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Subject: **Control of Automated Container Terminals**

In order to meet the increasingly tight demands on transport performance, manufacturers are developing robots for transport technology (such as cranes, AGVs, lifts, …) that can in an automated or even fully autonomous way transport materials and/or equipments from one place to another. Fig. 1 shows an example: a container terminal consisting of multiple automated cranes, made by ZPMC in China. Each of the cranes operates in a part of the overall container terminal, picking up containers at one point, and delivering them to another.

The operation of such robots involves all kinds of uncertainty. Dynamic properties of robots may change due to aging of wheels, floors or tracks may be unexpectedly slippery, weather conditions may influence swinging of container grabbers, containers may arrive in unexpected order, equipment fail, etc.

Fig. 1: Model of an automated container terminal (ZPMC, Shanghai).

In order to ensure adequate operation of autonomous robots, the possible uncertainties and disturbances that can emerge have to be taken into account in their operation and handled effectively. Obtaining an overview of uncertainties, disturbances, and ways of dealing with these is the topic of this literature study.

In particular, you will address questions like:

- What are autonomous robots? For what kind of transport technology are they used? How would you define the systems within which these autonomous robots operate?
- How do the autonomous robots determine what they have to do? What kind of information do they require in order to determine their actions? How much uncertainty is there in this information?
- What kinds of techniques have been proposed in the literature to obtain the information required, and how do these techniques handle uncertainty and disturbances?

It is expected that you conclude your literature study with a written report, including conclusions and recommendations for future research. The report must be written in English and must comply with the guidelines of the section. Details can be found on the website.

For more information, contact Dr. Rudy Negenborn.

The supervisor,
Dr. Rudy Negenborn

Control of Automated Container Terminals

A Literature Review on Automated Container Handling Equipment

Johan van Jole

Literature Research

Delft
University of
Technology

Control of Automated Container Terminals

A Literature Review on Automated Container Handling Equipment

LITERATURE RESEARCH

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June 19, 2014

Faculty of Mechanical, Maritime and Materials Engineering (3mE) · Delft University of Technology

Assignment Description

In order to meet the increasingly tight demands on transport performance, manufacturers are developing robots for transport technology (such as cranes, AGVs, lifts,) that can in an automated or even fully autonomous way transport materials and/or equipments from one place to another. Fig. 1 shows an example: a container terminal consisting of multiple automated cranes, made by ZPMC in China. Each of the cranes operates in a part of the overall container terminal, picking up containers at one point, and delivering them to another.

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Table of Contents

Chapter 1

Container Handling at Container Terminals

This chapter concerns the motivation for automated container terminals. An automated container terminal is a terminal where the operations are performed without any human intervention. The first section provides an introduction into the background and the trends surrounding container terminals. The second section describes the processes of automated container terminals. The final section covers the structure of the report.

Currently, more and more container terminals are automated in order to increase the productivity and lower the costs of handling containers. A lot of research has been performed at this subject. This literature research project provides an overview on the current state of automation at container terminals as well as the future developments regarding automated container terminals.

This research concerns automated deep-sea container terminals. The inland container terminals which are used to offload barges (vessels which are only applied for inland transportation) are not considered. This research focusses on the automation of container handling equipment.

1-1 Background and Trends in Containerized Transport

In order to obtain an insight into the relevance of automated container terminals, the background of containerized transportation is outlined in this section. The current trends on container terminals will be presented in this section as well, in order to clarify the relevance of automated container terminals.

Containers have become an important asset in international trade for over 50 years. Micheal Bohlman (chairman of the ISO committee regarding containerized transport) argued even that "freight containers are, and are expected to remain, the most economical balance between cargo security, transportation cost and speed of delivery for the majority of packed cargo" [1]. Over 90 percent of trade in non-bulk goods is transported by containers [1]. In the year 2010, 114 million TEU (twenty foot equivalent unit) were shipped globally [2], of which 1.6 million were handled in the Netherlands. Growth in container volumes are expected to last at least until 2020 [3].

Container terminals are very important links in containerized transport. At container terminals, the containers change transport modality (the containers are transferred between trucks, trains and vessels). This enables the containers to reach their proper destination, with the proper mode of transportation (trucks, trains and vessels). The deep-sea vessels that provide the so called "economy of scale" for long distance transportation of containers are not able to reach the final destinations of the containers. The container terminal expands the transportation network dedicated to containerized transportation and links all container transportation modes together. An example of a container terminal is shown in Figure 1.

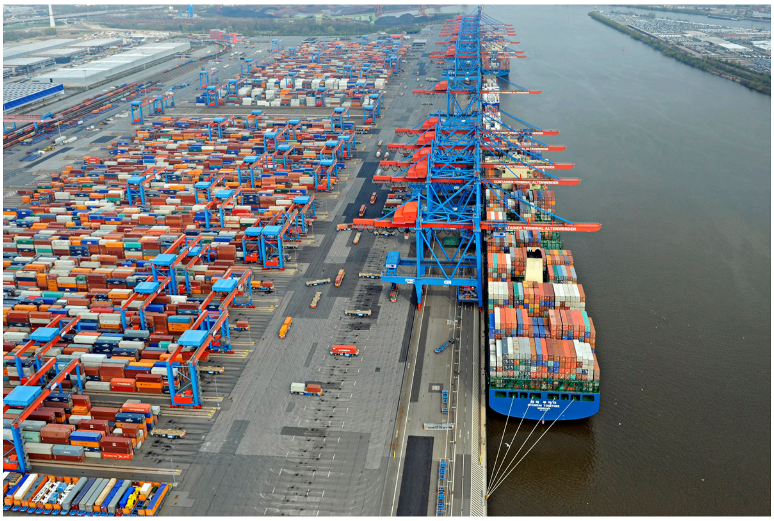


Figure 1: Overview of a container terminal (source:www.gcaptain.com)

The performance of container terminals is an important factor in the succes of containerized transportation. The container terminals form the links between different transportation modes, creating a transportation network that spans the entire globe. The outlook on increased volumes of container transportation calls for an increase in the productivity of container terminals in order to maintain the handling times of the vessels within acceptable limits. The productivity of the container terminals needs to increase because otherwise they might turn into the bottlenecks of containerized transport.

