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Ship Collision Avoidance Using Scenario-Based Model Predictive Control *

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Abstract: A set of alternative collision avoidance control behaviors are parameterized by two parameters: Offsets to the guidance course angle commanded to the autopilot, and changes to the propulsion command ranging from nominal speed to full reverse. Using predictions of the trajectories of the obstacles and ship, the compliance with the COLREGS rules and collision hazards associated with the alternative control behaviors are evaluated on a finite prediction horizon. The optimal control behavior is computed in a model predictive control implementation strategy. Uncertainty can be accounted for by increasing safety margins or evaluating multiple scenarios for each control behavior. Simulations illustrate the effectiveness in test cases involving multiple dynamic obstacles and uncertainty associated with sensors and predictions.

Keywords: Autonomous Ships; Collision Avoidance; Trajectory optimization; Hazard; Safety;

1. INTRODUCTION

Rules for ship collision avoidance are given by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), (IMO). COLREGS was made for ships operated by a crew, but is to some extent applicable for automatic collision avoidance systems, as decision support systems for the crew or in autonomously operated and unmanned ships, Manley (2008); DNV-GL (2015); Rolls-Royce-Marine (2014); Elkins et al. (2010).

Ship collision avoidance control algorithms, many of them implementing compliance with the main rules of COLREGS, are discussed in Statheros et al. (2008); Tam et al. (2009); Kuwata et al. (2014). They generally do not scale very well to manage a large number of highly dynamic obstacles in dense traffic, and at the same time accurately take into consideration the dynamics of the ship, steering and propulsion system, as well as environmental disturbances such as winds and ocean currents. Some of the methods apply heuristic optimization methods such as evolutionary algorithms or A* search algorithms with a finite planning horizon, e.g. Szlapczynski (2011, 2006); Blaich et al. (2015); Lisowski (2005); Loe (2008). This motivates our investigation on a new approach that employs ideas from optimization-based model predictive control (MPC). MPC is a general and powerful control method that can numerically compute an optimal trajectory on a finite moving horizon based on predictions of obstacles' motion, robustly account for their uncertainty, employ a nonlinear dynamic vehicle model including environmental forces, and formalize risk, hazard, operational constraints and objectives as a cost function and constraints in an optimization problem. In fact, MPC has been extensively studied for collision avoidance in automotive vehicles, Shim et al. (2012); Gao et al. (2010), aircraft and air traffic control, Bousson (2008), ground robots, Liu et al. (2013) and underwater vehicles, Caldwell et al. (2010).

MPC's main limitations are related to the convergence of the numerical optimization. It is known that complex collision avoidance scenarios may lead to non-convex optimization formulations exhibiting local minimums, and that shortest possible computational latencies are highly desirable for real-time implementation. This makes it challenging to implement an MPC for collision avoidance, and the formulation of models, control trajectory parameterization, discretization, objectives, constraints, numerical algorithms, and representation of uncertainty need to be carefully considered. In order to reap the main benefits of MPC, and mitigate the issues related to local minimums, computational complexity and dependability, one can take a rather simple approach that turns out to be effective and with low complexity of software implementation. More specifically, in the literature on robust MPC the concept of optimization over a finite number of control behaviors is well established, e.g. Bemporad and Morari (1999); Scokaert and Mayne (1998). In its simplest form, it amounts to selecting among a finite number of control behaviors based on a comparison of their cost and feasibility, e.g. Bemporad (1989); Chisci et al. (2001); Kerrigan and Maciejowski (2003), although most approaches also incorporates optimization over some control parameters.

In this paper, we will consider a relatively small finite number of control behaviors, parameterized by offsets to the ship autopilot's course and propulsion command, and merely require evaluation of their performance by simulation. Additional scenarios are created by considering realizations of the uncertain factors such as obstacle trajectories and environmental forces. Hence, we completely avoid numerical optimization and the associated compu-

