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Control of interacting machines in automated container terminals using a sequential planning approach for collision avoidance

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ABSTRACT

The control of automated container terminals is complex since Quay Cranes (QCs), Automated Guided Vehicles (AGVs) and Automated Stacking Cranes (ASCs) interact intensively for transporting containers, while collision avoidance of equipment must be ensured. This paper proposes a methodology to generate collision-free trajectories of free-ranging AGVs in automated container terminals, while minimizing the makespan of the whole container handling system. A hierarchical control architecture is proposed to integrate the scheduling of interacting machines and trajectory planning of AGVs. Following a so-called overall graph sequence by a scheduler, the collision-free trajectories of AGVs are determined by solving a collection of mixed integer linear programming problems sequentially. Simulation results illustrate the potential of the proposed methodology.

1. Introduction

Over the last decades, there has been a significant growth of global freight transport due to the enormous growth in international commercial trade. Over 60% of worldwide deep-sea cargo is now transported by containers (Stahlbock and Voß, 2007). As a transport hub in freight transport, a container terminal represents the interface between the modalities of vessel, barge, train and truck, providing flexibility and scalability for covering different geographical areas (Li et al., 2015). Therefore, the performance of container terminals influences freight transport significantly.

It has been demonstrated that automation could significantly increase throughput and reduce cost of container terminals (Liu et al., 2002, 2004). Due to these advantages, the research on automated container terminals has received much attention, wherein three types of decision problem are identified: strategic, tactical and operational (Vis and de Koster, 2003). Strategic decision problems concern the layout of the terminal (Zhen et al., 2012) and equipment selection of the terminal (Vis and Harika, 2004). Tactical problems typically focus on the capacity level of equipment and determine the necessary number of pieces of equipment for completing specific operations efficiently (Vis et al., 2005; Alessandri et al., 2008). At the operational level, the detailed operation of equipment for transporting containers should be determined. The operational level involves the most complex processes of the terminal operation, leading to extensive investigation of operational control of equipment (Voß and Stahlbock, 2004; Stahlbock and Voß, 2007; Carlo et al., 2014).

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The types of operational control of equipment can be categorized into two directions: scheduling and routing. In automated container terminals, unmanned pieces of equipment, e.g., Automated Guided Vehicles (AGVs) and Automated Stacking Cranes (ASCs), are used for transporting containers. The transport of containers involves the interaction of these different types of machines, leading to the scheduling problem of these interacting machines (Cao et al., 2010; Meersmans and Wagelmans, 2001; Chen et al., 2007, 2013). The routing problem is related to AGVs, aiming for generating feasible trajectories for safety reasons. Therefore, the routing problems focus on the avoiding collision and deadlock between different AGVs (Zeng and Hsu, 2008; Gawrilow et al., 2008).

Emerging technologies for more intelligent and autonomous AGVs (e.g., Gelareh et al., 2013) are being developed, and newly developed GPS-based AGVs are expected to enter the market (Carlo et al., 2014). This new AGV allows free-ranging behavior, which can shorten the driving distance considerably compared to fixed path guided vehicles using makers, wires, lasers or computer vision (e.g., mesh routing) (Duinkerken et al., 2006b; Carlo et al., 2014). However, the implementation of free-ranging AGVs brings great challenges for operational terminal control, since the planning problem of free-ranging AGVs for container terminals is more complex. On the one hand collision avoidance of AGVs must be considered for safety reasons, while AGVs need to cooperate with other types of machines (e.g., QCs and ASCs) for loading or unloading vessels on the other hand.

Currently, scheduling of interacting machines in container terminals typically neglects the actual trajectory planning of machines (see, e.g., Cao et al., 2010; Meersmans and Wagelmans, 2001; Chen et al., 2007, 2013). It is assumed that the operation of machines can be carried out without disturbances (e.g., due to possible collision conflicts); such a scheduling scheme cannot incorporate the disturbances resulting from collision avoidance consideration. Furthermore, the investigated routing problems of AGVs are based on the mesh routing layout instead of the free-ranging one. It is still not clear how a schedule of the interacting machines that maintains a high handling capacity when implementing free-ranging AGVs can be determined.

The main contribution of this paper is a methodology for scheduling of interacting machines taking collision-free trajectory planning for free-ranging AGVs into account. The scheduling includes determining the sequence of jobs for each particular piece of equipment and the time window during which each job is processed. A hierarchical control architecture is proposed in order to decompose the complexity of this problem. The job sequences for the pieces of equipment are determined by solving a hybrid flow shop scheduling problem, after which a so-called overall graph sequence is obtained. Given the overall graph sequence, the actual time window of each job incorporating collision-free trajectories of AGVs is determined by solving a collection of mixed integer linear programming problems sequentially. This paper extends the previous work (Xin et al., 2014) which investigates the case of one QC, multiple AGVs and multiple ASCs. There, only few AGVs are involved and the dynamics of the AGV is modeled in one dimension without considering collision avoidance. For the case of *multiple* QCs that requires more AGVs, collision avoidance must be considered. The collision avoidance is considered using 2-dimensional dynamics of the AGV in this paper.

This paper is organized as follows. Section 2 describes the discrete-event dynamics and the continuous-time dynamics of a typical automated container terminal. Section 3 proposes a sequential planning approach for generating the schedules, taking into account the collision-free trajectory planning. Section 4 illustrates the proposed trajectory planning approach in a number of representative simulations. Section 5 concludes this paper and provides directions for future research.

2. Modeling of container terminal dynamics

In general, in a container terminal there are multiple types of equipment used to handle containers (Stahlbock and Voß, 2007). A container terminal is referred to as an automated container terminal when the equipment can be controlled fully automatically without any human intervention. In an automated container terminal, multiple Quay Cranes (QCs), multiple AGVs and multiple ASCs work interactively for unloading or loading a vessel.

The handling operation involves the combination of discrete-event dynamics and continuous-time dynamics. For a piece of equipment, discrete events take place when a container is transferred from one piece of equipment to another. Meanwhile, the continuous dynamics, i.e., the position, the speed and the heading (if applicable) of the piece of equipment, evolve between these discrete events. The dynamics of transporting containers can therefore be represented by the combination of discrete-event dynamics and continuous-time dynamics.

As addressed in Xin et al. (2014), the combination of those dynamics can be considered as two levels aimed at reducing the control complexity of automated container terminals. The higher-level represents the discrete-event dynamics, while the lower-level represents the continuous-time dynamics. The actual operation of the machines is determined by the coordination of these two levels. Below the discrete-event model for the interaction of equipment and the continuous-time model for equipment will be discussed in detail.

2.1. Higher-level discrete-event dynamics

In the system that we consider, there are multiple QCs, multiple AGVs, and multiple ASCs for unloading a vessel. The discrete-event dynamics represent within which time interval and in which sequence a number of containers is handled by these pieces of equipment. The operations of the three types of machines can be considered as a three-stage hybrid flow shop, as proposed in Xin et al. (2014) for the case of only one QC. In a hybrid flow shop, a so-called job has to pass through a