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# Uncertainty-Aware BIT*: Collision-free Path Planning for Maritime Autonomous Surface Ships under Target Ship Position Uncertainty

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*Abstract*— **This paper proposes a BIT*-based collision-free path planning method for remotely operated Maritime Autonomous Surface Ships (MASS) under target ship position uncertainty. In a remote operating environment, the Remote Operating Center (ROC) receives target ship position data from long-range sensors such as AIS and radar. This data inherently contains uncertainty due to measurement errors and communication delays, making it essential to account for such uncertainty during path planning. As MASS must comply with the International Regulations for Preventing Collisions at Sea (COLREGs) during navigation, path planning must also reflect these requirements. The proposed method models target ship position uncertainty as a two-dimensional Gaussian distribution and incorporates it into edge evaluation as a collision risk cost, while applying penalty costs to edges that enter COLREGs non-compliant regions. A turning radius constraint is also incorporated into the edge selection process to ensure navigational feasibility. The method is validated through head-on and crossing encounter simulations on an Electronic Nautical Chart (ENC)-based grid map of Ulsan Port, South Korea. The results show that higher levels of position uncertainty lead to more conservative avoidance paths, resulting in greater Distance to Closest Point of Approach (DCPA).**

## I. INTRODUCTION

MASS are increasingly operated in fully remote configurations without onboard crew, even in complex maritime environments. In such settings, manually managing collision avoidance against both static and dynamic obstacles imposes significant cognitive load on remote operators, highlighting the need for automated path planning. Target ship positions are typically obtained from the Automatic Identification System (AIS) and radar; however, as sensing range increases, measurement errors and communication delays also increase, introducing uncertainty into the estimated positions. When this uncertainty is ignored, deterministic position estimates may fail to accurately represent collision risk, making it essential to explicitly model and incorporate uncertainty into path planning. To address this, this paper integrates target ship position uncertainty and COLREGs-based avoidance rules into the BIT* framework by designing an uncertainty-aware edge cost function and a corresponding edge evaluation strategy.

## II. UNCERTAINTY-AWARE BIT*

### A. Uncertainty-Aware BIT*-based Path Planning

BIT* [1] is an efficient sampling-based path planning algorithm that generates candidate paths in batches and searches the most promising candidates first based on heuristic edge costs. It uses the informed set sampling from Informed RRT* to restrict the search space to states that can improve the current solution, allowing the path cost to asymptotically converge to the optimal solution. In this paper, the edge evaluation cost of BIT*, which was originally based on distance, is extended to incorporate target ship position uncertainty and COLREGs-based avoidance rules.

### B. Edge Cost Function of Uncertainty-Aware BIT*

The proposed edge cost function is formulated as a weighted sum of three components: distance cost, collision risk cost, and COLREGs-based penalty cost.

$$c(\mathbf{v},\mathbf{x}) = w_d c_d(\mathbf{v},\mathbf{x}) + w_r c_r(\mathbf{v},\mathbf{x}) + w_p c_p(\mathbf{v},\mathbf{x}) \tag{1}$$

where $\mathbf{v}$ and $\mathbf{x}$ denote the parent vertex in the search tree and the candidate sample, respectively, and $w_d$, $w_r$, $w_p$ are the corresponding weights satisfying $w_d + w_r + w_p = 1$. The total path cost is the sum of all edge costs along the path.

The distance cost $c_d$ discourages unnecessary detours and guides the search toward shorter paths.

$$c_d(\mathbf{v},\mathbf{x}) = \frac{d(\mathbf{v},\mathbf{x})}{d_{\mathrm{ref}}} \tag{2}$$

where $d(\mathbf{v},\mathbf{x})$ is the Euclidean distance of the edge and $d_{\mathrm{ref}}$ is a reference distance for normalization.

The collision risk cost $c_r$ quantifies the collision probability along the edge. The target ship position is modeled as a 2D Gaussian distribution, from which samples are drawn to represent spatial uncertainty. At each discretized point along the edge, the collision probability is computed as the ratio of samples falling within the own ship's safety domain. The final cost is computed as the average of these probabilities over all evaluation points.

$$c_r(\mathbf{v},\mathbf{x}) = \frac{1}{n+1}\sum_{i=0}^{n} p(\mathbf{p}_i), \quad p(\mathbf{p}_i) = \frac{n_{c,i}}{N_o} \tag{3}$$

$$n_{c,i} = \sum_{k=1}^{N_o} \mathbf{1}[\|\mathbf{o}_k - \mathbf{p}_i\| \leq R_{safe}] \tag{4}$$

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where $n$ is the number of discretized evaluation points along the edge, $\mathbf{p}_i$ is the position of the $i$-th evaluation point, $n_{c,i}$ is the number of risk assessment samples falling within $R_{safe}$ at $\mathbf{p}_i$, $N_o$ is the total number of risk assessment samples drawn from the Gaussian distribution, $\mathbf{o}_k$ is the position of the $k$-th such sample, and $R_{safe}$ is the safety domain radius of the own ship.

