

Optimal control for coordination of equipment in automated container terminals

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Abstract

Over the last decades there has been a considerable growth in freight transportation. Most of the transportation of consumer goods is realized by shipping those goods in standardized containers across different modalities of transportation. The requirements of high productivity and container throughput at low costs bring operational challenges to terminal operators as physical infrastructure is limited and the volume of container transshipment increases. We are investigating how to effectively manage the volume growth by considering a more integrated way of looking at transport of freight, i.e., by considering transport over one large-scale transport system, done in an inter-modal way. In particular in this paper, we propose to use the hybrid automaton modeling framework for modeling the handling of containers by equipment. Distributed model predictive control will be employed to achieve the desired performance.

Keywords

Automated container terminals, model predictive control, modeling of hybrid systems

1 Introduction

1.1 Intermodal container terminals

During the last decades, there has been a significant growth of global freight transport due to the enormous commercial trade. Over 60% of worldwide deep-sea general cargo is transported by containers (Stahlbock & Voß, 2007). Accordingly the management of freight transport needs to accommodate this increasing demand of containers. Intermodal transport (Crainic & Kim, 2007) is widely used nowadays since different transport modalities can cover different areas with respect to transport distance, bringing flexibility and scalability.

Intermodal transport can be defined as the transport of a person or a load from its origin to its destination by a sequence of at least two transport modes. The transfer from one transport mode to another for containers is performed at an intermodal container terminal. Usually an intermodal container terminal represents the interface among the modes of vessel, barge, train and truck. Therefore, container terminals play a significant role in freight transport.

Typically container terminals handle three types of containers: inbound, outbound and transshipment containers. Inbound containers are shifted from container vessels and are delivered to customers on land via railways or trucks. Outbound containers are the opposite of inbound containers. The containers from railways and trucks are transported to container vessels. Transshipment of containers relates to the shift of containers from ship to ship.

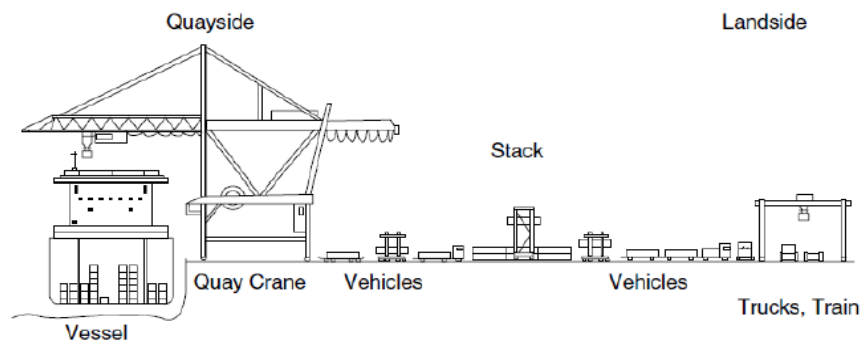


Figure 1: Overview of a typical container terminal system (Voß & Stahlbock, 2004).

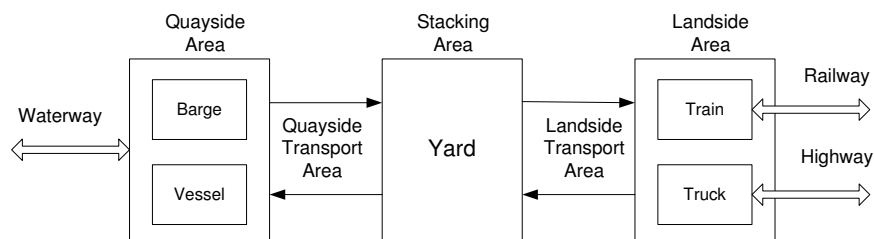


Figure 2: The main areas in a container terminal.

The overview of a typical intermodal container terminal system is given in Fig. 1. It illustrates the handling areas and the equipment employed in a container terminal visually. An intermodal container terminal basically consists of the areas as shown in Fig. 2:

1. Quayside area

In the quayside area, vessels are located at the berth for loading or unloading of containers using Quay Cranes. Single or dual-trolley cranes can be used in the quayside area.

2. Stacking area

The stacking area is considered as a place for temporary storage of containers that are potentially shifted from one transport mode to another. Container stacking is either performed by gantry cranes or by straddle carriers. Stacking cranes could be rail-mounted gantry cranes or rubber-tired gantry cranes. The stacking area is sometimes also referred as the yard area.

3. Landside area

The landside area is connected to the mainland where trucks pass through gates and trains are loaded and unloaded by gantry cranes.

