Formal Verification of Maritime Autonomous Systems Using UPPAAL STRATEGO

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Abstract

Lately the demand for autonomous ships has grown substantially. Autonomous ships are expected to navigate safely and avoid collisions following accepted navigation rules. We model the autonomous system as a Stochastic Priced Timed Game using UPPAAL STRATEGO. The behaviour of the controller is optimised and verified in order to achieve the goal to safely reach the destination at a minimum cost.

1 Introduction

The demand for unmanned ships has risen aiming at reducing operation costs due to minimal crew on board and safety at sea but also promoting remote work. Autonomous ships are expected to make more and more decisions based on their current situation at sea without direct human supervision. This means that an autonomous ship should be able to detect other vessels and make appropriate adjustments to avoid collision by maintaining maritime traffic rules. However, the existence of a 'virtual captain' from the shore control centre (SCC) is still a must to perform critical or difficult operations [1]. The presence of virtual captains also increase the chances of spotting a cyber-attacks [10]. The connectivity between ships and SCC has to guarantee sufficient communication for sensor monitoring and remote control [5] when SCC intervention is needed. This connectivity also plays an important role for the safety of operations concerning collision avoidance in the remote-controlled scenarios as it needs to be fast for transforming the data and receiving information regarding the decision from SCC. For preventing collisions at sea, the International Maritime Organization (IMO) [6] published navigation rules to be followed by ships and other vessels at sea which are called Convention On the International Regulations (COLREG).

When developing the autonomous ship navigation system, quality assurance via model-based control synthesis and verification is of utmost importance. UPPAAL STRATEGO [4] is a branch of the UPPAAL [2] family of model checker tools. It uses machine learning and model checking techniques to synthesize optimal control strategies. Hence, it is a good candidate for control synthesis tool which satisfies above mentioned requirements.

In our research, we aim at adapting formal modelling with UPPAAL STRATEGO for verifying and synthesizing safe navigation of autonomous ships. As an additional contribution, we improve the autonomous ships navigation performance regarding its safety and security at the same time planning for optimal route and scheduling maneuvers according to COLREG rules. Furthermore, this study relies on experience reports regarding the identified challenges for formal modelling of autonomous systems.

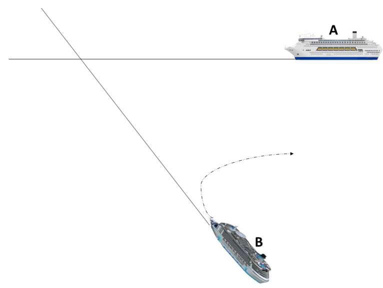

Figure 1: Autonomous Navigation of Ships

2 Related work

There have been a variety of studies on autonomous ship navigation obeying COLREGS rules. Among these fuzzy logic [8], interval programming [3], and 2D grid map [11] could be mentioned. However, the previous approaches do not deal with verification for modelling safe navigation. Moreover, non-deterministic behaviour of autonomous ship, communication delays, sensor failure and weather feature are not considered in their models.

Recently, in MAXCMAS project [12], COLREGs rules have been implemented in collision avoidance module (CAM) software where generates collision avoidance decision and action as soon as collision risk is detected. In spite of their various simulation tools, verification methods are discussed only implicitly.

UPPAAL STRATEGO has proven its relevance in several case studies, where optimal strategies have been through statistical model checking and machine learning. Examples include for instance adaptive cruise control [7].

3 Model

When modelling navigation manoeuvres of autonomous ships, we start with standard situations, addressed in COLREG. As an example, let us consider a scenario where two ships have intersecting courses as depicted in Figure 1.

In this example, in spite of the existence of monitor from the SCC, we assume also that ships are equipped with intelligent controllers. According to Rule 15 of COLREG [9]; when two power driven vessels have intersecting courses with the risk of collision, the vessel which has the other on her own starboard (right) side shall keep out of the way and avoid crossing ahead of the other vessel. If there is a risk of collision between vessels headed for a crossing situation, a vessel has to give way to the vessel on its starboard side. In this case the vessel giving way should adjust its speed and/or course to pass behind the incoming vessel. The adjustment will therefore be made to the starboard side. In the case depicted in Figure 1, Ship B should give way while ship A maintains its direction and speed.

The controller of ship B has a choice to slow down its speed instead of altering its path to pass ship A. By doing this, the expected arrival time might not be as late as when following a redirected route. However, if for some reason ship A is slowing down, then the controller should navigate ship B safely to another route.

We model the system as a Stochastic Priced Timed Game using the tool UPPAAL STRATEGO where the controller of ship B should dynamically plan its maneuver, while the opponent (ship A) moves according to its preset trajectory forces ship B to change its route. In this game, we define the fuel consumption (FC) as a the price to be minimized under the safe strategy. The change in velocity of the ship is directly related to FC, so that the consumption of fuel increases if the ship slows down or speeds up rather than changes the route, causing the price to increase.

The goal is that the ships move to their target positions in a safe way (without the risk of a collision) while at the same time optimizing the travel times and also the fuel consumption. We rely on reinforcement learning and Q-learning supported via UPPAAL STRATEGO to optimize and verify the behaviour of the controller in order to achieve the goal.

4 Conclusion

In this paper, the approach for the control synthesis has been stated as a stochastic two players game with the goal of collision avoidance. Taking into account several practically important side constraints such as wind, currents, navigation mistakes by adversary's vessel, and involvement of other obstacles (nautical signs, small boats) complicates the synthesis task and presumes the validation of the approach under extra constraints not studied in standard game-theoretic setting yet.

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