Control of the existing infrastructure is one of the methods that are used in order to increase the container handling capacity of ports. Another method which increases the container handling capacity of ports is constructing more container terminals. Both approaches can be automated, the existing infrastructure can be automated or the newly constructed terminals are automated container terminals. Automation of container terminals is preferred over building new terminals due to large investment costs involved when constructing new container terminals. New terminals are only constructed when the capacity marge not sufficient to satisfy the expected growth of container volumes of the port. New container terminals are currently only constructed in Rotterdam (Maasvlakte 2 [4]) and Qatar [5]. Most of the capacity increases at container terminals are realized by automating existing container terminals.

Automating the container handling processes improves the productivity regarding these processes. The cycle times of human operators vary across their shift and the handling performance depends on their level of skill and experience. In human operated terminals, there is a reduced production during shift changes, which is no concern at an automated terminal. The performance of automated equipment remains costant, which is an improvement compared to the performance of human operated terminals.

Another reason for automation is the reduced need for human operators. This factor is especially important in countries where human labor is relatively expensive. Areas with high labor costs are for instance the European countries and countries in North America. Automation reduces the total operating costs of a container terminal. Automated container handling equipment can be more expensive than the human operated container handling equipment. The payback time of the investment costs thus might be longer. The higher investment costs can be justified when the operating costs are reduced significantly. The profit margin per container handling move rises, meaning that the terminal makes more profit per handled container.

Next to the trend for automation of container terminals there is another trend: the trend of increasing the overall energy efficiency of the container terminal. The energy consumption of container handling equipment at a terminal is fairly large. The price of energy in Europe is expected to rise more than 30 percent in the period 2010-2020 [6]. In order to keep handling costs as low as possible, the energy efficiency of the various types of equipment can be increased. This development is not necessarily combined with the effort to automate the equipment. However, reduction of the energy requirement of automated container handling equipment is easier to be obtained with respect to human operated machinery. When the controller is able to operate the equipment, it is only a relatively small step to incorporate energy saving strategies.

Reduction of the total energy consumption at a container terminal also serves the demand for more sustainable processes by society. Sustainability in this context was defined in [7] as "improving the social and economic conditions of an increasingly urbanized population while preserving the life systems and maintaining environmental quality". This means that the terminal should operate with a minimized influence on the environment without increasing handling costs.

Table 1 lists the automated terminals that are either already in operation or are under development [8], [9]. Examples of automated container terminals that are currently under development are the APMT2 container terminal in Rotterdam [10] as well as terminals in the port of Brisbane, Australia [11].

Table 1: A list of automated container terminals.

Container Terminal	City	Country	Region	Year
Container Terminal Altenwerder	Hamburg	Germany	Europe	2002
Container Terminal Buchardkal	Hamburg	Germany	Europe	2010
ECT Euromax	Rotterdam	The Netherlands	Europe	2008
ECT Delta Terminal	Rotterdam	The Netherlands	Europe	1993
TTI Algeciras	Algeciras	Spain	Europe	2010
BEST Container Terminal	Barcelona	Spain	Europe	2012
DPW Antwerp Gateway Terminal	Antwerp	Belgium	Europe	2007
London Thamesport	London	Great-Britain	Europe	2000
APMT Norfolk	Norfolk	United States	North America	2010
APM Terminals Virginia	Portsmouth	United States	North America	2007
TraPac	Los Angeles	United States	North America	2013
Global Terminals	New Jersey	United States	North America	2013
Patrick Brisbane Autostrad Terminal	Brisbane	Australia	Australia	2009
Sydney International Container Terminals	Sydney	Australia	Australia	2012
Brisbane Container Terminals	Brisbane	Australia	Australia	2012
Khalifa Port Container Terminal	Khalifa	Abu Dhabi	Middle-East	2012
Hong Kong International Terminal 6-7	Hong Kong	China	Asia	2013
Pasir Panjang Bridge Crane Terminal Singapore	Singapore	Singapore	Asia	1997
Kaohsiung Evergreen Terminal	Kaohsiung	Taiwan	Asia	2005
Tobishima Terminal	Nagoya	Japan	Asia	2008
Pusan Newport International Terminal	Busan	South Korea	Asia	2009
Korea Express Busan Container Terminal	Busan	South Korea	Asia	2007
Hanjin New Port	Busan	South Korea	Asia	2009
Taipei Port Container Terminal	Taipei	Taiwan	Asia	2010
Hyundai Pusan New-Port Terminal	Busan	South Korea	Asia	2010
Kao Ming Container Terminal	Kaohsiung	Taiwan	Asia	2010
Ohi Terminal	Tokyo	Japan	Asia	2003
APMT 2	Rotterdam	The Netherlands	Europe	2014
Rotterdam World Gateway	Rotterdam	The Netherlands	Europe	2014
Long Beach Container Terminal	Long Beach	United States	North America	2014
Vado Ligure	Vado	Italy	Europe	2016
Kaohsiung Intercontinental Terminal	Kaohsiung	Taiwan	Asia	t.b.a.
DP World Brisbane	Brisbane	Australia	Australia	t.b.a.