4. Quayside transport area

Between the quayside area and the yard area, containers are transported by trucks with trailers, multi-trailers, AGVs or straddle carriers. A group of vehicles owned by the terminal is referred to the vehicle fleet.

5. Landside transport area

Between the yard area and the landside area, containers are moved by trucks with trailers, multi-trailers, or straddle carriers.

The operations of unloading and loading containers at a container terminal can be described as follows: When a vessel arrives at a berth, the containers have to be taken off the vessel by quay cranes. Then each container is transported by a vehicle from the quayside area to the yard area after being unloaded from a quay crane. A stacking crane will pick up the container and locate it at one position in the stacking area. Later the containers are retrieved by a stacking crane from the stacking area and transported to another mode, such as barge, train or truck.

A container terminal can be categorized as a manual or an automated container terminal. In a manual container terminal the handling machines of containers are operated by humans. In an automated container terminal containers are all transported by automated machines. In an automated container terminal, quay cranes, AGVs and automated stacking cranes are used to handle containers. The use of human operations is minimal in an automated container terminal.

This paper is organized as follows: In Section 2, the motivation for the research problem considered is given. In Section 3, a literature study of existing approaches is presented from a system and control perspective. The methodology proposed is provided in Section 4 as potential answer to the research question. First steps to realizing the methodology are given in Section 5.

2 Problem Statement

The main research question is how to improve the performance of a container terminal. This involves two components: throughput maximization and emission reduction.

2.1 Throughput maximization

As mentioned in Section 1, there is an increasing demand in freight transport that is realized by containers. Meanwhile, the size of containerships has increased significantly (Rodrigue et al., 2009). The increasing amount of containers that arrive and depart with the containerships provides much pressure for terminal operators. The throughput in which the number of container is handled per hour is expected to be improved. New terminal construction and terminal management are two main ways to reduce this pressure. New infrastructure can be built to accommodate more containers at a port, although this is costly. Alternatively terminal management can search for the maximum throughput of existing infrastructure is a cheaper way. A number of works with respect to improving the throughput of container terminals has been done (Vis & de Koster, 2003; Voß & Stahlbock, 2004; Stahlbock & Voß, 2007; Günther & Kim, 2007; Angeloudis & Bell, 2011; van Zijverden & Negenborn, 2012).

The operations involving containers in the terminal, such as unloading and loading, do not rely on single equipment but on coordination of multiple pieces of equipment normally. Hence, the move of one container between one transport mode and the stacking area involves multiple machines or vehicles. The modeling of handling containers for a complete container terminal becomes very complex when the number of equipment considered increases.

Due to this complexity of modeling, existing literature has considered either only individual areas in details, or integrated areas in a highly simplified way. Research dealing with individual areas include the quayside area (Park & Kim, 2003; Liang et al., 2009), the quayside transport area (Duinkerken & Ottjes, 2000; Vis et al., 2005; Angeloudis & Bell, 2010) and the stacking area (Chen & Langevin, 2011; Ng & Mak, 2006; Lee et al., 2008). For the quayside area, (Park & Kim, 2003) and (Liang et al., 2009) study the problem of scheduling quay cranes and allocating berth. As to the quayside transport area, (Duinkerken & Ottjes, 2000) study the problem of quayside transport which is carried out by AGVs; (Vis et al., 2005) investigate the minimization of vehicle fleet size; (Angeloudis & Bell, 2010) propose an assignment problem for AGVs. Regarding the stacking area, multiple stacking cranes and single stacking crane are considered by (Chen & Langevin, 2011) and (Ng & Mak, 2006) respectively; the restacking problem is discussed by (Lee et al., 2008).

Integrated approaches have been studied as well (Soriguera et al., 2006; Lee et al., 2009; Petering, 2011). (Soriguera et al., 2006) consider different strategies of vehicles both for the quayside transport and the landside transport area. (Lee et al., 2009) combine the truck scheduling and the stacking allocation problem. (Petering, 2011) presents nine problems within the stacking yard and the quayside transport area which influence the productivity of quay cranes.

Nevertheless, the handling of a container depends on the actions of multiple pieces of equipment from areas all over the container terminal. The management of a complete

terminal is not simply the sum of management for independent areas. Currently, there is still a gap between the control of one part of a terminal and a complete terminal. Therefore, control of a complete terminal is investigated since it can improve the throughput of the terminal as a whole.

