CORLEGS BASED ADVANCED NAVIGATION SYSTEM FOR UNMANNED SURFACE VESSELS

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WHAT WE PROPOSE?

- As maritime autonomy advances, the need for safe, efficient, and COLREGs-compliant navigation in increasingly complex environments is more critical than ever.
- Most USVs are still operated in "remote control" mode, with a human operator navigating them from a nearby station.
  - This is primarily due to the challenges associated with fully autonomous operation, which relies on Artificial Intelligence for navigation and decision-making.
- **A two-stage approach:**
  - ❑ Dynamic Collision Avoidance
  - ❑ Compliance with CORLEGs (International Maritime Collision Regulations)

OUTLINE

Introduction

Contribution

Problem Definition, Assumptions and Notations

The Proposed Approach

Experiments

INTRODUCTION

[1] Y. Wang, X. Yu, X. Liang, and B. Li, "A COLREGs-based obstacle avoidance approach for unmanned surface vehicles," *Ocean Eng.*, vol. 169, pp. 110–124, 2018

- Limitations of Traditional Methods:
  - Based on ground vehicles (e.g. AGVs)
  - Ignore USV-specific kinematics, environmental forces
  - Lack CORLEGs compliance in real-world maritime settings
- Recent efforts in motion planning for Unmanned Surface Vessels (USVs) have focused on ensuring compliance with COLREGs to enable safe and predictable navigation in complex maritime environments.
- One notable method involves generating navigation waypoints using bell-shaped curves [1] derived from normal distribution functions.
  - This strategy allows for smooth trajectory shaping and provides guidance to the USV controller that aligns with collision avoidance standards.

INTRODUCTION

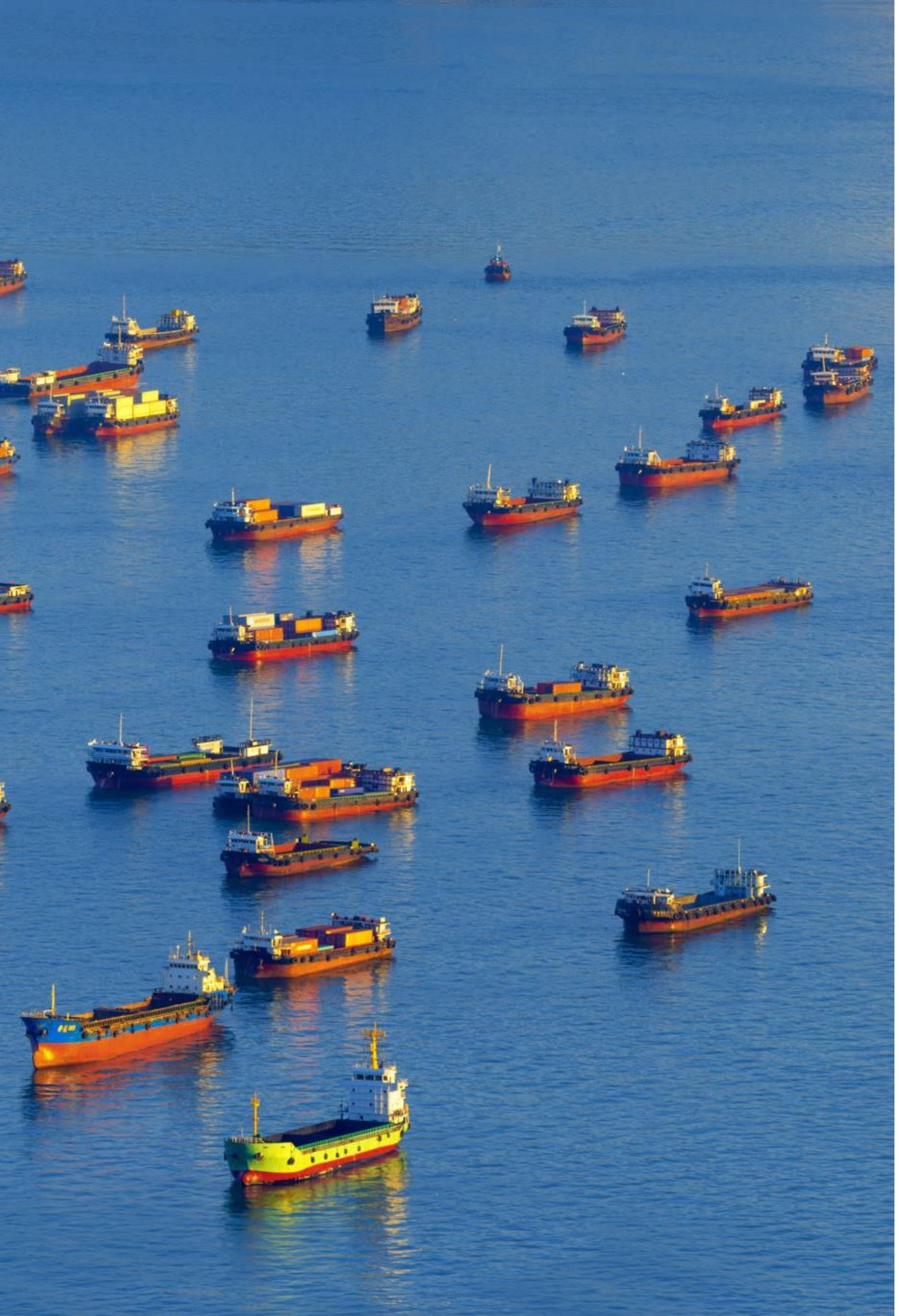
[2] X. Xu, Y. Lu, X. Liu, and W. Zhang, "Intelligent collision avoidance algorithms for USVs via deep reinforcement learning under COLREGs," *Ocean Eng.*, vol. 217, no. 107704, p. 107704, 2020.
[3] A. L. Song, B. Y. Su, C. Z. Dong, D. W. Shen, E. Z. Xiang, and F. P. Mao, "A two-level dynamic obstacle avoidance algorithm for unmanned surface vehicles," Ocean Eng., vol. 170, pp. 351–360, 2018.

