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Distributed model predictive control for vessel train formations of cooperative multi-vessel systems

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ABSTRACT

Recently, the cooperative control of multiple vessels has been gaining increasing attention because of the potential robustness, reliability and efficiency of multi-agent systems. In this paper, we propose the concept of Cooperative Multi-Vessel Systems (CMVSs) consisting of multiple coordinated autonomous vessels. We in particular focus on the so-called Vessel Train Formation (VTF) problem. The VTF problem considers not only cooperative collision avoidance, but also grouping of vessels. An MPC-based approach is proposed for addressing the VTF problem. A centralized and a distributed formulation based on the Alternating Direction of Multipliers Method (ADMM) are investigated. The distributed formulation adopts a single-layer serial iterative architecture, which gains the benefits of reduced communication requirements and robustness against failures. The impacts of information updating sequences and responsibility parameters are discussed. We furthermore analyze the scalability of the proposed method. Simulation experiments of a CMVS navigating from different terminals in the Port of Rotterdam to inland waterways are carried out to illustrate the effectiveness of our method. The proposed method successfully steers the vessels from different origins to form a vessel train. Due to the effective communication, vessels can timely respond to the velocity changes that others make. After the formation is formed, the distances between vessels become constant. The results show the potential to use CMVSs for inland shipping with enhanced safety.

1. Introduction

1.1. Background

Autonomous vessels have been developed for more than 20 years. Many works have been done to improve the autonomy of vessels (see Campbell et al., 2012; Liu et al., 2016). Seeing the advantages of multi-agent cooperation, including robustness, reliability and efficiency, an increasing number of researchers pay attention to the cooperative control of multiple vessels in recent years.

The advantages of cooperation between vessels are also the reasons that motivate the related research. Firstly, cooperation can enhance the safety of waterborne transport with communication between vessels. In current waterborne transport systems, vessels do not actively coordinate their actions with others. When encountering other vessels, vessels may misunderstand the intentions of others, which may lead to oscillation (Van den Berg et al., 2008) and even collisions (Kujala et al., 2009). Communication among the vessels can provide additional information, such as data about the objects beyond the reach of sensors, the intentions of others, etc. The additional information can assist agents in negotiating and collaborating with others to take effective actions. Secondly, inland

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shipping can benefit from Vessel-to-Vessel and Vessel-to-Infrastructure cooperation. For instance, with cooperation, vessels can coordinate their voyage plans to avoid congestions at ports and locks (Li et al., 2016). Furthermore, when combining voyage planning with infrastructure scheduling, vessels can adjust their speed to arrive at a required time, and make better use of infrastructure resources (Li et al., 2015). Thirdly, with cooperation, a group of vessels can carry out tasks more efficiently and effectively, such as search and rescue, ocean sampling, hydrographic survey etc. (see Liu et al., 2016). Applications such as towing of large structures, underway replenishment and tandem loading need cooperation, as well.

Therefore, in this paper, we focus on the cooperation of multiple vessels. We propose the concept of a Cooperative Multi-Vessel System (CMVS). A CMVS is a system in which vessels utilize Vessel-to-Vessel (V2V) and Vessel-to-Infrastructure (V2I) communication to negotiate and collaborate with each other for the aim of improving overall safety, efficiency, or for performing specific tasks. As the first step, we hereby in particular focus on the V2V cooperation in a CMVS.

1.2. Related works

A number of methods have been proposed for the cooperative control of multi-agent systems, see Olfati-Saber et al. (2007), Murray (2007) and Ren and Beard (2008) and the references therein. Regarding the similarity of vessels and vehicles, existing studies on cooperative driving of vehicles can provide valuable references for the study of vessel coordination. Nevertheless, those methods and algorithms cannot directly be applied to the control of vessels. So far, the main focus of cooperative driving has been on longitudinal control (Monteil et al., 2014; Hafner et al., 2013). However, due to the large inertia and hydrodynamic influences, the execution time needed to accelerate or decelerate a vessel is much longer than to accelerate or decelerate a vehicle. In practice, steering (lateral control) is regarded as the ordinary practice of seamen to avoid collisions. Moreover, the movement of vessels is significantly affected by the external environment, such as wind, wave, and current, which brings more uncertainties in vessel motion control.

Recently, some approaches have been proposed for the cooperative control of vessels. Depending on the goals of cooperation, two types of research are found in the literature: formation tracking and collision avoidance. Formation tracking aims at steering a group of vessels to form a specific geometric configuration and move along a given path. Learning from the formation control of vehicles, most studies on vessel formation tracking employ the three approaches (Ihle, 2006), i.e., leader-follower architecture (Almeida et al., 2010; Shojaei, 2015; Liu and Bucknall, 2015), behavioral methods (Arrichiello et al., 2006), and virtual structures (Ihle et al., 2006), while considering the characteristics of vessels and external disturbances.

In the research on cooperative collision avoidance, vessels only communicate and cooperate with others when there are collision risks. In existing non-cooperative collision avoidance methods, such as potential field (Daily and Bevly, 2008), velocity obstacles (Huang et al., 2018), and optimization-based methods (Zhang et al., 2015), vessels have to predict the actions that other vessels may take. Instead, in the methods for cooperative collision avoidance, vessels share their intentions. The actions of the involved vessels are determined by following a certain protocol (Tam and Bucknall, 2013) or negotiating through iterations (Zheng et al., 2016). Tam and Bucknall (2013) proposed a cooperative path planning method for collision avoidance using the regulation, COLREGS, as a protocol. In Zheng et al. (2016, 2017), a coordinator was responsible for the coupling collision avoidance constraints. Agreements among vessels were reached through iterations alternate between the coordinator and local path following controllers.

However, the cooperative behavior of vessels in a CMVS for transporting goods is neither typical formation tracking nor cooperative collision avoidance. When sailing in ports, waterways, or canals, it is not necessary for vessels to maintain a specific configuration. Nevertheless, collision avoidance is not the only connection between vessels. For instance, vessels can share voyage plans to avoid a long waiting time at ports or locks; sailing in groups also help to keep the vessels being connected, especially when we consider the effective range of ship-borne sensors, which help them to deal with unexpected changes; another attractive advantage to motivate vessels sailing in groups is the potential of reduced drag forces (Ihle et al., 2006).

Due to the limitation of waterway boundaries, the cooperative sailing of vessels will result in train-liked formations. Therefore, we define the cooperative behavior of vessels in a CMVS as moving into a Vessel Train Formation (VTF). This behavior relaxes the constraints on formation keeping. At the same time, compared with cooperative collision avoidance, vessels in a VTF enjoy the benefits of sailing in groups with a closer connection.

1.3. Contributions

This paper focuses on Vessel Train Formation of Cooperative Multi-vessel Systems. A method based on Distributed Model Predictive Control (DMPC) is proposed to solve the VTF problem. The proposed method has a single-layer distributed structure. Each vessel determines its own actions. Agreements are achieved via serial iterative negotiations. Through communication, the formation and safety constraints are satisfied, and both local and overall performance can be improved. Compared with existing approaches, the proposed method has the following characteristics.

Firstly, the proposed method solves the VTF problem with a single-layer control structure. Existing cooperative methods usually consider multiple layers, in which a leader or coordinator is used to deal with coupling constraints. For example, in Zheng et al. (2016), there is a coordinator responsible for the collision avoidance constraint. Iterations are alternating between the coordinator and each vessel until agreements have been reached. On the contrary, there is no coordinator in our framework. The final agreement is achieved when the trajectory that a vessel finds is the same as the one it sends to others in the former iteration. The updating of