Formal Development of Multi-vessel Navigation of Maritime Autonomous Systems using UPPAAL STRATEGO

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Introduction

There is a very actively progressing field of Multi-Agent Systems (MAS), which can be viewed as safety-critical systems. The key reason for applying formal methods to MAS is to ensure the correctness of such a system and bring trust for a wide range of application conditions.

Autonomous ships constitute a class of safety-critical multi-agent systems that have to operate under maritime specific conditions. An autonomous ship should be able to detect other vessels and make appropriate adjustments of speed and course to avoid collisions at the same time maintaining maritime traffic rules. The challenge in this area is the development of a formal modelling and verification technique relevant for the domain specifics. In particular such systems must guarantee safe performance of each agent in the shared environment considering various environment conditions and other agents on the route. One important feature that needs to be particularly addressed in formal modelling of such systems is the agility, efficiency and safety of the ships' dynamic reaction also to the stochastic behaviour of other agents under extreme circumstances such as drift of ice fields or loss of radio link. In addition to collisions avoidance, agents are expected to reduce fuel consumption for a voyage for cost saving and minimising air pollution.

To analyse the safety-critical scenarios of multi-vessel systems, game theory has become the standard method in the formal modelling and analysis. This is due to the fact that it studies the problems of how interaction strategies can be designed that will maximise the welfare of an agent in a multi-agent encounter, and how mechanisms can be designed that have certain desirable properties [8].

To prevent navigation accidents at sea, the International Maritime Organisation (IMO) [4] has issued navigation rules to be followed by ships and other vessels at sea. These rules are called Convention On the International Regulations (COLREG).

When developing the autonomous ship navigation system, quality assurance via tool supported model-based control synthesis and verification is of utmost importance that needs both scalable engineering techniques and mature tool support.

In our research, we use UPPAAL STRATEGO [2] for verifying and synthesising safe navigation of autonomous ships. It is a branch of UPPAAL [1] that has proven its relevance in several case studies, e.g. [5]. As an additional contribution, we improve the multi-vessel navigation quality characteristics regarding its safety and security and with that improving the planning of the optimal route and scheduling manoeuvers according to COLREG rules.

This paper is an extended version of our preliminary work.

We expand the maritime game theory that we introduced in [10] to consider a multi-agent setting and illustrate this extension with related models.

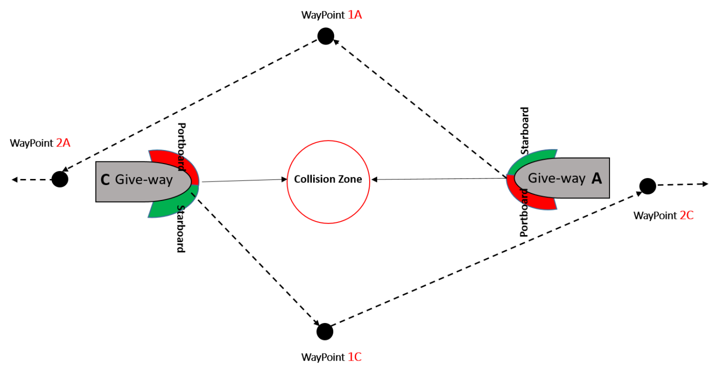

Figure 1: Autonomous Navigation of multi-vessel

Related work

There has been a variety of studies on autonomous ship navigation obeying COLREG rules. Recently, in project MAXCMAS [12], COLREG rules have been implemented in collision avoidance module (CAM) software where a collision avoidance decision is generated and an action is taken as soon as a collision risk is detected. In spite of their various simulation tools, verification methods are discussed only implicitly.

There are a few publications on formal development of multi-agents using Statistical Model Checking (SMC) [3] [6]. In [3] the authors focus on mission planning in Multi-Agent Systems (MAS) where agents are expected to calculate collision-free paths and schedule their tasks, while the authors in [6] use the Iterated Prisoners Dilemma (IPD) game as a case study to demonstrate its practical usefulness through modelling and analysis in SMC.

Overview of the Case Study

When modelling navigation manoeuvres of autonomous ships, we focus on standard situations, addressed in COLREG. As an example, let us consider a scenario where two ships have head-on situation as depicted in Figure 1.

According to Rule 14 of COLREG [9]; when two power-driven vessels meet on reciprocal or nearly reciprocal courses, to avoid the risk of collision, each shall alter her course to starboard (right) so that each shall pass on the port (left) side of the other. In this case both vessels are give-way vessels and they should do the adjustment to avoid collision. The course adjustment will therefore be made to the starboard side. Both vessels are expected to navigate safely to another route returning to the initial route after the manoeuver.

Multi-agent reinforcement learning for maritime games

To analyse the navigation options of autonomous ships, and more importantly, to verify the navigation decisions, especially in combination with the other ships, we use game theory as a base formalism for modelling and for optimising the ships' navigation scenarios.

Reinforcement learning (RL) is commonly used for solving Markov-decision processes, where an agent interacts with the world and collects rewards [11]. Multi-agent Reinforcement Learning can be considered in the context of a game, a multi-player game in a shared environment where the optimal policy of an agent depends not only on the environment, but on the policies of the other agents as well [7]. To guarantee convergence to the global goal, coordination and cooperation between agents are required. In this setting, we assume that the agent may be able to observe the actions of other agents and the environment using some sort of sensor and ship-to-ship and ship-to-costal service communication media. For modelling multi-agent maritime games introduced in [10], we consider each vessel as a player who has access to the same set of actions to achieve a desirable outcome of the game. This means that we assume symmetry of players, i.e. each player having the same strategies, goals and rewards. As an extension of paper [10], instead of two players maritime game we introduce the notion of multi-agent maritime game to address most of the safety rules specified in COLREG.

Conclusions

The contribution of this paper is further developing the Maritime theory to capture multi-vessel navigation and constructing the formal model of the autonomous navigation using UPPAAL STRATEGO. The practical usability of our approach (maritime game) is to develop a theory for autonomous ships, safe navigation and for that purpose to analyse the navigation problem in a rigorous state-based model development. In this paper, the approach for the navigation control synthesis of safe navigation has been presented as a stochastic multi-player game with the goal of collision avoidance and reduction of navigation cost.

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