- **Deep reinforcement learning** [2] has also been explored as a means of developing intelligent, adaptive collision avoidance systems.
  - These models can learn to extract relevant state features from the environment and make navigation decisions that conform to COLREGs.
  - However, such approaches face challenges in scalability and reliability, particularly as the number of Interacting vessels increases and the state space becomes more complex.
- Other researchers have proposed hybrid systems that combine multiple planning techniques.
- For instance, a two-level dynamic obstacle avoidance framework [3] integrates the **Velocity Obstacle (VO) algorithm** for standard, non-critical situations with the **Artificial Potential Field** (APF) method for emergency avoidance maneuvers.
  - ➢ *This approach is further enhanced by embedding COLREGs rules directly into the VO logic, ensuring standardized and interpretable behavior*.

INTRODUCTION

[4] S. Ni, Z. Liu, D. Huang, Y. Cai, X. Wang, and S. Gao, "An application-orientated anti-collision path planning algorithm for unmanned surface vehicles," *Ocean Eng.*, vol. 235, no. 109298, p. 109298, 2021.
[5] L. Du, F. Goerlandt, O. A. Valdez Banda, Y. Huang, Y. Wen, and P. Kujala, "Improving stand-on ship's situational awareness by estimating the intention of the give-way ship," *Ocean Eng.*, vol. 201, no. 107110, p. 107110, 2020.

- Building on this, some studies [4] have fused **modified VO approaches** with **APF-based methods** to improve both the practicality and responsiveness of the planning solution.
- More advanced techniques also include intention estimation mechanisms using **non-linear VO algorithms** [5], which aim to predict the behavior of nearby vessels—particularly the give-way ship—in order to assess risk more accurately and construct an additional layer of navigational safety.



INTRODUCTION

- Current methods show potential but lack robust early-stage decision-making.
- A need exists for integration collision avoidance with vessel maneuverability under complex maritime conditions.

CONTRIBUTION

- **Two-Stage Approach for USV Trajectory Planning:**
  - **1st stage: Global Planning via Modified PRM & Dijkstra Algorithm**
    - ✓ Generates a navigation graph from maritime environment maps.
    - ✓ Accounts for free/occupied areas and adds start/goal states.
    - ✓ Optimizes for fuel efficiency and safety, factoring in weather.
  - **2nd stage: Local Obstacle Avoidance During Execution**
    - ✓ Onboard sensors detect moving obstacles in real time.
    - ✓ Decision system assesses collision risk and activates local planner if necessary.
    - ✓ Local planning respects COLREGs and ensures continuous safe navigation.

CONTRIBUTION

Main Advantages of the Proposed Method

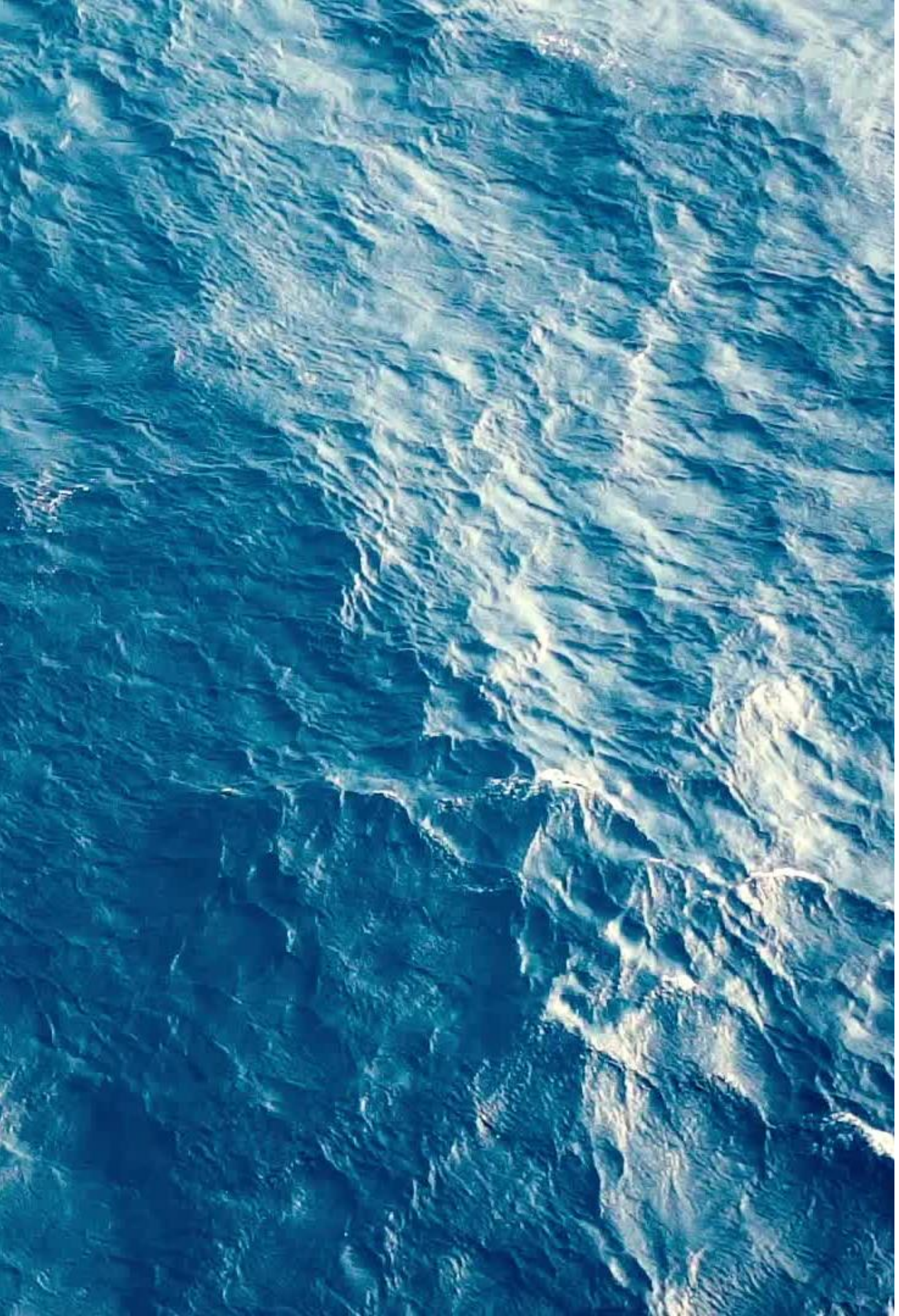
I. **Simplicity & Safety**: Ensures safe motion without algorithmic complexity.