1-2 Container Terminal Processes

The previous section stated that automation of container terminals serves to meet the ongoing trends on container handling. In order to automate the container terminal, the processes necessary to handle containers need to be determined. This section concerns the processes that are necessary in order to operate a container terminal. The terminal processes are split between the container handling processes and the business processes. The container handling processes are the services that the terminal provides to its customers (the shipping lines, train operators, trucking operators etc.). The business processes deal with the organization and administration taking place at the container terminal.

A process is a collection of related activities that produce a specific service or product for particular customers. The business processes are related to the container handling processes, this is shown in Figure 2. The business processes impose the boundary conditions on the container handling processes. These boundary conditions mainly originate from port regulations. The goods that are shipped in the containers are controlled by the customs. The customs have dictated procedures with respect to the container handling processes which the container terminal needs to comply with.

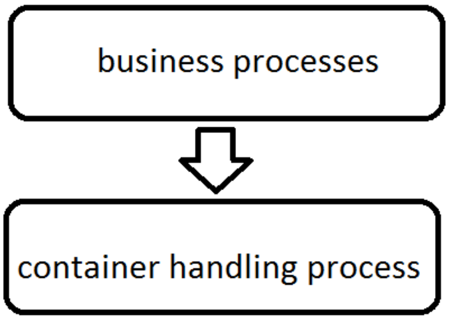


Figure 2: Hierarchy between the business processes and the container handling processes.

1-2-1 Container Handling Processes

The container handling processes are divided into waterside and landside operations. The waterside operations concern the unloading and loading of the various container vessels that will visit the container terminal. Landside operations involve the unloading and loading of the trucks and the trains that come to the terminal. Landside operations also deal with storage of the containers on the stacking yard. The containers are transported between these handling processes [12]. Figure 3 shows a general overview of the container handling process. It should be noted that the container handling process occurs in both directions; to and from the vessels.

The container handling process at the waterside starts with mooring the vessel at the quay. The containers that need to be unloaded are lifted off the vessel. These containers are transported to the container stack, where the containers are stored until they're picked up by another client. The containers that are loaded onto the vessel are retrieved from the stack, transported towards the vessel and the containers are subsequently lifted onto the vessel.

The handling processes at the landside operation unload the import containers from the trucks and trains. The containers are stored in the stack and the export containers are retrieved from the stack and transported to the trucks and the trains. The containers are subsequently lifted on the trucks and the trains. Landside operations are also in control of the stack.

Scheduling of the container handling operations (vessels, trains and trucks) is also considered to be a part of the container handling process. Scheduling of the container handling operations concerns determining the order in which the vessels, trucks and trains are handled.

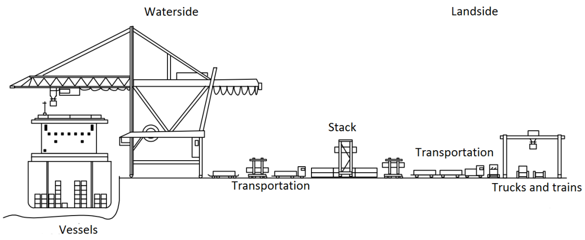


Figure 3: Overview of the container handling processes at a container terminal [13]

Table 2 shows the types of equipment that are in use at the 10 most recently automated container terminals. Not all container terminals are entirely automated, some container terminals deploy reach stackers in order to handle containers. There is little variation in the equipment types used to handle the vessels and trains, the only difference concerns the horizontal transportation function at container terminals. When considering the horizontal transportation in Table 2 the AGVs are most frequently used. One terminal uses automated straddle carriers, while the rest of the terminals still use human operated equipment in order to perform the horizontal transportation function.

Table 2: Equipment used at automated container terminals

container terminal	horizontal transportation	handling of vessels	handling of trains	handling of trucks	stacking containers	reference
Rotterdam World Gateway	AGV	Quay crane	RMG	ASC	ASC	[10]
APMT2	AGV	Quay crane	RMG	ASC	ASC	[10]
Long Beach Container Terminal	AGV	Quay crane	RMG	ASC	ASC	[14]
Hong Kong International Terminal 6-7	Reachstackers/ Frontloaders	Quay crane	RMG	RTG	RTG	[15]
Khalifa Port Container Terminal	Shuttle Carriers	Quay crane	Reach stackers	ASC	ASC	[16]
Brisbane Container Terminal	Automated straddle carriers	Quay crane	RMG	Automated straddle carriers	Automated straddle carriers	[11]
Sydney International Container Terminals	Tractor-trailer systems	Quay crane	RMG	ASC	ASC	[17]
Global Terminals	Straddle carriers	Quay crane	RMG	ASC	ASC	[18]
TraPac	Reach Stackers	Quay crane	RMG	ASC	ASC	[9]
BEST Container Terminal	AGV	Quay crane	RMG	ASC	ASC	[10]

1-2-2 Business Processes

Business processes support the container handling processes of the container terminal. Examples of business processes are contact with the clients, charging of the clients, checking for compliance with port regulations and maintenance of the container handling equipment.

One important business process is checking for compliance with port regulations. Ports are in general areas which are heavily regulated. Port regulations state which procedures are allowed and under which circumstances. For instance, when a container is lifted from the vessel directly onto a truck in the port of Salalah (a port in Oman), the port authorities must receive a notification 24 hours in advance [19]. These kind of regulations are found in all ports around the globe.

The container handling processes must comply with these regulations and a process must be in place to check for compliance with the regulations that are enforced by the authorities.

