

The main contributions are as follows:

- A collision avoidance strategy compliant with COLREG using potential fields.
- Simulation-based validation demonstrating improved safety and regulatory compliance across varied environmental conditions.

II. Methodology

A. System Overview

C-APF is a method that incorporates quantitative COLREG compliance for safe and reliable maritime navigation.

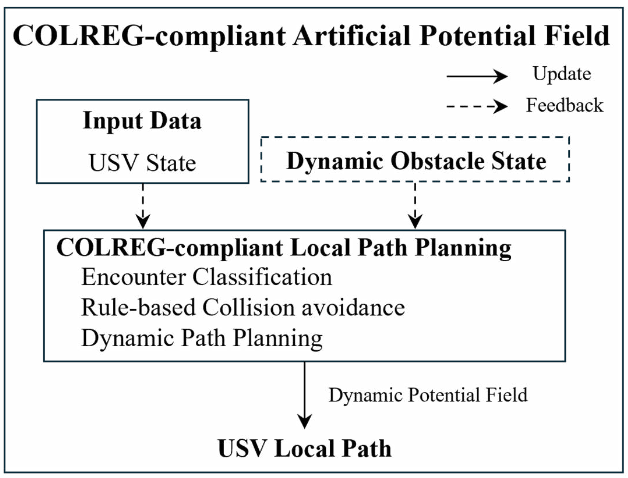

Fig. 1. System diagram of C-APF.

As shown in Fig. 1, C-APF method consists of a core module and a set of input data. When dynamic obstacles are detected during navigation, the COLREG-compliant Local Path Planning module classifies the encounter scenario and generates the COLREG-Compliant Potential (CCP) accordingly, enabling safe avoidance. Dynamic Potential Field from the local path planning facilitates the generation of a local path for the USV that guarantees COLREG-compliant collision avoidance during navigation.

B. COLREG-compliant Local Path Planning

CCP guides evasive maneuvers based on encounter types, enabling real-time, COLREG-compliant local path generation within the APF framework.

As illustrated in Fig. 2, five representative COLREG encounter scenarios are considered: (a) Head-on, (b) Crossing from the starboard side, (c) Crossing from the port side, (d-e) Overtaking. G represents the give-way vessel, while S represents the stand-on vessel. In scenarios C and D, the own ship acts as the stand-on vessel according to COLREG; therefore, no separate path planning is required. In contrast, scenarios A and B correspond to give-way vessel situations and are considered in the path planning process.

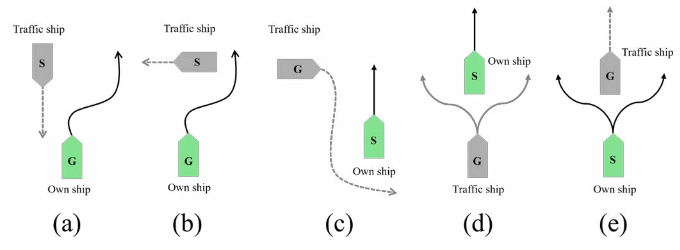

Fig. 2. Main COLREG scenarios.

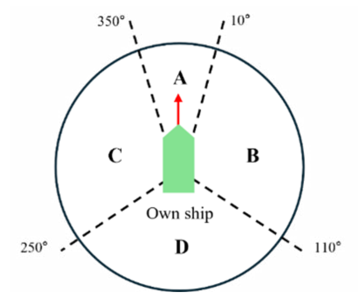

Fig. 3. Region surrounding the own ship.

The region around the own ship is divided into four sectors (A, B, C, D) as shown in Fig. 3, based on the relative bearing between the own ship and nearby ships, which are then used to determine the encounter type. In this study, only situations where the traffic ship enters regions A or B are considered, as the own ship has the right-of-way in regions C and D and can maintain its current heading.

In general ship intersections, the risk of collision between the own ship $(\mathrm{x_t}, \mathrm{y_t})$ and the traffic ship $(\mathrm{x'_t}, \mathrm{y'_t})$ is evaluated using Time to Closest Point of Approach (TCPA) T and Distance at Closest Point of Approach (DCPA) D [7]:

$$\mathrm{T} = -\frac{(\mathrm{y'_t} - \mathrm{y_t})(\mathrm{v'_y} - \mathrm{v_y}) + (\mathrm{x'_t} - \mathrm{x_t})(\mathrm{v'_x} - \mathrm{v_x})}{(\mathrm{v'_y} - \mathrm{v_y})^2 + (\mathrm{v'_x} - \mathrm{v_x})^2}, \quad (1)$$

$$\mathrm{D} = \sqrt{\left[(\mathrm{y'_t} - \mathrm{y_t}) + (\mathrm{v'_y} - \mathrm{v_y}) \cdot \mathrm{T}\right]^2 + \left[(\mathrm{x'_t} - \mathrm{x_t}) + (\mathrm{v'_x} - \mathrm{v_x}) \cdot \mathrm{T}\right]^2}, \quad (2)$$