II. **Environmental Awareness**: Takes into account the USV's geometry and real-world maritime conditions (e.g., sea state).

III. **Fast & Compliant Collision Assessment**:

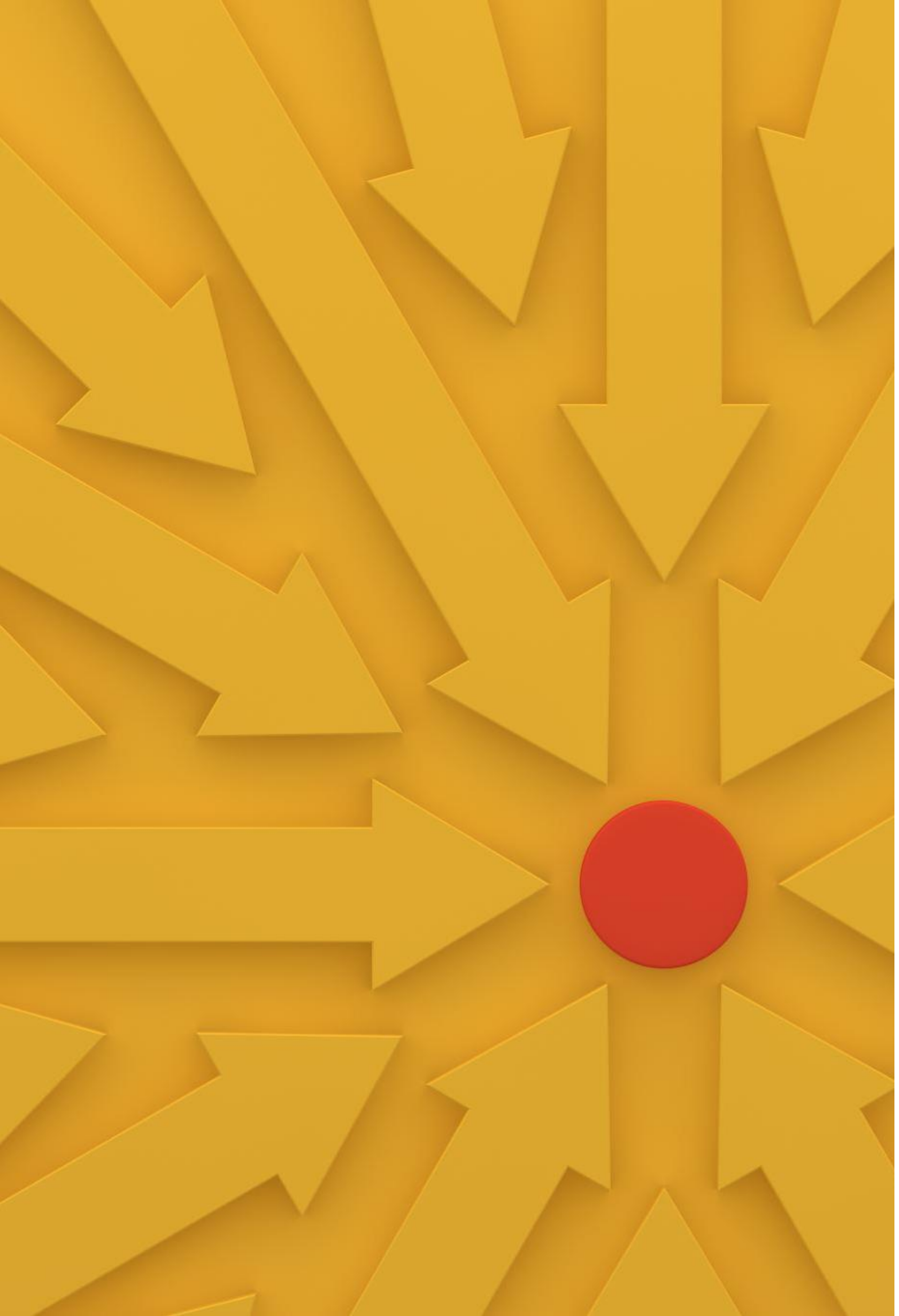
- The Advanced Navigation System (ANS) evaluates collision risk within milliseconds.
- It executes COLREGs-compliant maneuvers to ensure legal and safe interaction with other vessels.

IV. **Efficiency**: Minimal computational overhead—suitable for real-time applications.



PROBLEM DEFINITION

- **Scenario:**
  - A USV must navigate from a **start point** to a **goal point** in a **cluttered maritime environment** which includes landmasses, coastlines, and dynamically moving vessels.
- **Operational Assumptions**
  - **Environmental Data Sources**: AIS, radar, and nautical charts provide data on:
    - Static obstacles: land, depth contours, coastline.
    - Dynamic obstacles: real-time position, speed, and heading of vessels.
  - **USV Sensor Capabilities**:
    - Detects object position, shape, and velocity.
  - **Environmental Simplifications**:
    - All vessels (including the USV) move at **constant velocity**.
    - Weather effects (wind, waves, currents) are **not modeled**.
    - Safe clearance from coastlines is **predefined on the map**.