Automation of container terminals does not only apply to the container handling process, the business process is automated as well. An example concerns the Dutch custom procedures at all ports that are located in the Netherlands. The Dutch customs have developed a software tool which is able to automatically handle the custom declarations of the shipped cargo [20].

Terminal management software tools are developed in order to automate some of the administrative processes that are in place at container terminals [21]. For example, transport planning processes are automated and the system is coupled with the ERP system of a terminal in order to automatically charge the client when a container is leaving the terminal.

A connection between the container handling and business process exists through the planning of the container handling operations. When containers leave the terminal, the container handling process lets the business process know that the task has been fulfilled and the client can be charged. When the container terminal receives a new request to service a vessel, train or truck, this request will be forwarded to the container handling process. The container handling process subsequently schedules this new request.

The business processes need to be considered when a container terminal is automated entirely due to the connection between the container handling and the business processes. However, because the scope of this research is on the automation of the container handling process, automation of the business processes will not be covered in this report.

1-3 Structure of the Report

This report lists the results of a literature review of container terminals, with the focus on deep-sea container terminals. This section contains the research questions, the research approach as well as the structure of the report

1-3-1 Research Questions

This report concerns the automation of deep-sea container terminals. The main research question is:

"How can container handling equipment be automated?"

The main question is supported by 4 subquestions. The 4 subquestions that support the main question of this research are:

- What are the current trends on containerized transporation and container terminals?
- What is the current state of automation of container handling equipment?
- What parameters are involved in automating container handling equipment?
- What models and control techniques are used in automated container handling equipment?
- What are the current limitations in automating container terminals?

1-3-2 Approach

Table 2 shows that the equipment that is used at (automated) container terminals is different for each terminal. All types of container terminal equipment need to be discussed, along with their potential to be automated. Table 2 also indicated that in the case of automated container terminals that are estiblished recently (this table consists of data from terminals automated from 2011 onwards) a number of equipment types are deployed more frequently than others. These types of equipment are AGVs, RMGs, ASCs and quay cranes.

The control of individual pieces of equipment is considered for the frequently used types of container handling equipment. The next step is to consider the control of these types of equipment at container terminal level. These two levels of control need to be considered in order to determine the current limitations of automating container handling equipment.

When the current state of automation of container terminal equipment is established, directions for future research in this field are constructed.

1-3-3 Structure of the Report

This chapter discussed the motivation for automation of container terminals as well as the trends concerning container terminals. The major trend next to automation is the reduction of energy consumption of container terminal equipment. The container handling and business processes at container terminals are discussed in this chapter as well.

Chapter 2 continues with the types of equipment that are used in the container handling process at automated container terminals. The frequently used types of container handling equipment as well as the alternative types of equipment that are also suited to be used at automated container terminals are covered.

Subsequently, the frequently used types of terminal equipment at automated container terminals are emphasized. As one of the frequently used types of automated terminal equipment; the control of AGVs at an individual level and at a system level level is discussed in chapters 3 and 4 respectively.

The other types of frequently used terminal equipment are gantry cranes. Chapter 5 concerns the control of gantry cranes at an individual level. Chapter 6 discusses the control of gantry cranes at terminal level.

Chapter 7 concludes this report with a summary on the automation of container handling equipment. The answers to the research questions are presented and suggestions for future research on this subject are provided.

Figure 15 shows the schematic representation of the structure of the report.

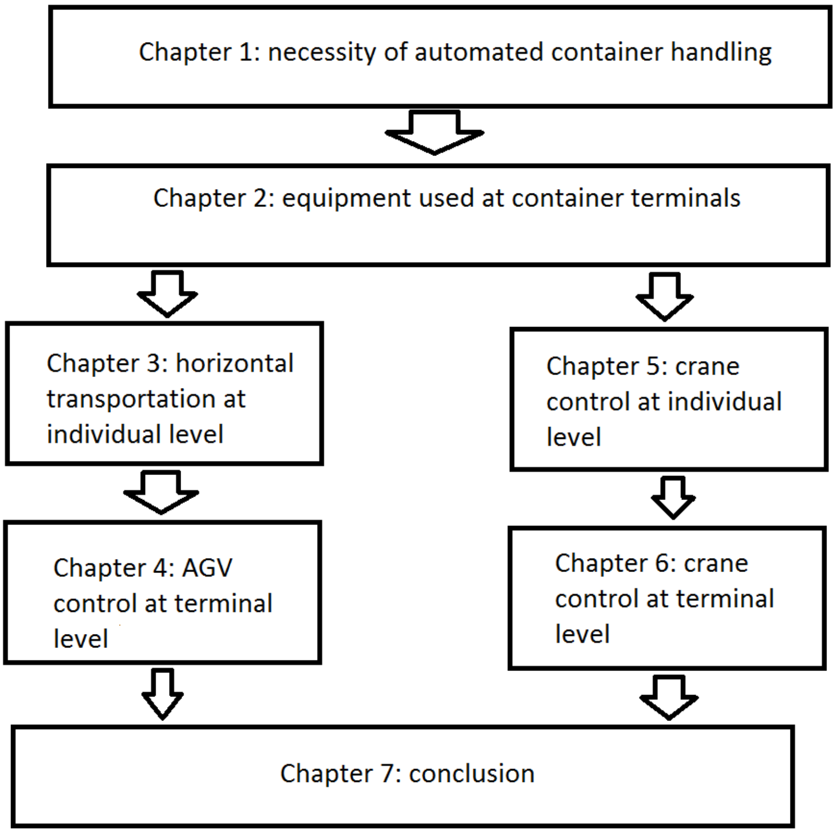


Figure 4: The structure of the report

Chapter 2

Equipment at Automated Container Terminals

The previous chapter introduced the container handling processes. This chapter lists the types of equipment that are used in these processes. The first section covers the common types of equipment found at automated container terminals. The second section covers the alternative types of equipment that can be used at automated container terminals. The general characteristics of the various types of equipment are evaluated in both sections. The last section concludes this chapter.