2.2 Emission minimization

Besides the need to increase the throughput of container terminals, there are other objectives for terminal operators. One of these objectives involves the increasing concern about environmental issues in container terminals. Making the terminal more environmental friendly deserves increasing attention (Cannon, 2009; Wijnhuizen & Meeussen, 2008). The direct emission of PM_{10} and NO_x come from the fuel powered equipment (straddle carriers, AGVs) and the indirect exhausted CO_2 come from the electricity generation for electric equipment (quay cranes, automated stacking cranes).

The solution to the sustainability of container terminals can be addressed by improving individual equipment or by coordinating the use of the equipment in the system as a whole. For individual equipment, the crane is investigated by (Hellendoorn et al., 2011). The solution for the whole system perspective is still unclear.

2.3 Research questions

For a container terminal, the equipment has dynamics that not only influence the throughput of a container terminal but also produce the emissions to the environment. The operations of individual pieces of equipment for handling containers are coupled. There is a large number of equipment, leading to a large number of variables playing a role in the terminal. In addition the environment of a container terminal is dynamically changing. Therefore the control of a complete terminal leads to difficulty and complexity of modeling and control. This motivates the research question:

How to control fully automated container terminals to improve the volume throughput in order to accommodate the growth of containers in a sustainable way?

This brings about several sub-questions:

1. How to model a container terminal efficiently for control purposes?
2. How to control complete automated container terminals in order to achieve the maximal throughput?
3. How to reduce emission of automated container terminals?
4. How to balance the tradeoff between the throughput and emissions?

Work in this area has been done before. It has, however, so far, not resulted in satisfactory solutions. In the next section we review some of the existing approaches.

3 Literature review

As a basis for making comparison and understanding existing approaches for improving container terminals performances, we make a distinction between the modeling and

control. On one hand, modeling emphasizes describing the behavior of a container terminal; on the other hand, control provides solutions to research problem characteristics based on a developed model. Existing approaches for the modeling and control of a container terminal can be generally addressed either from a programming-based or a mathematics-based perspective.

3.1 Programming-based approaches

Programming-based approaches use a computer language to describe the behaviors of equipment for handling containers in a container terminal. Object-oriented approaches (Bielli et al., 2006; Ha et al., 2007) and agent-oriented approaches (Xiao et al., 2011; L. Henesey & Persson, 2009; Thurston & Hu, 2002) are mainly used. Based on a programming model of a container terminal, the way in which the performance of a container terminal can be improved can be analyzed.

3.1.1 Object-oriented approaches

Object-oriented approaches provide a programming paradigm using objects which are data structures consisting of data fields and methods together with their interactions to design applications and computer programs. In object-oriented programming, the equipment of a container terminal can be modeled as objects. Each object contains a set of attributes and a set of methods. The attributes can include the physical features of equipment. The methods are functions that enable the object to manipulate its attributes and communicate with other objects (Martin & Odel, 1992). Based on the objects that describe equipment, a container terminal is constructed.

In (Bielli et al., 2006) a distributed object-oriented model is developed with a standard visual modeling language UML to simulate container terminal operations in order to improve the efficiency of management. This simulator, which is discrete-event driven, is used to evaluate (un)loading operations in terms of time and costs as well as different storage strategies and resource allocation. The control policies of storage are heuristics. Performance indicators such as the global productivity, the net productivity, quay crane, yard crane utilization index, shuttle utilization index and average ship waiting time are considered.

(Ha et al., 2007) proposes an object-oriented model with detailed equipment for container terminals. This model reproduces detailed behavior of container terminal equipment, including not only movements of yard tractors or cranes but also those of trolleys, spreaders and other machinery. This simulation is based on Plant Simulation which is commercial discrete-event simulation. The objective of a container terminal is assessed from various points of view:

1. berth productivity with regards to the speed of yard cranes and the number of yard tractors
2. berth productivity with regards to the number of blocks and the speed of yard cranes
3. berth productivity with regards to the cycle time of quay cranes and the number of blocks

The control methods are heuristic, implemented by altering the speed and number of machine as control variables under the constraint of assumed generation of vessel pattern.

The object-oriented approach offers one framework to describe the dynamics of a container terminal. It can describe the behavior of equipment in the terminal. However, object-oriented approaches typically emphasize the discrete-event dynamics without consideration for continuous timed dynamics. The object-oriented approaches cannot provide on-line solutions to adjustment of environment because it provides off-line optimization. The control methods are more heuristic, for instance by changing the number and the speed of equipment.

3.1.2 Agent-oriented approaches

Besides the object-based approach, the concepts of software agents (Xiao et al., 2011; L. Henesey & Persson, 2009; Thurston & Hu, 2002) can be used to model and control a container terminal. In contrast to the object-oriented programming approach, agent-oriented programming considers “intelligent” agents which can act on their own behalf and interact with a software environment. The agent-oriented approach simulates the simultaneous operations and interactions of multiple agents. In agent-oriented approaches agents are classified into groups in which the higher layer manages the lower layer.