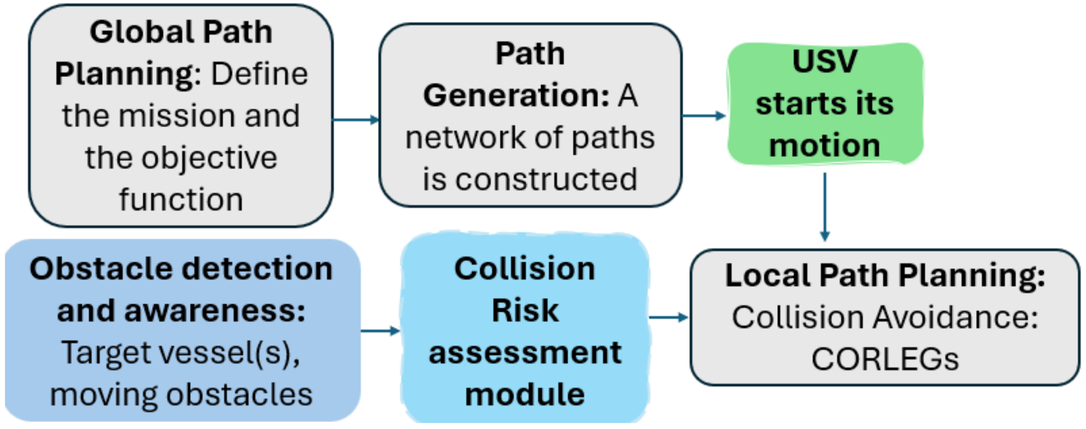
PROBLEM DEFINITION

Path Planning Objectives

- **Collision Avoidance**: The path must remain free of intersection with static and moving obstacles.
- **Energy Efficiency**: Optimize route for minimal energy consumption along the path.
- **COLREGs Compliance**: USV motion must respect international maritime navigation rules (CORLEGs).

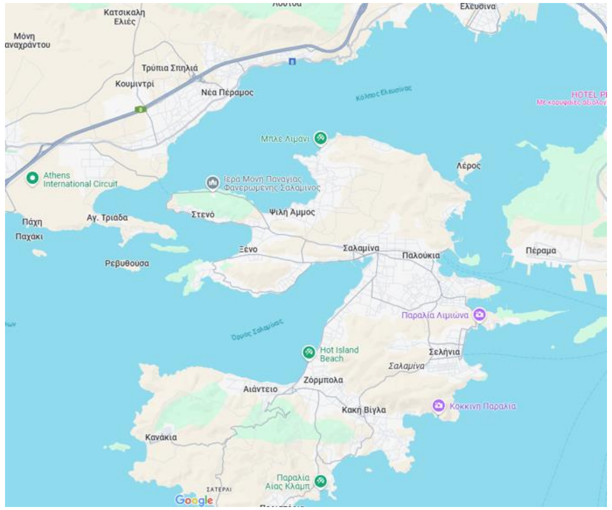
PROPOSED APPROACH: OVERVIEW

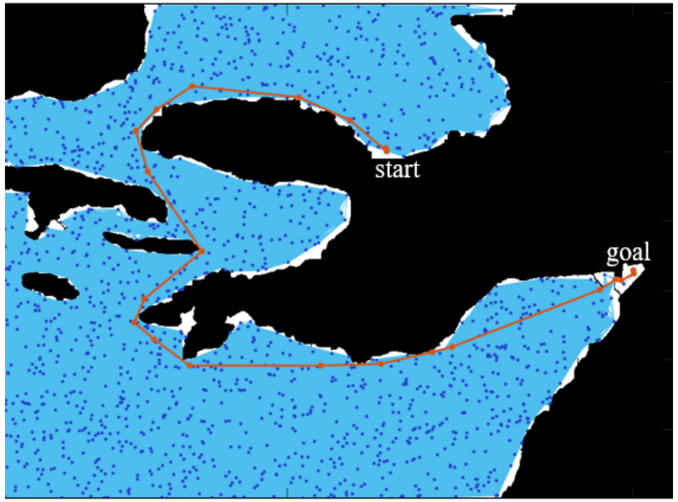
- The USV navigation process is divided into two **main planning stages**:
  - **Global Path Planning**
  - **Local Collision Avoidance**
- **Global Path Planning**
  - Initiated with **mission definition** and an **objective function** (minimum path length).
  - A **modified Probabilistic Roadmap (PRM)** is used to construct a navigable path network.
  - **Weather conditions** are considered in graph generation.
  - Waypoints are generated and **smoothed** for feasible execution.
- **Real-Time Obstacle Detection & Local Planning**
  - While the USV follows the global path:
    - Onboard sensors detect moving obstacles and target vessels.
    - The system continuously assesses **collision risk**.
  - If a potential collision is detected:
    - **Local path planning is triggered**, compliant with **COLREGs**.
    - Path is adjusted using **Dubins curves** and **Genetic Algorithms** to ensure safe avoidance.



PROPOSED APPROACH: GLOBAL PATH PLANNING

- **Objective:** Efficiently compute a **safe and fuel-optimal path** for a USV from start to goal, considering:
  - Environmental constraints
  - Weather effects (wind, waves).
- **Method Overview**
  - **Poisson Disk Sampling** generates evenly spaced points in the environment.
  - A **local planner** builds an undirected graph (PRM):
    - Nodes: Sampled positions
    - Edges: Feasible paths (unsafe edges are discarded)
  - **Edge weights** reflect environmental difficulty (e.g., rough seas, wind).
  - **Modified Dijkstra algorithm** identifies the lowest-cost path:
    - Minimizes **fuel consumption and travel time.**