2-1 Typical Automated Terminal Equipment

This section concerns the most used types of equipment at automated container terminals. At automated container terminals, vessels are handled by quay gantry cranes, stacking is provided by automated stacking cranes, train loading is performed by rail mounted gantry cranes and terminal transportation is performed by automated guided vehicles.

The choice between different types of container handling equipment is based on several performance indicators. The performance indicators reflect the objectives of the terminal operator. The performance indicators are used to determine which type of equipment is suited for the task that is considered as well as the specification of that type of equipment. Saanen [22] proposes a number of performance indicators for all aspects of a container terminal. The proposed performance indicators reflect the productivity of equipment and are measured in moves per hour, equipment cycles per hour and the number of containers handled per hour.

The type and number of container handling equipment that is used at the terminal depends on the specification. The specification of a certain type of container handling equipment lists the required capacity, required operating velocities, its maximum weight and its maximum or minimum dimensions. The performance objectives of the container terminal are determined by each terminal operator, therefore the performance objectives of each container terminal are different [22]. Thus the major performance indicators are different for each container terminal, which means that the specifications of container handling equipment are different at each container terminal. Although the conditions at each terminal are different, many automated terminals make use of the same types of equipment. The general characteristics of these types of equipment are covered in this section.

2-1-1 Quay Gantry Cranes

Quay cranes are used to load and offload the vessels. The vessels that are serviced by the terminal differ in size (around 35 for a small barge, 18.000 for the largest deep-sea vessel). Deep-sea vessels are deployed on long distance travel between large ports. Feeders are vessels of a much smaller size which will transport the containers across a smaller distance. Barges are even smaller vessels used to transport the containers inland.

The quay cranes that are used at container terminals nowadays are gantry quay cranes (see Figure 5). The reason that they are preferred over rotating cranes is that the gantry cranes have a higher container handling capacity. The handling capacity of a container crane is listed as the number of moves a crane can make per hour [22].

When unloading a vessel, the quay crane will lower the spreader towards the container and lifts it up. The trolley moves towards the quay and the container is subsequently transferred onto the transportation vehicle. The crane will move the spreader towards the vessel, starting a new cycle. The quay crane is mounted on rails, enabling it to move along the quay wall in order to line up with the vessel correctly.

Figure 5: Quay gantry cranes (source:maritimejournal.com)

Two important measures that improve the productivity of the crane are double trolley cranes as well as special spreaders.

Double trolley quay cranes decouple the processes of handling the vessel and (un-)loading the transportation equipment. The main trolley handles the vessel and the secondary trolley handles the horizontal transportation equipment. Both trolleys are connected by a platform that is mounted on the crane. The total cycle time of the quay crane is lowered, improving the productivity of the crane.

With tandem operation, two or more spreaders are be attached to the trolley [23]. This enables the crane to lift two or three 40-foot containers in one cycle. The handling capacity is improved, given that the terminal transportation is able to keep up with the handling speed of the crane. At the end of each cycle, the number of horizontal transportation equipment must equal the number of spreaders that are attached to the trolley.

Alternatively, twin-lift operation can be considered. Twin-lift operation is when one spreader is able to lift two 20 foot containers in one cycle. The advantage with respect to tandem operation is that this system can be implemented at every container terminal without adjustments in the horizontal transportation infrastructure. The disadvantage is that the performance gain is relatively small.

Automation of container cranes is considered because the quay cranes can become the limiting factor in container terminal productivity in the future [24]. Automation of quay cranes is in a less developed state when compared to the cranes used elsewhere at the terminal because the operating environment poses more challenges. Examples of these challenges are movements of the vessels and increased influence of the wind impacting on the container and the crane.

Table 3 shows the key parameters of a quay crane. The parameters are from a Liebherr super post-panamax/megamax STS container crane [25].

Table 3: Key parameters of a quay crane.

parameter	value	unit
maximum crane width (buffer to buffer)	27	m
gantry width	18.2	m
gantry span (distance between the rails)	15-35	m
maximum lifting height	35-49	m
outreach (length of boom that is above the vessel)	46-70	m
backreach (part of boom that points towards the landside)	0-25	m
maximum width of trolley	7.6	m
safe working load tandem operation	85	ton
safe working load twin-lift operation	65	ton
hoisting speed	60-150 (1-2.5)	m/min (m/s)
trolley speed	180-210 (3-3.5)	m/min (m/s)
crane travel speed	45 (0.75)	m/min (m/s)
trolley weight	-	ton
total crane weight	1920-2560	ton

2-1-2 Rail Mounted Gantry Cranes (RMGs)

Rail-Mounted Gantry Cranes (RMGs) are used at a number of container terminals for loading and offloading trains. Figure 6 shows a human-operated RMG, which is in construction entirely identical compared to an automated RMG. The RMGs that are used at terminals generally span several train tracks.

Figure 6: Human operated RMG (source:www.konecranes.com)

RMGs can already be automated because (contrary to the vessels at the quay cranes) the trains and trucks are stationary with respect to the RMG crane. The position of the spreader on an RMG is measured with laser based guidance systems [26]. The crane gantry position can be monitored by RFID sensors that are located alongside the track. The trolley position is measured in two ways; one way is to use an incremental encoder, the other is to use a laser range finder. The hoist position of the spreader is often measured using incremental encoders. Table 4 shows the specification of an RMG built by Konecranes [27].