Based on agent-oriented approaches, a large complex problem can be decomposed into a few smaller and manageable ones with information exchange between the agents. So the management of a container terminal can be solved in a more efficient and effective way by reducing the difficulty of management of a container terminal.

On the basis of the ideas of software agents, (Xiao et al., 2011) proposes a distributed agent system for dynamic port planning and scheduling, as shown in Fig. 3. A whole terminal is considered in the model which consists of four agents: a port planning manager, a berth control agent, a shuttle allocation agent and a yard storage agent. The port planning manager is regarded as the manager who maintains all the necessary information and communicates with all the other three local agents. Based on the berth schedule and the shuttle availability, a yard storage agent is used to work out the storage allocation and the truck and the train schedule for transporting containers out of the terminal. Multiple computers are used to reduce the computation burden and therefore improve the performance of port scheduling. The objective of this approach is to build up distributed coordination among different managers. The berth scheduling is obtained by a genetic algorithm-enhanced scheduling toolbox. The speed of shuttles is considered for evaluating the operations of shuttles. The operations of yard storage are not mentioned in this scheme. This system pays much attention to construct a distributed communication and negotiation scheme for the upper layer of the terminal not for the equipment of a terminal.

(L. Henesey & Persson, 2009) develops an agent-based simulation architecture developed to evaluate the operation policies for transshipping containers. A decentralized structure is proposed for assisting human container terminal operators in the decision making process. This decentralized simulation is based on four agents: port captain, ship agent, stevedore and terminal manager. Those four agents can be connected with each other by exchanging information on scheduling. Quay cranes and stacking cranes

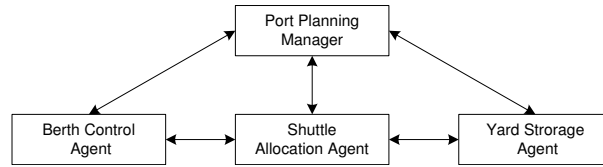


Figure 3: The distributed agent system for port planning and scheduling (Xiao et al., 2011).

are considered as additional cranes that are managed by the stevedore manager. Each agent assigns all the equipment or components within its subsystem. The total distance for all straddle carriers, the average ship turnaround time, the average waiting time and the total costs are used as the performance together. Different policies of sequencing, berthing and stacking are compared. The results indicate a short turnaround time of vessels can be achieved by stacking by destination policies.

Similarly, (Thurston & Hu, 2002) proposes a distributed multi-agent framework to increase the productivity of terminal and reduce the turn-around time of vessel. The yard is divided into the short-term area and the long-term area. Four types of agents are modeled to represent physical resources of the system: quay crane agent, straddle carrier agent, traffic agent and manager agent. Every piece of equipment is controlled by one agent correspondingly. The system was prototyped in Java. The objective of distributed multi-agent approach is to maximize the utilization of quay cranes whilst using a minimal amount of yard vehicles. The paper emphasizes the proposal of the architecture; and numerical result is not available yet.

In brief, agent-oriented approaches emphasize the architecture of communication and negotiation for the upper layer which is close to the manager. Meanwhile, for the lower level close to the equipment, the control problem is simplified as an assignment problem or scheduling problem without consideration for dynamics of equipment.

3.2 Mathematics-based approaches

Besides the programming-based approaches, mathematics-based approaches have been investigated. Such approaches use mathematical languages to model and control container terminals have been investigated.

(Alessandri et al., 2008) proposes a dynamic discrete-time model to consider the management of available handling resources in a strategic view. The model describes the container flows as a system of queues. The handling equipment, like the quay cranes and the yard cranes, has a certain handling capability to unload, load or transport containers. Waterway, railway, highway are connected to the container terminal in terms of intermodal transport. The objective of this approach is to minimize the lay times of carriers, i.e. ships, trains and trucks by giving different priorities. Due to its prediction, model predictive control is implemented to optimize the resource management. The one-step-ahead strategy is adopted to minimize the objective function by taking the dynamical model and constraints of inputs and control variables. The inputs of the controller are the arrival time and quantity of containers from vessel, trains and trucks. Assuming the handling abilities of different machines are known, the percentages of those limited handling machines corresponding to different queues are determined by solving this optimization problem.