A collision risk is considered to exist when TCPA is positive and less than 60 seconds, and DCPA falls below ρ_0, reflecting a realistic time window for evasive maneuvering. When the obstacle is located in region A or B, CCP is defined as follows:

$$U_{\mathrm{COLREG}} = \begin{cases} U_{\mathrm{HO}}, & \text{if } \mathbf{p}'_t \in \mathrm{A} \\ U_{\mathrm{CR}}, & \text{if } \mathbf{p}'_t \in \mathrm{B}, \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$\mathbf{p}'_t$ denotes the position of the traffic ship. If the obstacle is in region A, the situation is considered Head-on, and U_{COLREG} is defined as U_{HO}. If the obstacle is in region B, indicating Cross from the starboard side, U_{COLREG} is defined as U_{CR}:

$$U_{\text{HO}} = \begin{cases} \frac{1}{2}k_{\text{HO}}\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)^2, & \text{if } \rho < \rho_0 \\ 0, & \text{if } \rho \geq \rho_0 \end{cases}, \tag{4}$$

$$U_{\text{CR}} = \begin{cases} \frac{1}{2}k_{\text{CR}}\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)^2, & \text{if } \rho < \rho_0 \\ 0, & \text{if } \rho \geq \rho_0 \end{cases}, \tag{5}$$

where k_{HO} and k_{CR} are gain parameters for Head-on and Cross from the starboard scenarios, respectively, and ρ is the actual distance between the two ships, while ρ_0 is the safety distance. To prevent collisions in these scenarios, repulsive force $\mathbf{F}_{\text{COLREG}}$ are defined using the gradient of U_{COLREG} in the preferred evasion direction $\mathbf{u}_{\text{r}}(\theta_{\text{r}})$:

$$\mathbf{F}_{\text{HO}} = |-\nabla U_{\text{HO}} \cdot \mathbf{u}_{\text{r}}(\theta_{\text{r}})| \cdot \mathbf{u}_{\text{r}}(\theta_{\text{r}}), \tag{6}$$

$$\mathbf{F}_{\text{CR}} = \frac{1}{\|-\nabla U_{\text{CR}}\| + \varepsilon} \cdot \mathbf{u}_{\text{r}}(\theta_{\text{r}}), \tag{7}$$

$$\mathbf{u}_{\text{r}}(\theta_{\text{r}}) = \begin{bmatrix} \cos\theta_{\text{r}} & -\sin\theta_{\text{r}} \\ \sin\theta_{\text{r}} & \cos\theta_{\text{r}} \end{bmatrix} \cdot \frac{\mathbf{v}}{\|\mathbf{v}\|}, \tag{8}$$

$\mathbf{u}_{\text{r}}(\theta_{\text{r}})$ is the unit vector in the preferred evasion direction, with θ_{r} defined as the starboard side. This directional repulsive force guides the own ship away from obstacle based on its relative location, generating safe avoidance path in accordance with COLREG.

The attractive potential is formulated by the following equation:

$$U_{\text{A}} = \frac{1}{2}k_{\text{A}}\left(\mathbf{p} - \mathbf{p}_{\text{G}}\right)^2, \tag{9}$$

$\mathbf{p}_{\text{G}}$ is the position of the goal, and $\mathbf{p}$ is the position of the USV.

To generate a locally COLREG-compliant path under dynamic conditions, Dynamic Potential Field U_{SD} is constructed by summing two components: CCP U^i_{COLREG} from each traffic ship and the attractive potential U_{A} toward the goal:

$$U_{\text{SD}} = \left(\sum_i U^i_{\text{COLREG}}\right) + U_{\text{A}}, \tag{10}$$

Total force applied to the USV is then computed as the negative gradient of the combined field:

$$\mathbf{F}_{\text{SD}} = \left(\sum_i \mathbf{F}^i_{\text{COLREG}}\right) + \mathbf{F}_A, \tag{11}$$

This force determines the USV's direction, enabling safe and COLREG-compliant local avoidance of dynamic obstacles.

