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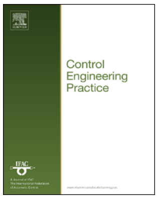

Event-driven receding horizon control for energy-efficient container handling

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ABSTRACT

The performance of container terminals needs to be improved to adapt the growth of containers while maintaining sustainability. This paper provides a methodology for determining the trajectory of interacting machines that transport containers between the quayside area and the stacking area in an automated container terminal. The behaviors of the interacting machines are modeled as a combination of discrete-event dynamics and continuous-time dynamics. An event-driven receding horizon controller (RHC) is proposed for achieving energy efficient container handling. The underlying control problems are hereby formulated as a collection of small optimization problems that are solved in a receding horizon way. Simulation studies illustrate that energy consumption of container handling can indeed be reduced by the proposed methodology. Moreover, an assessment is made of performance of the proposed RHC controller under different types of uncertainties.

1. Introduction

Over the last decades, there has been a significant growth of global freight transport due to the growing commercial trade. Over 60% of worldwide deep-sea cargo is transported by containers (Stahlbock & Voß, 2007). The management of freight transport needs to accommodate this increasing demand for container transport. Intermodal transport (Crainic & Kim, 2007) is hereby considered frequently since it provides flexibility and scalability as different transport modalities can cover different areas with respect to transport distance. As an intermodal transport hub, a container terminal represents the interface among the modalities of vessel, barge, train and truck. Therefore, container terminals play a crucial role in freight transport.

The increasing amount of containers that arrive and depart with container ships provides much pressure for terminal operators. In 2000, the capacity of a container vessel was at most 6000–8000 twenty for equivalent unit (TEU); in 2013, the number of containers carried by a container vessel can be up to 18,000 TEU (Rodrigue, Comtois, & Slack, 2013), and this number is expected to increase further. The turnaround time of a container vessel could increase significantly, if no appropriate measures are taken. Hence, the handling capacity of a container terminal must be maximized to reduce the turnaround time of a container vessel. Meanwhile, energy consumption needs to be reduced to adapt sustainability. Contrarily to building new terminal infrastructure, terminal management can be improved in order to maximize the performance of the existing infrastructure, possibly in an environmental friendly way.

The research on the operational management of container terminals can be divided into two categories: the analytical approaches and the simulation approaches. The analytical approaches address the mathematical formulation of the management problem and search for the optimal solution for performance improvements (e.g., makespan Cao, Lee, Chen, & Shi, 2010; Chen, Lee, & Cao, 2012; van Boetzelaer, van den Boom, & Negenborn, 2014). Typically the analytical approach is to solve a scheduling problem mathematically by minimizing the makespan of the handling operations (i.e., the finishing time of all transport jobs). The simulation approaches model the dynamical behavior of a container terminal by means of computer programming languages (e.g., agent-oriented programming (Xiao, Li, & Chun, 2011) and object-oriented programming (Bielli, Boulmakoul, & Rida, 2006; Duinkerken & Ottjes, 2000), which can then be used to evaluate different management policies.

Despite the accumulation of literature on improving the performance of container terminal control (see, e.g., Stahlbock & Voß, 2007), little attention has been paid to energy efficiency of container terminals. Energy efficiency of container terminals is discussed merely at the strategic level (Rijsenbrij & Wieschemann, 2011; Wijlhuizen & Meeussen, 2008), instead of at the operational level. At the operational level, energy efficiency is expected to be obtained, during the real-time operation of equipment. In real-time operation uncertainties (e.g., operation delays and the precise time at which new containers arrive) can change the process of transporting containers and influence energy efficiency of the

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Nomenclature

Variables	Definition
x_{ij}	$x_{ij}=1$ means that job j is handled directly after job i in stage 1, otherwise $x_{ij}=0$
y_{ij}	$y_{ij}=1$ means that job j is handled directly after job i in stage 2, otherwise $y_{ij}=0$
z_{ij}	$z_{ij}=1$ means that job j is handled directly after job i in stage 3, otherwise $z_{ij}=0$
t_i^h	the processing time of operation O_i^h with $h\in\{1,2,3,4\}$
a_i	the starting time of O_i^1, i.e., the time at which the QC handling job i leaves P_i^2
b_i	the starting time of O_i^2, at which the AGV handling job i leaves P_i^2
c_i	the starting time of O_i^3 for the ASC and the departure time of O_i^4 for the AGV
M	a large positive number

container handling system. Therefore, real-time decisions must be determined to adjust changes in the dynamically operating environments of container terminals. The literature that does consider the operational level, usually considers an open-loop perspective (Bielli et al., 2006; Cao et al., 2010; Chen, Bostel, Dejax, Cai, & Xi, 2007; Duinkerken & Ottjes, 2000; Xiao et al., 2011), which is not able to handle these uncertainties. In this open-loop perspective, an open-loop controller considers an entire scheduling problem once as the off-line solution. Typically the open-loop controller focuses on the control of discrete-event dynamics, neglecting of highly simplifying any continuous-time dynamics. In particular, the control of the continuous-dynamics is simplified as a fixed driving behavior locally (Duinkerken & Ottjes, 2000). Consequently, it is still not clear how energy efficiency can be achieved when it comes to container terminal management for real-time operation.