Another alternative to consider the problem of resource allocation in a dynamic way is to use Petri nets and max-plus algebra. (Contu et al., 2011) proposes a mathematical model based on Petri Nets and max-plus algebra to describe the operation inside a container terminal at the operational level. The quayside area, the transport area and the stacking area are considered. The straddle carrier transport containers from the quayside area unloaded by a trailer to the stacking area as an import cycle. Other operations between the stacking area and the landside area can be modeled by using the similar framework. The operations characterizing this import cycle are represented as a connection of the places and transitions by a Petri Net model. The state equations which indicates the sequence of the firing times of all transitions is described by max-plus algebra. The firing time is the time when one transition is enabled. There is no control methods associated with this model. However, the sensitivity analysis of cycle time with regards to the firing time is discussed. The results show decreasing some values of delays does not reduce the cycle time.

In short, on the one hand, the modeling and control of all the equipment in a complete container terminal by means of mathematics is rather complicated. So the handling of equipment is described as handling capacity dynamically to simplify the model (Alessandri et al., 2008). On the other hand, the operations of equipment in a container terminal can be modeled as a Petri net being regarded as a discrete-event system (Contu et al., 2011). However, in that case there are no continuous-timed dynamics and no control actions for the equipment.

3.3 Potential improvements

Based on the discussion of different approaches above, a list for improvements of existing approaches is made:

- The continuous-timed dynamics and the discrete-event dynamics exist in the handling of containers in a container terminal. However, the continuous-timed dynamics and the discrete-event dynamics cannot be identified together in the existing dynamical models. The dynamics of the existing approaches represent either continuous-timed dynamics or discrete-event dynamics.
- On-line optimization for operational control of equipment has the potential to reduce the uncertainties of a container terminal, but this is hardly seen with the current approaches;
- The distributed control has the potential to improve the reliability of controller and reduce the computation burden for optimization. Nevertheless, most of approaches for control of a container terminal are done in a centralized way;
- The performance of container terminals can be improved by considering multiple objectives. Still, a single objective is typically considered in existing approaches;
- Good analysis is helpful for the control of a container terminal. The control strategies for software-based approaches are heuristic. The constraints on variables are hardly taken into account. It is therefore difficult to analyze the performance of a programming-based approach compared with the mathematical approaches.

4 Proposed methodology

To realize potential improvements pointed out above, we propose a methodology combining modeling of hybrid systems, model predictive control and distributed optimization. This methodology has a number of advantages:

- Modeling of hybrid systems combines both continuous-timed dynamics and discrete-event dynamics;
- Model predictive control considers a large number of variables with constraints, and can handle multiple objectives. It can enable a mathematical analysis for control of a container terminal.
- Distributed optimization has the potential to reduce the computational burden and provide on-line optimization. Below, each of those components is discussed further.

4.1 Modeling of hybrid systems

A hybrid dynamical system (Henzinger, 1996) is a dynamical system with both discrete-event dynamics and continuous-time dynamics. A hybrid automaton is a formal model for a mixed discrete-continuous system. Hybrid systems appear in many applications, like traffic and transportation, electricity distribution, and logistics. In a container terminal, the operations of containers handling equipment can be modeled as a hybrid automaton due to the presence of the following mix of discrete-event dynamics and continuous dynamics:

- Discrete-event dynamics

The dynamics of equipment are driven by discrete events when a container is handed over from one piece of equipment to another one. For instance, the transport of a container by AGVs is determined by the event that the unloading of a quay crane has finished. Additionally, a piece of equipment needs to change its actions when it is in different modes of operations, like unloading or waiting. A quay crane needs at some points to change its dynamics from moving a container horizontally to (un)loading vertically.

- Continuous dynamics

The continuous dynamics exist for equipment between the changes of discrete states. For example, an AGV has continuous dynamics while driving around between the ending of loading from one quay crane and the waiting of unloading by a stacking crane. The variables of position and speed change continuously.

Hence, the dynamics of equipment for containers can be modeled as the collection of multiple small interacting hybrid systems.

The components of a container terminal interacting between quayside and yard include vessel, quay crane, AGV and yard crane. Each component has a set of finite discrete states, in each of which there are continuous dynamics. Fig. 4, shows a hybrid system representation for an AGV. The model has five discrete modes: $s^1 - wait, s^2 -$

pickup, s^3 – *carry*, s^4 – *unload*, s^5 – *retrieve*. Each discrete mode has continuous dynamics $x(k+1) = f(s_i, x(k))$ where $x(k)$ is the position of the equipment, s_i is the corresponding discrete mode and f describes the evolution of the position. The transition from the discrete state s_i to the discrete state s_j can be triggered by the condition $G(s_i, s_j)$ when the transaction occurs. $R(s_i, s_j)$ resets the relating variables. Besides, other components like quay cranes and stacking cranes are presented similarly.