Table 4: Key parameters of an RMG crane.

parameter	**value**	**unit**
maximum crane width (buffer to buffer)	-	m
maximum gantry span (distance between the rails)	50	m
maximum lifting height	21	m
safe working load	50	ton
hoisting speed with an empty spreader	90 (1.5)	m/min (m/s)
hoisting speed with 40 ton load	45 (0.75)	m/min (m/s)
maximum trolley speed	76 (1.27)	m/min (m/s)
crane travel speed with an empty spreader	150 (2.5)	
crane travel speed with 40 ton load	140 (2.33)	m/min (m/s)
trolley weight	-	ton
total crane weight	-	ton

2-1-3 Automated Stacking Cranes (ASCs)

ASCs are in structure equivalent to the RMGs. At automated terminals, they are used to stack the containers in the storage area. They also load and offload the trucks. Figure 7 shows an ASC handling trucks.

Figure 7: An ASC handling trucks at the stack (source:www.terex.com).

It is favorable with respect to the total amount of handling moves to serve the trucks directly from the stack. The horizontal terminal transportation is connected at the other end of the stack. The ASC spans several rows of containers, the amount of rows being covered by the ASC depends on the specification of the equipment objectives. The specification of the ASC is determined by the terminal operator.

When stacking a container, scanning lasers which are mounted on the trolley measure the position of the container with respect to the containers below it. Optical laser systems are used in order to determine the distance and angle to any surface. This enables the ASC to accurately position the spreader in order to lift a container.

Collision prevention is an important feature, because in most cases two or more ASCs are mounted on the same rail. The ASCs are equipped with laser range finders which are able to detect all kinds of objects (transport equipment, other cranes, etc.) in order to prevent collisions from happening.

Table 5 lists the specification of an ASC built by Terex Port Solutions [28].

Table 5: Key parameters of an ASC.

parameter	**value**	**unit**
maximum crane width (buffer to buffer)	13.5	m
gantry span (for a stack with 9 container rows)	28	m
maximum lifting height (for a stack of max. 5 containers high)	17	m
safe working load	-	ton
hoisting speed at full load	39 (0.65)	m/min (m/s)
hoisting speed with empty spreader	72 (1.2)	m/min (m/s)
maximum trolley speed	60 (1)	m/min (m/s)
crane travel speed	240 (4)	m/min (m/s)
maximum trolley acceleration	0.4	m/s^2
maximum gantry acceleration	0.4	m/s^2
maximum hoisting acceleration	0.35	m/s^2
minimum working distance between two ASCs	2	TEU
trolley weight	-	ton
total crane weight	-	ton
end-to-end container spacing	0.5	m
side-to-side container spacing	0.4	m

2-1-4 Automated Guided Vehicles (AGVs)

Automated Guided Vehicles (AGVs) are frequently used for transportation tasks at automated container terminals. The vehicles are autonomous in the sense that they will calculate their own route towards the destination position. AGVs are deployed at automated container terminals for transporting containers at the container terminal.

AGVs are self-propelled chassis capable of carrying 2 TEU. Power comes from a diesel engine or from a battery pack. A new type of AGV has been developed that decouples the container handling processes at the stack, this type of AGV is called the lift-AGV. When delivering containers to the stack, the lift-AGV will lift its platform and drives towards a rack. The platform is than lowered, leaving the containers on the rack. The AGV then drives off, it does not have to wait until the ASC picks up the containers. Lift-AGVs will be installed at the newly constructed APMT2 terminal in the port of Rotterdam. This concept is illustrated in Figure 8. Table 6 lists the key parameters of an AGV built by Terex Port Solutions [29]. Lift-AGVs are AGVs fitted with a platform, this means that the parameters of the AGVs also hold for the lift-AGVs.

Figure 8: A lift-AGV delivering/collecting containers at a rack (source:www.terex.com).

Table 6: Key parameters of an AGV.

parameter	**value**	**unit**
length	14.8	m
width	3	m
height of load platform	2.4	m
maximum payload single container	40	ton
maximum payload two 20-foot containers	70	ton
forward/rearward velocity	6	m/s
maximum velocity during turning	3	m/s
maximum velocity during crab steering	1	m/s
positioning accuracy	± 25	mm
transportable container sizes	20,30,40 and 45	foot

2-2 Alternative Types of Equipment

This section covers alternative types of container handling equipment that can be used on automated container terminals. These types of container handling equipment are already developed and deployed at human-operated container terminals. When these types of equipment are automated, they can be used at terminals which have a lay-out or performance targets which require other types of equipment than the ones described in the previous section. The equipment types that are covered in this section are RTGs, overhead bridge cranes, straddle carriers, multi-trailer systems, multitainers and rail-mounted automated guided vehicles.

Figure 9 shows the position of the alternative types of equipment with respect to the logistic processes at the terminal. The Rail-mounted Automated Guided Vehicles (RGVs), Multi Trailer System (MTS) and multitainers are used for horizontal transportation. The Rubber-Tired Gantry Cranes (RTGs) and Overhead Bridge Cranes (OBCs) are used to stack the containers. Straddle carriers are used for horizontal transportation as well as stacking the containers.

The frequently used types of container handling equipment are included at the bottom of this figure, in order to illustrate their position with respect to the logistic processes at the container terminal.