III. Simulation Results

To validate the performance of the proposed C-APF, a comparative simulation was conducted against the traditional APF. The simulation environment was built using Virtual RobotX (VRX) Gazebo [8], allowing for various scenarios including not only dynamic obstacles but also environmental factors such as ocean currents and waves.

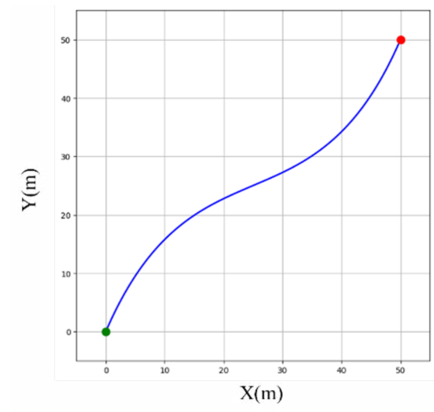

Fig. 4. Path Scenario used in the experiment.

As illustrated in Fig. 4, a single representative scenario were designed using S-shaped path. The USV was controlled using a propeller-based model to reflect realistic propulsion characteristics, and velocity and directional commands were applied independently. The mission concluded once the USV reached the target.

TABLE I
Current Data Specifications

No.	Direction (rad)	Velocity (m/s)
1	*0.0*	*8.041*
2	*0.5*	*6.56*
3	*1.57*	*10.18*
4	*-0.3*	*4.78*
5	*3.14*	*12.22*

The performance of C-APF under various ocean conditions was evaluated by applying five different current conditions in the simulation. In the straight path, both Head-on and Crossing from the starboard side situations were configured. In the curved path, only Crossing from the starboard side situation was considered. For the S-shaped path, a complex encounter situation was designed, where two dynamic obstacles simultaneously approached the USV in Head-on and Crossing from the starboard side. In each scenario, all dynamic obstacles moved at 1.0 m/s.

Fig. 5 visualizes the trajectories of the USV and dynamic obstacles under Head-on and Crossing from the starboard side situations in current condition 1. Specifically, Fig. 4(a) shows the trajectory generated using the traditional APF, while Fig. 4(b) shows the proposed C-APF's trajectory. C-APF generates the avoidance path only when both T and D meet the

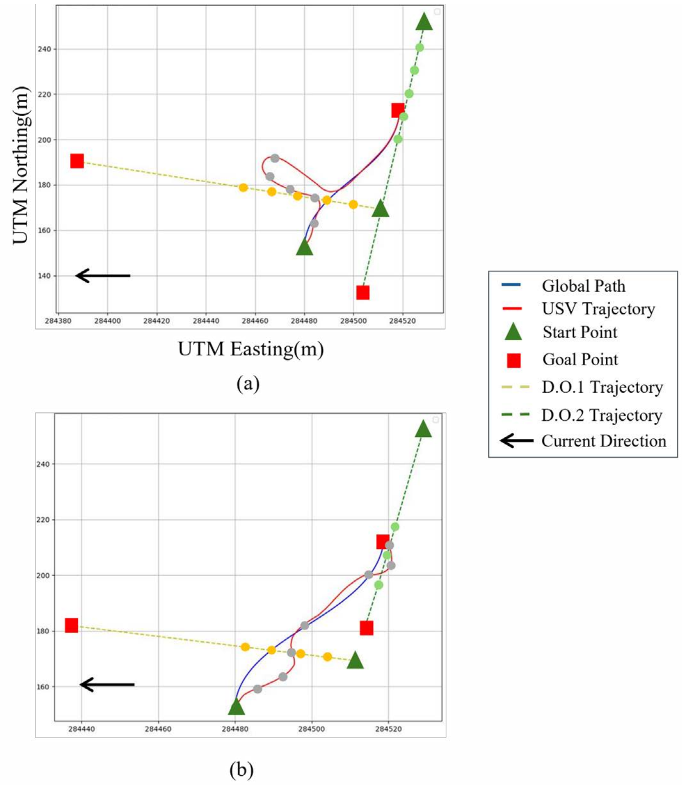

Fig. 5. Trajectory visualization in a USV mission scenario.

collision risk criteria, resulting in fewer unnecessary avoidance maneuvers compared to the traditional APF.

IV. Conclusion

This paper presents C-APF, a local path planning method that enhances traditional APF by embedding COLREG for safe dynamic obstacle avoidance. It ensures reliable collision avoidance during USV missions while adhering to maritime navigation rules. Simulation results show that C-APF successfully avoided collisions without unnecessary detours and outperformed the traditional APF in terms of maneuver smoothness and rule COLREG compliance.

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