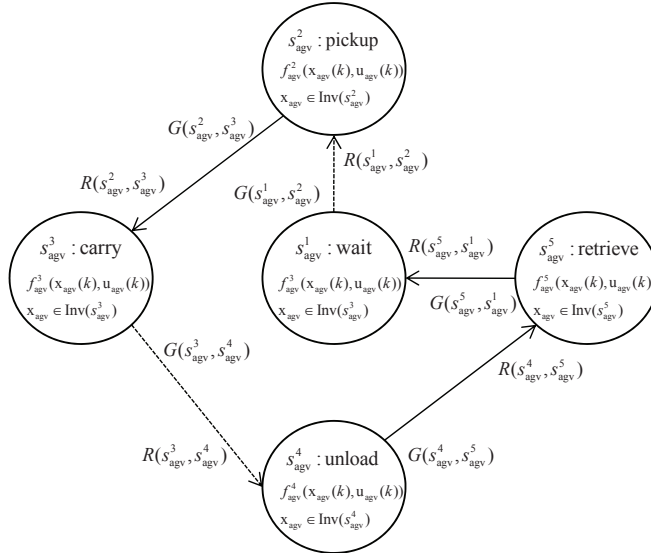


Figure 4: The automaton of an AGV.

4.2 Centralized Model Predictive Control for equipment

For control of equipment in container terminals used for handling containers, the controller has to determine the real-time planning trajectories that the equipment can follow. The jobs that indicate which containers have to be (un)loaded between one transport mode and the stacking area are assumed to be given. It is then the challenges to most efficiently control the equipment in order to handle the jobs.

Model Predictive Control (also known as receding horizon control or moving horizon control) (Camacho & Bordons, 2004; Rawlings & Mayne, 2009) has received much attention for finding control policies of complex and dynamical systems. Model Predictive Control has been successfully applied into the process industry (Morari & Lee, 1999; Maciejowski, 2002) and is currently receiving more attention in power networks (Geyer et al., 2003), road traffic networks (Hegyi et al., 2005), railway networks (De Schutter et al., 2002), supply chain management (Wang et al., 2007). Model Predictive Control has the following features:

- MPC can handle multivariable processes. There are a great number of equipment variables in a container terminal. MPC can take this into account.
- Intuitive to understand and tune
- MPC can handle constraints The variables of the systems have constraints as limitation. MPC can consider these constraints.

- MPC can handle actuator failures. As an on-line optimization technique, MPC can measure and detect the condition of actuators constantly and react timely.

Model Predictive Control has the following components:

- an objective function expressing which system behaviors and actions are desired;
- a prediction model describing the behavior of the system subject to action;
- possible constraints on the state, the inputs and the outputs of the system;
- possible known information about future disturbances;
- a measurement of the state of the system at the beginning of the current control cycle.

These control actions that achieve a desired performance are determined online by minimizing the cost specified through the objective function over a certain prediction horizon.

Considering the interactions of equipment for handling containers, one quay crane, one AGV and one automated stacking crane are used to transport one container. A job refers to transporting one container between one transport mode and the stacking area employing three pieces of equipment. For a number of containers, a number of pieces of equipment are used to handle these containers. All pieces of equipment is controlled by a MPC controller. The structure of the MPC controller is shown in Fig. 5. The MPC controller receives the position of all pieces of equipment and provides planning trajectories as actions to the equipment by taking the cost function and constraints on variables into account.

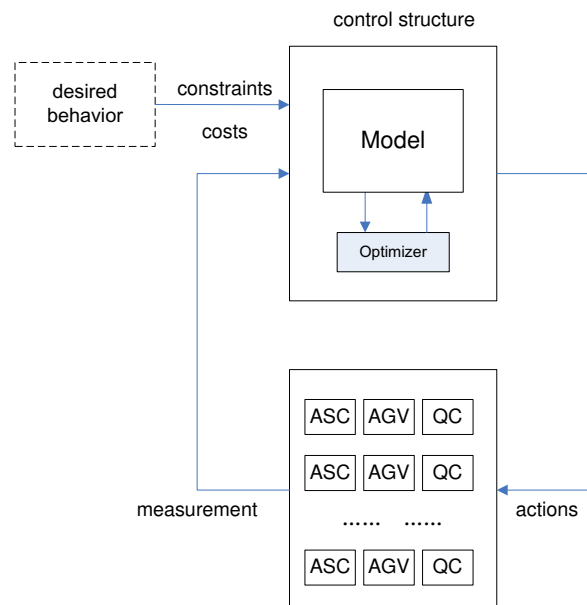


Figure 5: The structure of MPC controller.