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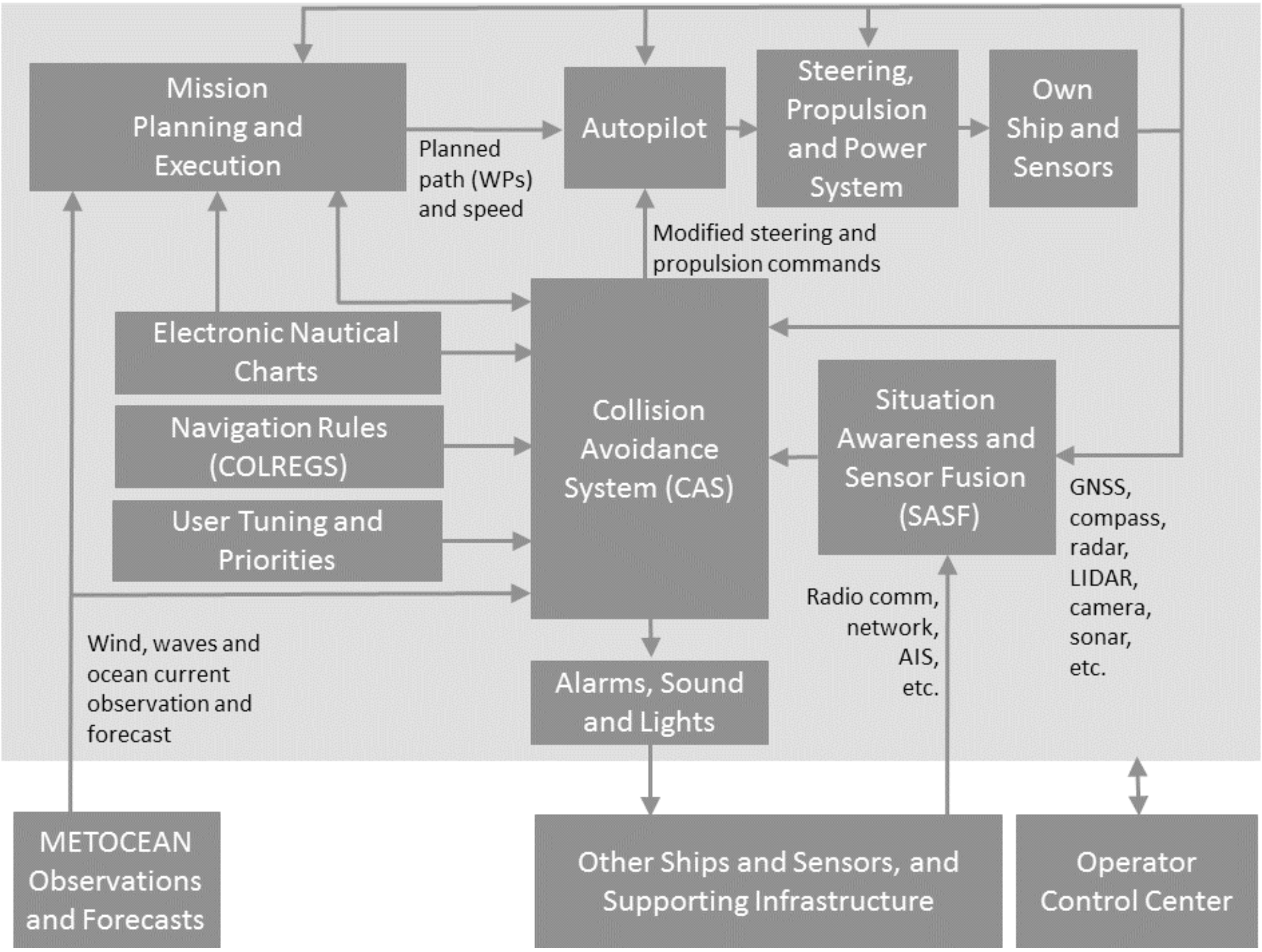

Fig. 1. System achitecture.

tation of gradients. This certainly restricts the degrees of freedom available for control, and the selection of the set of alternative control behaviors and scenarios must be carefully considered in order to ensure the required control performance and effectiveness of the collision avoidance system and COLREGS compliance.

2. SYSTEM OVERVIEW

Figure 1 illustrates the proposed system architecture, i.e. the main sub-systems and the information flow.

The ship's autopilot has two basic tasks, which are control of the ship's propulsion (typically constant thrust or power, or tracking of a speed reference) and steering (typically tracking of a course angle or path between waypoints). The autopilot interacts with the ship's steering, propulsion and power system in order to execute this task.

Commands to the autopilot, in terms of a nominal speed and nominal path, are given by a high level mission planning and execution system. It plans the mission in order to meet its objective (destination, time of arrival, fuel costs, etc.) while avoiding grounding and collision with mapped hazards that are identified in Electronic Nautical Charts (ENC). This planning often takes into account observations and forecasts of winds, waves and ocean currents provided by METOCEAN services.

The own ship has a set of basic sensors that are used to support navigation, including position and velocity-over-ground provided by GNSS (Global Navigation Satellite Systems) as well as heading provided by a compass. In addition, most ships have a maritime radar system with automatic radar plotting aids (ARPA) in order to detect and track fixed and moving obstacles. Ship's that are designed for autonomous or unmanned operations might also have addition sensors that provide redundancy and potentially enables them to detect and track a wider range of potential obstacles using LIDAR and cameras that can be used to scan the environment of the ship, Elkins et al. (2010); Wolf et al. (2010); Huntsberger et al. (2011). Cameras and microphones may also be needed to receive sound and light signals from other ships and traffic infrastructure.

The use of transponders, radio communication and networking with suitable protocols enable the other ship's to share their position and planned trajectories. Larger ships commonly use AIS (Automatic Identification System) today, and more extensive information sharing is emerging as communication technology is becoming more available and supported by terrestrial or satellite-based communication infrastructure. [1]

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[1] One may imagine that in the future there will be increased information sharing among vehicles, and by introducing standardized traffic control protocols and collision avoidance algorithms, the ships' collision avoidance systems will be able to quickly negotiate and