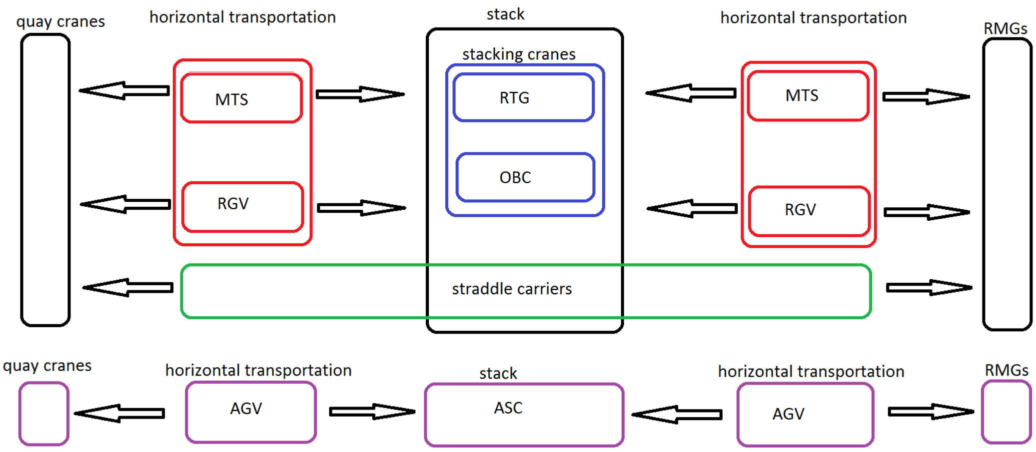


Figure 9: Schematic representation of the alternative types of equipment in the container handling processes.

2-2-1 Rubber Tired Gantry Cranes (RTGs)

RTGs are in function as well as construction similar to the RMGs, except for the fact that they are not mounted on a rail. Instead, they are supplied with (rubber tired) wheels. The data of an RTG is similar to the ASC. The main advantage of the RTG is that the crane is able to switch lanes across the stack. This implies that the RTG is not able to be connected to an electrical power grid, but it has to have its own power source. An illustration of an RTG is included in Figure 10.

The maintenance cost of an RTG is significant compared to an ASC, mainly due to the diesel engine. When a full electric RTG is considered, special bars have to be constructed in order to connect the RTG to an electrical power grid. These bars are significant in size and lower the area utilisation of the stack compared to ASCs. This is the reason why automated RTGs are not common at automated terminals.

Figure 10: An example of an RTG (source:www.konecranes.com).

The advantage of a conventional (diesel-powered) RTG over an ASC is the increased flexibility of the stacking equipment. However, the RTG is outperformed by the ASC due to its lower productivity. In general, the ASC is economically speaking a better choice than the RTG, although the purchase of the RTG is less expensive [30].

Recent developments concern the energy consumption of RTGs. In [31] a hybrid drivetrain uses a supercapacitor to store energy. The diesel engine only provides the average power demand for each cycle. The supercapacitor supplies energy during periods where the power demand is above average and the capacitor is charged during periods where the power demand is below the average power demand. Strategies are developed that will turn the diesel engine off completely and just consume the power of the supercapacitor until it is drained of energy. The supercapacitor is supplied with energy that is regenerated when a container is lowered [32].

These energy saving methods can be applied to other gantry type cranes as well, due to their similar construction. These two saving methods can be applied to ASCs and quay gantry cranes in order to reduce their energy consumption. The operating costs are reduced when the energy requirement is lowered.

2-2-2 Overhead Bridge Cranes (OBCs)

Overhead Bridge Cranes are used in stacking operations, an example is shown in Figure 11. Automated overhead bridge cranes are used to stack containers at an automated container terminal in Singapore. The height of the crane can be increased with respect to ASCs and RTGs due to their method of construction. The advantage of OBCs compared to ASCs is that the stacking area utilization is better (a result of the container stack being higher) In order to determine whether or not OBCs are preferred compared to ASCs, a trade-off has to be made between area utilisation and stacking efficiency.

The layout of the stack in this configuration is efficient with respect to the area used in stacking. However, this comes at the cost of a higher number of shuffle moves. Shuffle moves are moves that do not contribute to the productivity of the terminal. The amount of shuffle moves of ASCs and RTGs are lower, because the average stack height is higher at OBCs. When the average stack height increases, the amount of shuffle moves increases as well. This means that when considering the stacking efficiency, the OBC is outperformed by the ASC and the RTG.

Figure 11: An automated OBC (source:www.mediasixstudio.com).

An OBC will be built and designed for each specific application, general data does not apply because the sizes and speeds of the components are be chosen during the design process.

2-2-3 Straddle Carriers

Straddle carriers are used for two purposes; the straddle carrier is able to transport a container as well as stack the container. Figure 12 shows a straddle carrier that is transporting a container.

The area utilization of the accompanying stack layout is fairly low compared to the area utilization of ASCs, because of the spaces needed between the container rows for the straddle carriers to drive through the stack. The advantage of a system using straddle carriers is an increase in flexibility compared to a system using ASCs.

Figure 12: Example of a straddle carrier (source:www.konecranes.com).

In Brisbane, Australia, automated straddle carriers are already used at an automated container terminal. The performance of the automated system is equal to that of an equivalent human-operated fleet [33]. The navigation system of these automated straddle carriers uses four different measurement principles in order to have an accurate and redundant determination of the position of the straddle carrier.

The performance of straddle carriers and automated stacking cranes was compared [34]. When the stacking procedure is regarded only, the ASC will outperform the straddle carrier. This holds for an ASC with a span of nine rows of containers. When the number of rows of containers is larger than nine, the straddle carrier outperforms the ASC.

2-2-4 Multi-Trailer System (MTS)

An MTS consists of a number of trailers that are pulled by a terminal tractor (see Figure 13). The advantage of having an MTS occurs when the distance between the quay and the stack is large (more than 1 km) [35]. The trailers can be used as a buffer during peak demands.