PROPOSED APPROACH: GLOBAL PATH PLANNING

- The overall global path planning is described by,

$$\text{minFC}_{total} = min \sum_{(i,j)\epsilon V} fc_{ij}$$

Subject to,

$$135° < q_{ij} < 225°$$

$$V_{ij} > \frac{1.8\sqrt{L}}{\cos(180° - q_{ij})}$$

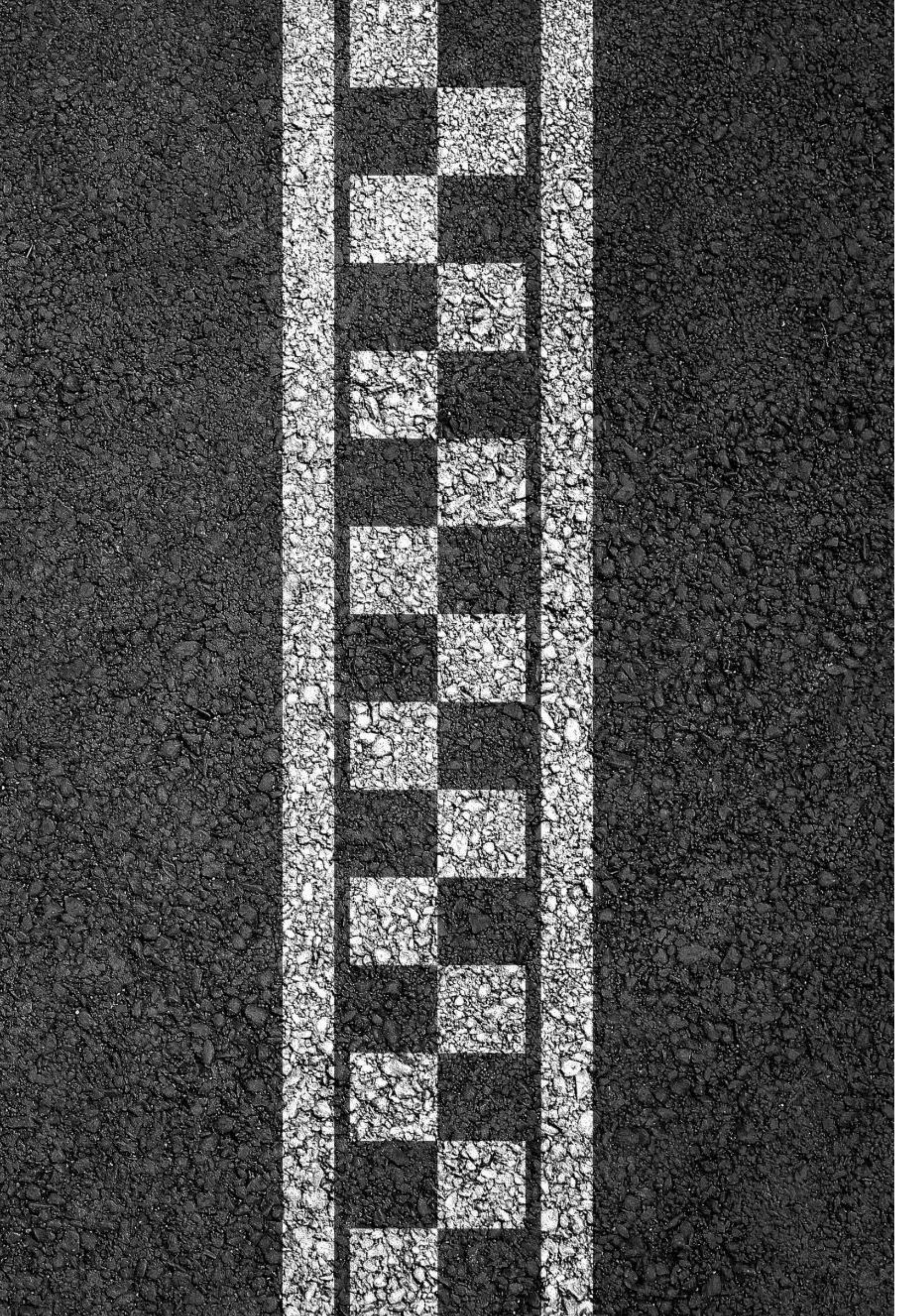
$$T_{E,ij} \approx T_{NR,ij}$$

where,

- FC_{total} is the total energy consumption,
- fc_{ij} is the energy consumption between the nodes $(i, j) \in V$,
- V is the set of nodes,
- q_{ij} is the angle between the USV heading angle and wave direction in rads,
- V_{ij} is the actual speed of the USV in knots and
- L is the USV length in meters,
- $T_{E,ij}$ is the encounter wave period and
- $T_{NR,ij}$ is the natural roll period of the USV.

LOCAL PATH PLANNING: COLLISION RISK ASSESSMENT

- **Real-Time Collision Detection & Avoidance**
  - **Assumption:** USV follows waypoints $WP_i \rightarrow WP_{i+1}$ at constant velocity $|\tilde{u}(t)|$ and with heading angle $\varphi(t)$.
  - If another vessel is detected:
    - Compute **relative velocity** along line of sight: $u_{ro}(t) = [u(t) - v(t)]^T \boldsymbol{n}_{ro}$, $\boldsymbol{n}_{ro}$is a unit vector pointing from the USV to the vessel.
      - If $u_{ro}(t) \leq 0$, no collision risk.
      - If $u_{ro}(t) > 0$, collision risk, initiate avoidance.
  - **CORLEGs – Compliant Behavior**
    - Enforce **nonlinear constraint** for safe passage: $\mathrm{A} = \sin\big(\varphi(t)\big) * \big(x(t) - x_o(t)\big) - \cos\big(\varphi(t)\big) * (y(t) - y_o(t)) \geq 0$
    - Ensures other vessel remains **to the left** of USV heading.

