MARCOL: A Maritime Collision Avoidance Decision-Making Testbed

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Abstract

Safe and efficient maritime navigation is fundamental for autonomous surface vehicles to support many applications in the blue economy, including cargo transportation that covers 90% of the global marine industry. We developed MARCOL, a collision avoidance decision-making framework that provides safe, efficient, and explainable navigation strategies and that allows for repeated experiments under diverse high-traffic scenarios.

Introduction

The goal of this paper is to develop and demonstrate an explainable AI decision-making system that consists of a multi-objective optimization framework within the maritime traffic regulations for support in Autonomous Surface Vehicles (ASVs) collision avoidance in the aquatic domain. The global marine industry comprises over 90 percent of the world's cargo transportation (United Nations 2022). Current maritime navigation heavily relies on high-stakes human decision-making under uncertainty. Automating decision-making in the maritime domain can reduce accidents and enable high-impact applications, e.g., autonomous shipping.

In-water navigation is typically more challenging compared to self-driving cars in the ground domain, due to (1) unstructured waterway conditions; (2) vehicle dynamics; and (3) traffic regulations – Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) – not explicitly covering real-world scenarios. Important examples include multiple encounters and using ambiguous expressions left to the interpretation of operators, e.g., 'ordinary practice of seaman' (International Maritime Organization 1972). A small error, e.g., non-compliance with COLREGs, in the decision-making process for motion planning can lead to a catastrophic accident and severe consequences, because of the high-cost of the vehicles (in the order of US$100k up to US$10M). For example, the collision between USS Fitzerald and containership ACX crystal off Japan Coast in 2017, resulted in total 7 deaths, several injuries, and severe damages on both vessels (JTSB 2019). On the other hand, actions that depart from COLREGs, assuming no negligence, might be necessary when a high risk of collision exists (Zhou et al. 2020).

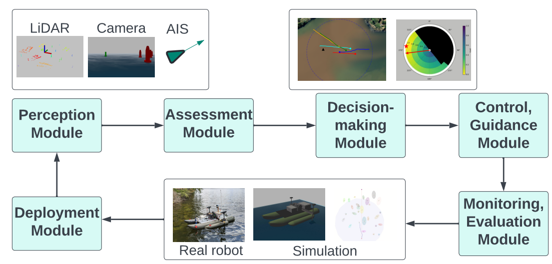

Figure 1: System architecture for ASV collision avoidance.

We present MARCOL (A Maritime Collision Avoidance Decision-making Testbed) as an **explainable** testbed and **knowledge base** decision-making tool for maritime navigation to answer the following question: "How can we test a collision avoidance decision by ASVs under dynamic traffic scenarios and why do we observe the corresponding behavior in a certain situation?". MARCOL is built upon a rule-based logical system and a multi-objective optimization framework (Jeong and Quattrini Li 2022) targeted for challenging scenarios like simultaneous encounters with non-cooperative and non-COLREGs-compliant actions by obstacles. Moreover, considering a human-in-the-loop system, a person can choose various configurations, e.g., type of planners, encounter situations, and properties of action and sensing. In addition to maritime vehicles, MARCOL can be extended to mobile robots in other domains. Therefore, MARCOL can contribute to answering further questions such as "Can an autonomous vehicle safely avoid an obstacle with non-COLREGs-compliance?", "What if a vehicle involved in an accident took a different action?". Such answers will contribute to analyzing common real-world scenarios and preventing future traffic accidents.

MARCOL System Overview

The MARCOL system is comprised of the following multiple modules (Figure 1): *deployment*, *perception*, *assessment*, *decision-making*, *control/guidance*, and *monitoring/evaluation* module. The main modules – perception, assessment, decision-making, and control/guidance – use **if-then** rule-based logical agent such that the motion planning can be

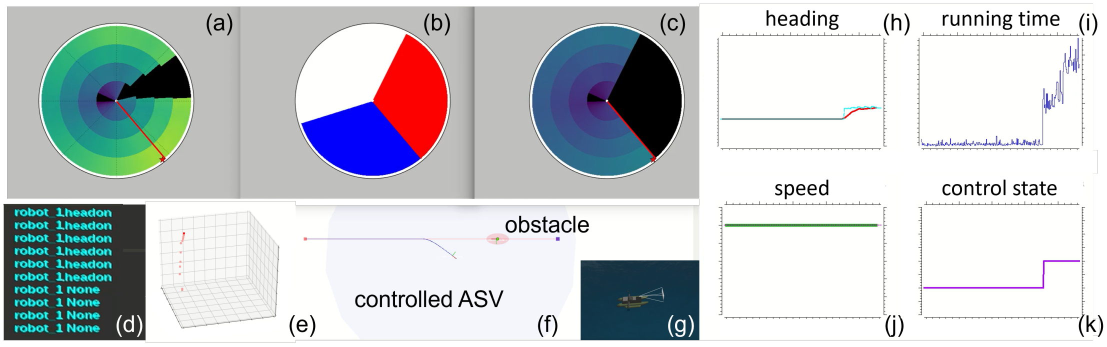

Figure 2: Overall MARCOL demonstration view of the head-on situation in simulation.