The main contribution of this paper is to investigate a methodology for improving energy efficiency of the container handling system during real-time operation, which reduces the computation burden and handles uncertainties. Hereby, the handling capacity and the energy consumption are both considered. A container handling system is modeled as the combination of discrete-event dynamics and continuous-time dynamics. We propose an event-driven receding horizon controller (RHC) for scheduling and rescheduling all operations involved in carrying out a number of jobs in an energy-efficient way. This RHC controller reduces the computation burden significantly compared to the open-loop scheduling problem. The control actions of the supervisory controller are determined using the state measurements of the ongoing operations. The trajectory relevant to each operation is hereby determined on-line by receiving the updated operations times from the supervisory controller. The proposed RHC controller is tested for different numbers of containers to be transported. The proposed supervisory controller can be used for real-time energy-efficient handling when two common types of uncertainties (in operation delays and precise arrival time of new containers) are considered.

The remainder of this paper is organized as follows: Section 2 describes the discrete-event dynamics and continuous-time dynamics of the container terminal separately. Section 3 proposes an event-driven RHC controller for carrying out the operations of jobs. Section 4 compares the performance of the proposed RHC controller and the existing controller. Section 5 concludes this paper and provides directions for future research.

2. Modeling of equipment

In general, in a container terminal multiple quay cranes (QCs), multiple automated guided vehicles (AGVs) and multiple automated stacking cranes (ASCs) are used for transporting containers from a vessel to the stacking area and vice versa. The size of containers can be 20 ft or 40 ft and their weight can vary based on the transported cargo. The groups of containers have the same arrival time at the terminal but may have different departure times and different storage places in the stack depending on their destination. In this paper, we consider the typical situation in which a number of containers have to be moved from a particular bay in a vessel to several stacks using one QC, multiple AGVs and multiple ASCs. The containers destined for a particular stack are assumed to have the same destination in the stack. The vessel and the stacking area are considered as components that do not actively handle containers. Instead the QC picks up a container from the vessel and then unloads it to the AGV. The AGV moves the container from the quayside to the stacking area, where it is unloaded by the ASC. The ASC transports the container to the storage position. Ideally the maximal handling capacity at lowest energy consumption is obtained. For this, the accelerations of the machines, regarded as control actions, have to be determined in an optimal way. The layout of the container handling system is shown in Fig. 2.

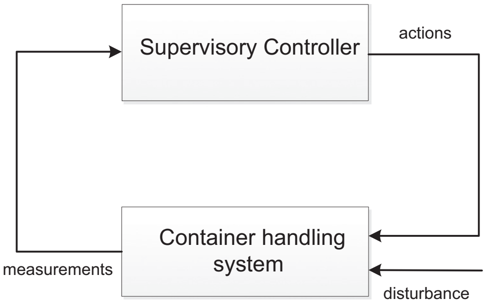

Fig. 1. The structure of the rescheduling scheme.

A machine refers in this paper to a piece of equipment used for transporting containers in the terminal. A machine can be a QC, an AGV or an ASC. Discrete-event dynamics and continuous-time dynamics, accounting for the handling capacity and the energy consumption, need to be considered. The dynamics of the interacting machines are driven by discrete events when a container is transferred from one machine to another one. Meanwhile, the continuous-time dynamics, e.g., the horizontal position, the speed and the acceleration of equipment, evolve for machines between the changes of discrete states. Both the modeling of discrete-event dynamics and continuous-time dynamics are presented in the following parts.

2.1. Modeling of interacting machines

The operations of the three types of machines can be considered as a three-stage hybrid flow shop. Here we extend the model proposed in Xin, Negenborn, & Lodewijks (2014a) and emphasize the operation of an individual machine which is used for rescheduling operations of interacting machines. In a hybrid flow shop, each job has to pass through a number of stages. At each stage a number of identical machines can be operated in parallel to process a part of a job. Each job is processed by the same sequence