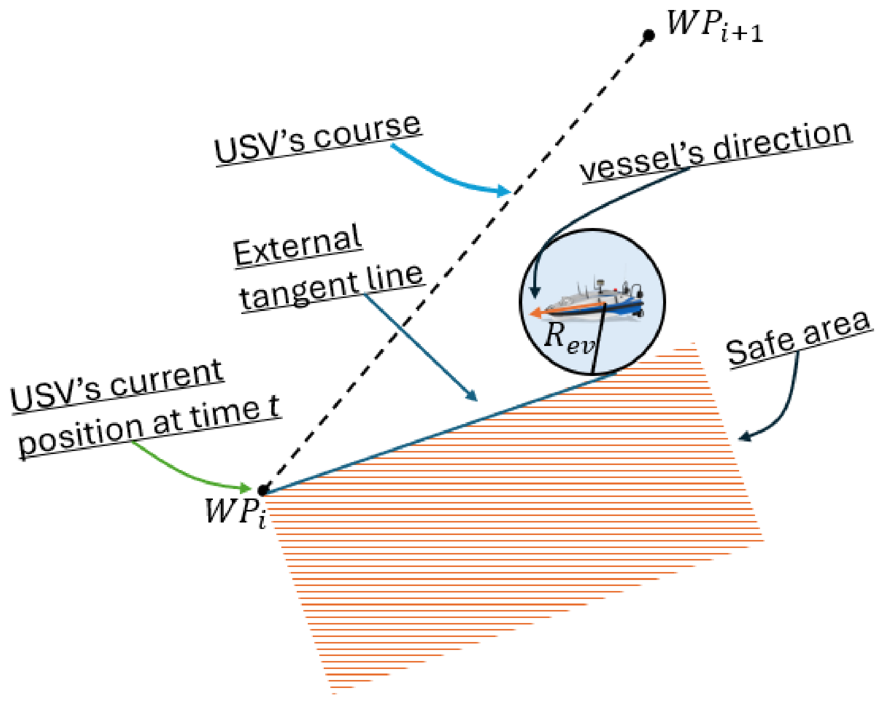


LOCAL PATH PLANNING: COLLISION RISK ASSESSMENT

- Encounter Classification (Rule-Based):
  - Overtaking: $u_{ro}(t) > 0$ and $|\varphi(t) - \varphi_O(t)| \leq \frac{\pi}{4}$
  - Head-on: $u_{ro}(t) > 0$ and $|\varphi(t) - \varphi_O(t) + \pi| \leq \frac{\pi}{4}$
  - Crossing from right: $u_{ro}(t) > 0$ and $\frac{\pi}{4} \leq \varphi(t) - \varphi_O(t) \leq \frac{3\pi}{4}$

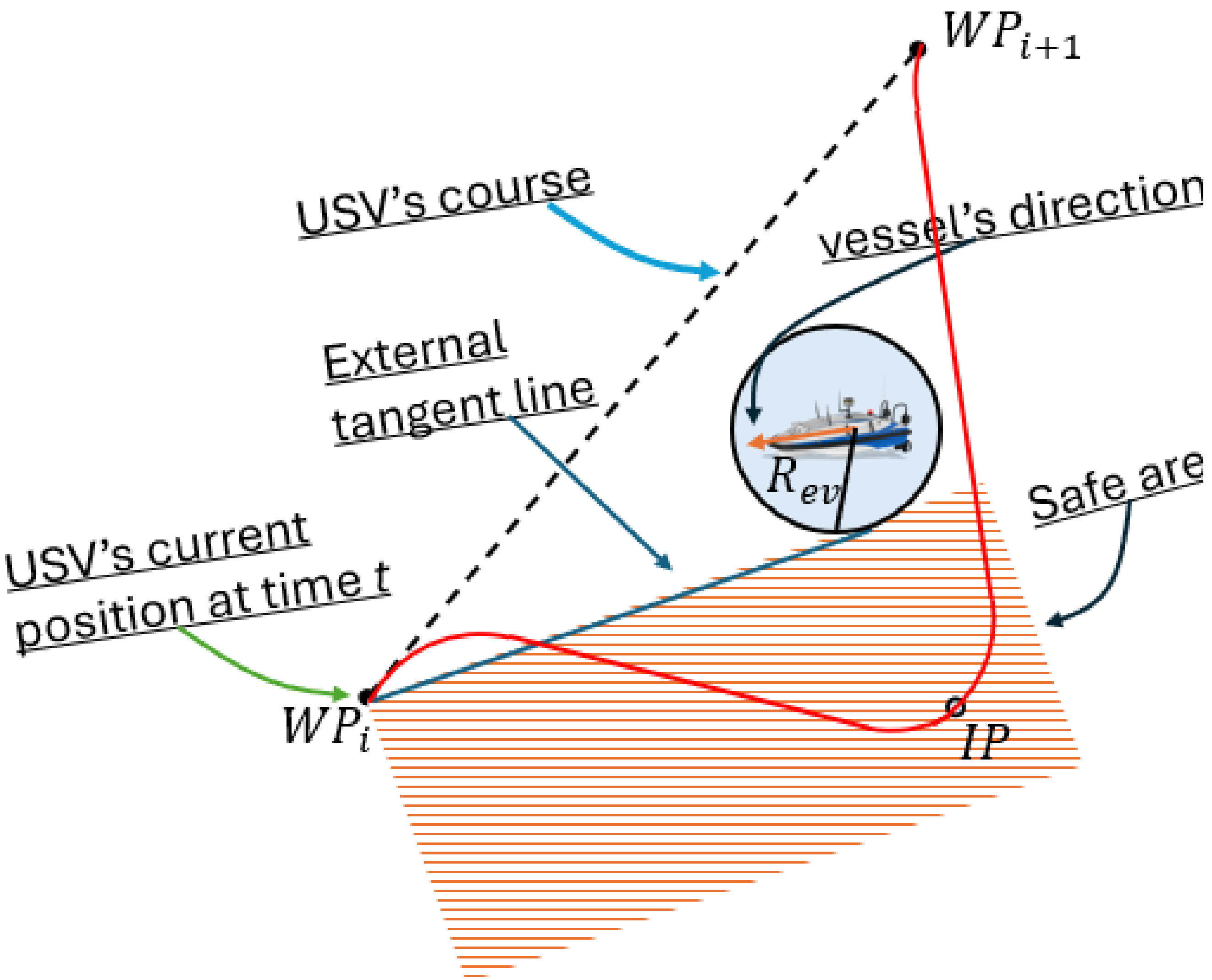
LOCAL PATH PLANNING: COLLISION AVOIDANCE MANEUVER

- **Scenario:**
  - The USV travels from waypoint WP_i to WP_{i+1}.
  - At time t another vessel is approaching → $u_{ro}\ (t) > 0$.
  - A COLREGs rule is triggered (overtaking, head-on, or crossing).
- **Approach:**
  - **Modeling:**
    - USV: treated as a **point**.
    - Encounter vessel: modeled as a **circle** (radius R_{ev}).
    - Draw **external tangent** from USV to obstacle → defines **safe semi-plane**