explainable, reproducible, and correctly configurable for future behavioral improvements. MARCOL is integrated with a middleware, the Robot Operating System (ROS) (Quigley et al. 2009). Also, the MARCOL system uses synchronous and asynchronous protocols such that messages can be communicated between modules or between vehicles.

Deployment Module. Based on the ROS integration, desired configurations and algorithm schemes can be easily run on an ASV deployed on a lightweight 2-D simulator Stage (Vaughan 2008), realistic 3-D simulator Gazebo (Koenig and Howard 2004), or on a real-world robot platform for repeated experiments.

Perception Module. MARCOL is integrated with sensor models for perception in the local domain of an ASV. The primary sensors are based on time-of-flight range sensors, e.g., LiDAR, RADAR, while 3-D simulation can be integrated with image inputs from vision sensors, e.g., camera. The sensor models include configurable parameters such as maximum range, resolutions, and uncertainty.

Assessment Module. According to COLREGs, there are two main assessments in an encounter situation: (1) risk of collision assessment; and (2) encounter type classification. There is still a lack of clear standards as they often depend on the specific scenario. Our assessment module has a knowledge base model that can adopt several motion attributes, e.g., time to Closest Point of Approach (TCPA), distance to CPA (DCPA), risk-vector (Jeong and Quattrini Li 2020). The main principle is to first assess if a current action is expected to be safe enough based on a desired combination of the motion attribute metrics. Then, the ASV determines which encounter situation it lies in.

Decision-making Module. With this module, an ASV initiates a collision avoidance strategy, e.g., turn to the right, according to the finite state machine and some parameters. First, the ASV can have a different rule-compliance level that enables adaptive analysis on a safer action despite the departure from COLREGs. Next, there is a selection of local planner methods for collision avoidance, e.g., Velocity Obstacle (VO) (Kuwata et al. 2014), Multiple Obstacle Avoidance (MOA) (Jeong and Quattrini Li 2022). The final desired action – heading and velocity – is determined by a Pareto optimization framework based on a weighted combinations of objective functions representing costs such as heading, velocity, rule-compliance, safety clearance. For example, when it is difficult to change a velocity component due to a large-scale vessel, MARCOL can be operated with the heading change preferred to the speed change.

Control/Guidance Module. Based on the output of the decision-making module and the current state, the ASV is maneuvered as a PID controller and follows a trajectory by a controller, e.g., Line of Sight controller.

Monitoring/Evaluation Module. The visualization and analysis tool is used to (1) monitor the collision avoidance in-real-time during navigation, e.g., desired action vs. current action; and (2) evaluate the performance of a motion planning as post-processing, e.g., success of navigation. With this "explainability" from rule-based AI system, MARCOL can reproduce a situation according to historical data and serve as an real-world accident analysis tool.

MARCOL Demonstration

The MARCOL demo shows (1) the overall architecture and decision framework; (2) the explainability of the decisions by visualizing the feasible action space with corresponding multi-objective values and the compliance to the regulatory framework according to the encounter classification; (3) its ability to enable traffic scenarios of different complexities in terms of number, dynamics,, etc.; (4) its modularity allowing for deployment on real robots. Figure 2 shows an example of head-on situation in simulation, where (a) shows the feasible action space according to the multi-objective criteria, (b) the current direction of the ASV, (c) the feasible action space based on COLREGs, (d) the classification of the encounter, (e) the assessment of the motion metrics, (f) the trajectory of the ASV and obstacle, (g) a view of the simulation, and (h)-(k) the plots about the current state of the ASV.

With these features, MARCOL allows (1) a more explainable decision-making system for ASV navigation and (2) a testbed for repeatable experiments to evaluate different strategies and scenarios. We plan to extend the testbed with higher-level decision-making, e.g., global planner, and uncertainty, e.g., external forces.

Acknowledgments

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