Using the MPC framework, a desired performance for terminal operators can be decided upon by choosing appropriate actions for equipment of a terminal in a dynamical way.

4.3 Distributed control

Currently, most applications of MPC are implemented in a centralized way. The centralized controller has the knowledge of the overall system and computes all the control actions. For a large-scale dynamical system, this brings the following problems:

- The computational burden increases significantly when the size of the system becomes large;
- The maintenance of one controller for a whole system can be hard;
- The single controller may be vulnerable to failures.

Considering the concerns above, distributed model predictive control (Keviczky et al., 2006; Venkat et al., 2007; Giselsson & Rantzer, 2010) is gaining increasing attention for parallelizing the computation of limited-size control problems, localizing the maintenance and improving the reliability of the system.

Considering again the interaction of equipment for handling containers (one quay crane, one AGV, and one automated stacking crane) a distributed control scheme relating to a number of controllers can be formulated: one controller per piece of equipment. The distributed scheme is shown as Fig. 6 which is different from Fig. 5.

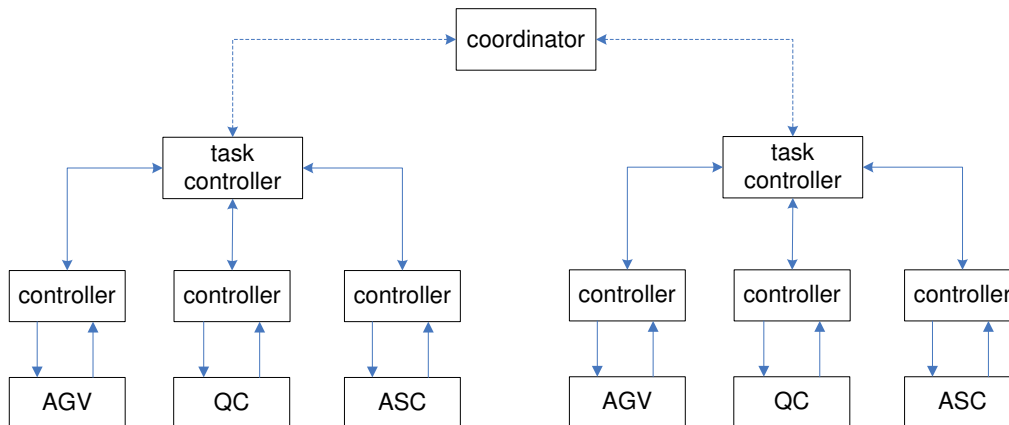


Figure 6: The structure of distributed MPC controller.

5 Modeling and control of equipment for a task controller in an automated container terminal

Considering a container terminal as a large-scale complex system, it is not realistic to construct the framework for control of a container terminal in one step. Rather, a number of steps will be carried out in the following, ultimately resulting in a methodology to improve the throughput of a container terminal in a sustainable. The control of equipment provides a certain handling ability in a container terminal, which can be used for (Lemos Nabais et al., 2012).

In particular, the following steps will be taken:

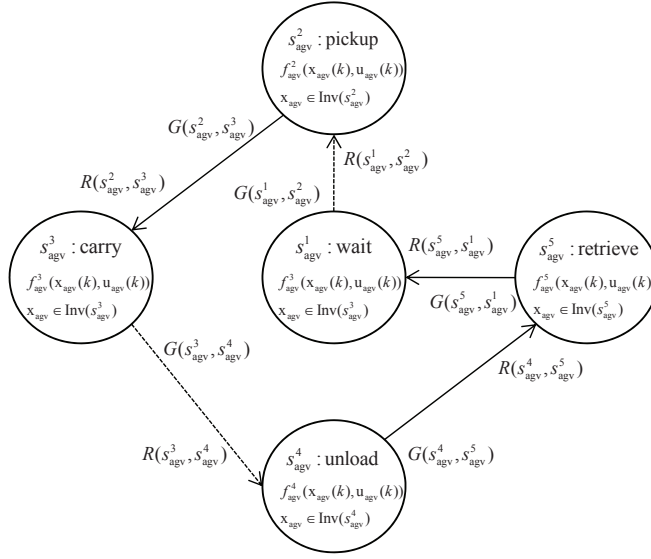


Figure 8: The hybrid automaton of AGV

one ASC, the continuous state $x(k)$ represents the position of the piece of equipment. The dynamics of the continuous state is given by:

$$x(k+1) = x(k) + u(k)\Delta t, \quad (1)$$

where $u(k)$ is the speed of the vehicle, considered to be a control variable. Constant Δt is the sampling time, equal to 10 second.