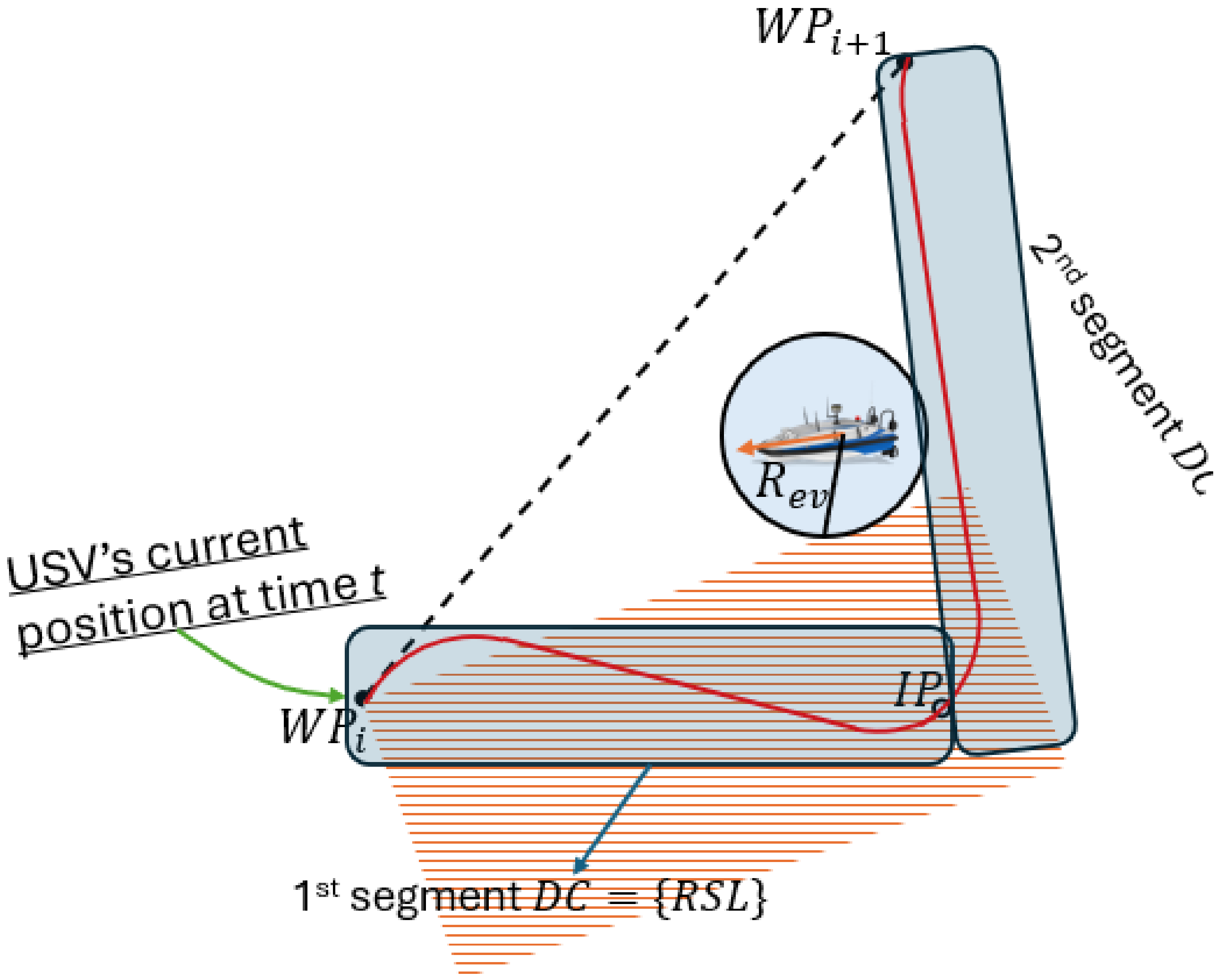
LOCAL PATH PLANNING: COLLISION AVOIDANCE MANEUVER

- **Safe Area:**
  - **Right semi-plane** of the external tangent.
- **Goal: Intermediate Point** (IP) selection which must lie in this region.
- **Determined using a Genetic Algorithm to:**
  - Minimize the local path length
  - Ensure safe distance from obstacle
  - **Considers:**
    - USV’s heading angle
    - Relative position to the obstacle.
    - Combined safely buffer R_{ev}



LOCAL PATH PLANNING: COLLISION AVOIDANCE MANEUVER

- **Path Construction with Dubins Curves**:
  - Path split into **two Dubins segments**:
    - Segment 1: $WP_i \rightarrow IP$
    - Segment 2: $IP \rightarrow WP_{i+1}$
  - Each segment consists of three movements:
    - Move straight
    - Turn left (max steering)
    - Turn right (max steering)
  - Only forward motion allowed (no reverse)