The COLREGs penalty cost $c_p$ assigns a binary cost to each evaluation point based on its position relative to the target ship: a cost of 1 is assigned if the point falls within the COLREGs non-compliant region $\mathcal{R}$, and 0 otherwise, to discourage paths that violate regulations.

$$c_p(\mathbf{v},\mathbf{x}) = \frac{1}{n+1}\sum_{i=0}^{n} q(\mathbf{p}_i),\ q(\mathbf{p}_i) = \begin{cases} 1, & \text{if } \mathbf{p}_i \in \mathcal{R} \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

### C. Turning Radius Constraint

Ships have a large turning radius, so edges requiring sharp course changes are not practically feasible. To account for this, the maximum allowable heading change $\theta_{\max}$ between consecutive edges is limited based on the edge length $l$ and the minimum turning radius $R_t$ of the own ship:

$$\theta_{\max} = 2\sin^{-1}\left(\frac{l}{2R_t}\right) \quad (6)$$

Edges that violate this constraint are rejected early, before more complex computations are performed, to avoid unnecessary calculations.

## III. SIMULATION

The system architecture used to validate the proposed method is shown in Fig. 1. Global waypoints, own ship and target ship information, and static obstacle data are provided as inputs. Uncertainty-aware BIT* generates a local path, which is tracked in real time by a ship simulator. The system is implemented in ROS2 with OMPL on Ubuntu 24.04, and validated on an ENC-based grid map of Ulsan Port. The own ship is the *Haeyangnuri-ho*, a Korean MASS testbed with a length of 26.5 m and a turning radius of approximately 1.79 times its length [2]. The uncertainty model assumes a larger standard deviation in the target ship's heading direction than in the lateral direction. The path is replanned every 2 s, matching the minimum AIS update interval.

Simulations are conducted for a head-on encounter scenario (Fig. 2) and a crossing scenario (Fig. 3), in both of which the own ship has a starboard avoidance obligation. All ships operate at a speed of 6 knots. In both scenarios, a higher level of uncertainty leads to more conservative starboard avoidance paths with greater DCPA. After avoiding the target ship, the Uncertainty-aware BIT* also generates a feasible path through complex static obstacles near the port entrance, reaching the destination and confirming the effectiveness of the proposed method.

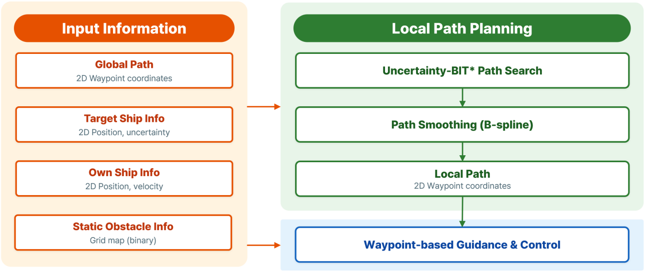

Fig. 1. System architecture of the proposed method

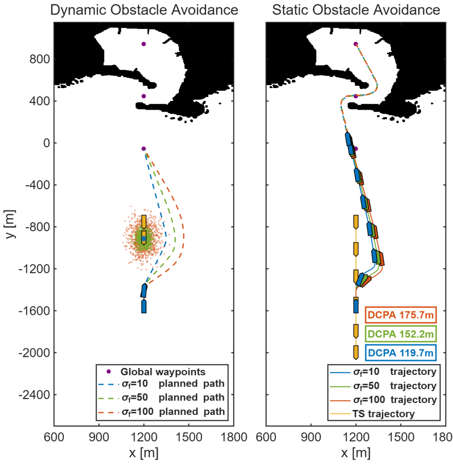

Fig. 2. Path planning result in the head-on encounter scenario

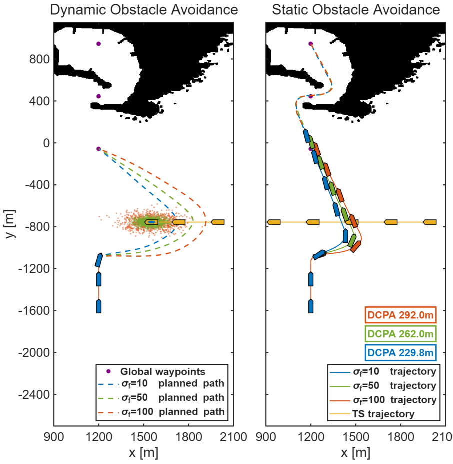

Fig. 3. Path planning result in the crossing encounter scenario

## IV. CONCLUSION

This paper presents Uncertainty-aware BIT*, which integrates target ship position uncertainty, COLREGs-compliant starboard avoidance, and turning radius constraints into a single BIT* framework. Simulations of head-on and crossing encounter scenarios confirm that a higher level of uncertainty leads to more conservative avoidance paths with greater DCPA, and that the planner successfully navigates through complex static obstacles to reach the destination after avoiding the dynamic obstacle. Future work will extend validation to multi-ship scenarios and various encounter situations.

## REFERENCES

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