For the AGV, the model is as follows:

$$x(k+1) = x(k) + u_1(k)\Delta t \cos(u_2(k)) \quad (2)$$

$$y(k+1) = y(k) + u_1(k)\Delta t \sin(u_2(k)), \quad (3)$$

where $x(k), y(k)$ is the position of vehicle and $u_1(k)$ is the speed and $u_2(k)$ the direction angle of the vehicle. u_1, u_2 are considered to be control variables.

The hybrid automaton representation is translated into a form suitable for control using HYSDEL. HYSDEL (Torrison & Bemporad, 2004) allows modeling a class of hybrid systems described by automata. Based on HYSDEL, a Mixed Logic Dynamical (MLD) model (Bemporad & Morari, 1999) which describes the hybrid automaton can be built up for control and analysis. The formulated MLD is presented generally as follows:

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}_1\mathbf{u}(k) + \mathbf{B}_2\delta(k) + \mathbf{B}_3\mathbf{z}(k) \quad (4)$$

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{D}_1\mathbf{u}(k) + \mathbf{D}_2\delta(k) + \mathbf{D}_3\mathbf{z}(k) \quad (5)$$

$$\mathbf{E}_2\delta(k) + \mathbf{E}_3\mathbf{z}(k) \leq \mathbf{E}_1\mathbf{u}(k) + \mathbf{E}_4\mathbf{x}(k) + \mathbf{E}_5, \quad (6)$$

where $\mathbf{x}(k), \mathbf{y}(k)$ are the state and the output of the MLD model, $\mathbf{u}(k)$ and $\delta(k)$ are the continuous control variable and the logic control variable, $\mathbf{z}(k)$ is the auxiliary variable. This model can be used by the controller below.

5.0.2 Control

The objective of the controller of the equipment is to determine actions of trajectories such that the handling of the jobs is done efficiently. The following assumptions for the controller are made.

- The controller can receive the information from the equipment;
- It is possible to measure the position of each AGV, stacking crane and quay crane;
- The controller can provide actions to each piece of equipment.

The task controller coordinates the three controllers for equipment. The task controller for the complete processing is formulated in the following.

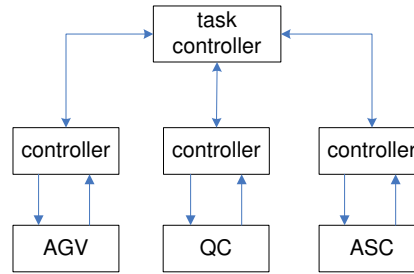


Figure 9: The task controller for the complete processing of a container.

Model predictive control can be implemented in (Torrissi & Bemporad, 2004) or (Löfberg, 2004) based on a MLD model to achieve a desired performance. An initial objective which refers to the turnaround time of a container is describe by $x(k)$, $u(k)$ and $\delta(k)$. A framework can be built up by the following:

$$\min \sum_{i=0}^{N_p} \{ \mathbf{x}(k+i)^T Q \mathbf{x}(k+i) + \mathbf{u}(k+i)^T Q \mathbf{u}(k+i) \} \quad (7)$$

$$\text{subject to : } \mathbf{x}(k+i+1) = \mathbf{A} \mathbf{x}(k+i) + \mathbf{B}_1 \mathbf{u}(k+i) + \mathbf{B}_2 \delta(k+i) + \mathbf{B}_3 \mathbf{z}(k+i) \quad (8)$$

$$\mathbf{E}_2 \delta(k) + \mathbf{E}_3 \mathbf{z}(k) \leq \mathbf{E}_1 \mathbf{u}(k) + \mathbf{E}_4 \mathbf{x}(k) + \mathbf{E}_5, i = 0, 1 \dots N_p-1 \quad (9)$$

where the formula 7, 8 and 9 give the objective function, the model of the system and the constrains for variables.

This optimization problem is a mixed integer linear programming problem. The solver Cplex or Gurobi will be used to solve the proposed optimization problem.

6 Conclusions and future research

This paper aims to apply the real-time control for the equipment in an automated container terminal by considering a container terminal as a large-scale system. Before the

modeling and control of handling of container by equipment, a literature review is given. The modeling of hybrid systems and distributed model predictive control is proposed to achieve the real-time control. The research plan is presented in the end. As future work the control of one QC, one AGV and one ASC will be carried out as starting point. Each equipment has its individual controller that coordinates its actions with the other controllers. Later, the coordination will be extended also to other pieces of equipment in the terminal, aiming for the maximum throughput at minimal emissions.

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