EXPERIMENTS

Experimental Setup

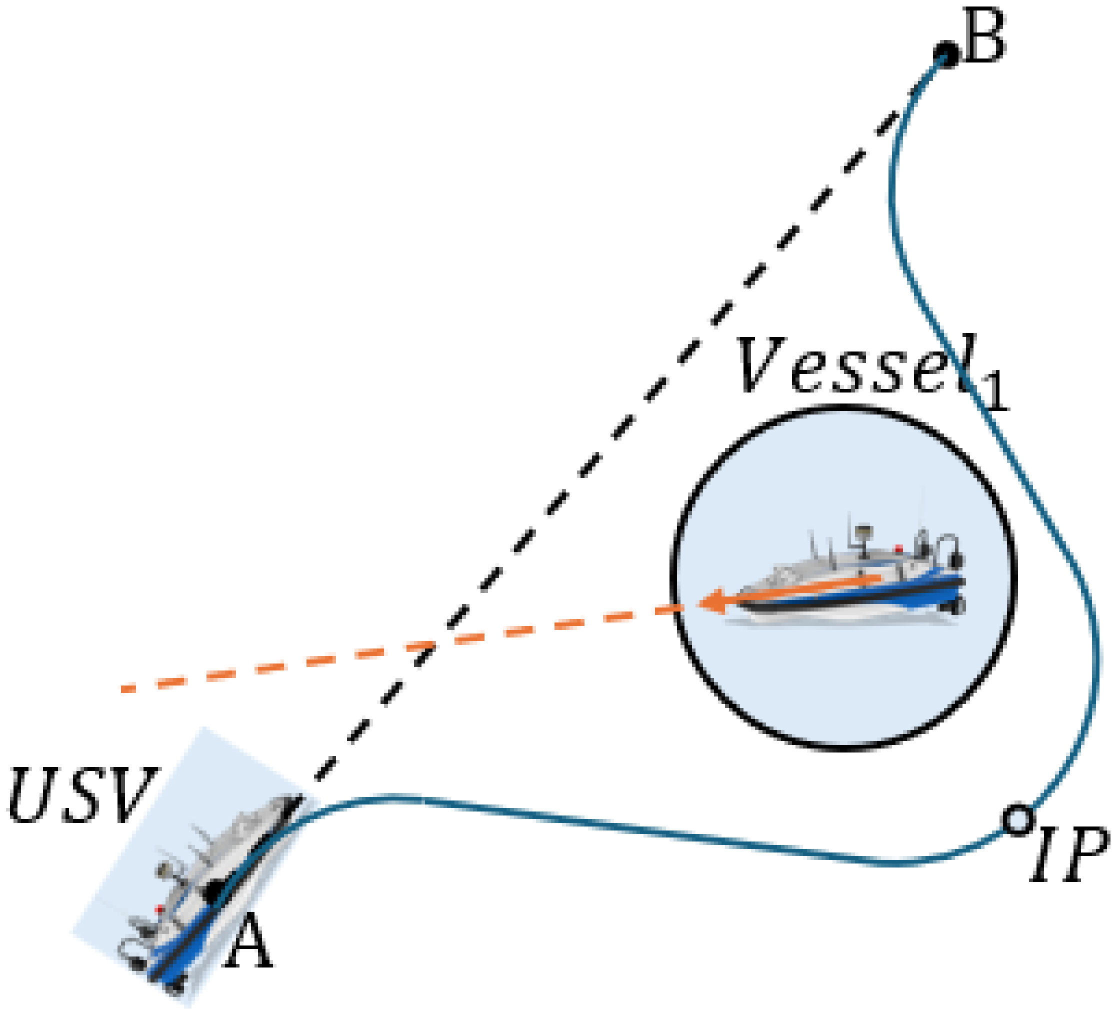
- **Objective:** Evaluate a collision-aware trajectory planning approach for USVs in a dynamic 2D maritime environment.
- **Environment:**
  - Bounded 2D maritime plane with:
    - Static obstacles (e.g., landmasses)
    - Moving vessels with constant speeds and known trajectories
  - Global path: generated via **Modified PRM**
  - Local planner: **Dubins Curves + Genetic Algorithm (GA)**
- **GA Control Parameters:**
  - Population size: **150**
  - Generations: **400**
  - Crossover rate: **0.75**
  - Mutation rate: **0.004**
- **Execution:**
  - MATLAB simulation
  - 3.50 GHz PC
  - Real-time decision latency: **< 110 ms**

EXPERIMENTS

- **Evaluation Metrics & Methodology**
  - **System Monitoring:**
    - Onboard sensors (simulated) monitor dynamic obstacles in real time
    - Local planner is triggered upon detection of collision risk
- **Performance Metrics:**
  - **Path Efficiency:** Total traveled distance vs. optimal direct path
  - **Path Deviation:** Deviation from global PRM trajectory
- **Robustness Testing:**
  - Varied simulation conditions:
    - Obstacle density
    - Vessel velocity
    - Encounter types (overtaking, head-on, crossing)

EXPERIMENTS

- **Scenario 1: Low-Density Environment**
  - Sparse traffic: 1 vessel in range
  - USV navigates from A to B
  - Vessel approaches from starboard → Collision risk
    - ANS triggered → Dubins-based re-routing
- **Results:**
  - **Path deviation:** ~14%
  - **ANS decision time:** <70 ms
  - Smooth and compliant path generation



EXPERIMENTS

Scenario 2: High-Density Encounters

Multiple dynamic vessels, frequent risks

The USV is repeatedly adjusted using the local designer

Results:

- **COLREGs compliance:** 91%
- **Average deviation:** 21.9%
- **Max computation time:** 110 ms

CONCLUSIONS & FUTURE WORK

Summary of Contributions

- Proposed a **real-time trajectory planning approach** for USVs in dynamic maritime environments
- Combined:
  - **Modified Probabilistic Roadmap (PRM)** for global path planning
  - **GA-based Dubins Curves** for local collision avoidance
- Ensures **safe**, **efficient**, and **COLREGs-compliant** navigation

Simulation Findings

- Effective avoidance of static and dynamic obstacles
- Maintained smooth, near-optimal trajectories
- Demonstrated fast local planning with real-time performance

Current Limitations

- **Environmental forces** (wind, waves, currents) not yet modeled
- Validation limited to **simulated environments**

Future Work

- Integrate **environmental disturbances** into planning models
- Improve **local planning speed** with more efficient algorithms
- Conduct **real-world maritime experiments** to validate system applicability

THANK YOU
ANY QUESTIONS