The disadvantage of this method is that the vehicle requires more space in order to complete a turn compared to an AGV. The MTS must travel to several locations in the stack to collect or deliver containers. Because of its size, this may create a blockage at the interface between the horizontal transportation and the stack. The type of trailers that performs well regarding tracking performance is off-hooked trailers [36]. This system used mechanical links to achieve good tracking performance, no control procedures are needed. Instead of terminal tractors, an adapted AGV can be enabled to pull several trailers in order to implement this system at automated terminals.

Figure 13: Example of an MTS system at the ECT terminal (source:www.brandigg.de).

2-2-5 Rail-Mounted Automated Guided Vehicles (RGVs)

Rail-Mounted Guided Vehicles (RGVs) are similar to AGVs, but for the propulsion system. The vehicles are mounted on rails and they are driven by a series of electromagnets [37].

The advantage of RGVs is that the control procedures are relatively simple when compared to AGVs. The RGV is only able to follow the rail, and control of motion becomes one dimensional. Because the uncertainties with respect to the actual position of RGVs are less than the uncertainties that are associated with AGVs, the spacing between two vehicles can be reduced. This means that a higher capacity can be achieved.

The reason that this approach is not used at container terminals is that in case of a failure of a single vehicle, the whole terminal transportation system fails. A queue of RGVs will form behind the broken RGV. AGVs do not have this problem, because they are able to drive around a vehicle that is broken down.

Like the AGVs, the RGV-system is completely automated. Position control is relatively simple, it is relatively easy to measure and effect the position of the vehicle. The concept of RGVs to be deployed at container terminals is illustrated in Figure 14.

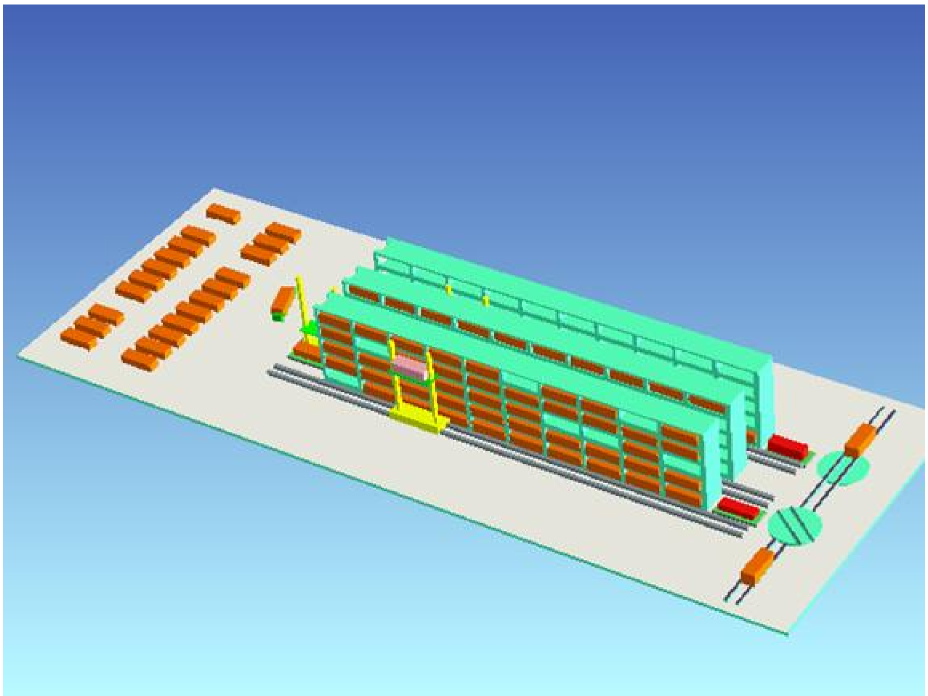


Figure 14: Impression of an RGV system at a container terminal (source:www.metrans.org).

2-3 Conclusion

The frequently used types of equipment are the AGVs, ASCs, RMGs and quay cranes. These types of equipment are already used at automated container terminals. Other types of equipment are in place as well, although not all types are ready for implementation at automated container terminals yet. It is possible to automate the alternative types of container handling equipment as well. These types of equipment can subsequently be used at automated container terminals at which the frequently used types of equipment are unfavorable.

Because the majority of container terminals all use the four frequently used types of container handling equipment, this report will focus on these four types in the subsequent chapters. In order to automate the container terminal, these four types of equipment need to cooperate in order to handle the containers in the best possible way.

Tables 7, 8 and 9 show the main strengths and weaknesses of the different pieces of equipment.

Table 7: Comparison between ASCs and straddle carriers

Equipment	Strengths	Weaknesses
ASC	better yard utilization compared to straddle carrier	high investment costs compared to straddle carriers
straddle carrier	high degree of flexibility	low area utilization of stack lay-out due to the space needed for the straddle carrier to drive through the stack

Table 8: Comparison between RMGs, RTGs and OBCs

Equipment	Strengths	Weaknesses
RMG	relatively easy to automate	high investment costs compared to RTGs (higher purchase price, cost of creating rails at the terminal)
RTG	high degree of flexibility, relatively low investment costs	relatively high maintenance costs, RTG cannot be connected to energy supply grids
OBC	high stacking area utilization compared to RMGs or RTGs	reduced stacking efficiency compared to RMGs or RTGs

Table 9: Comparison between AGVs, RGVs and Multi Trailer Systems

Equipment	Strengths	Weaknesses
AGV	high degree of flexibility	complex control procedures compared to other solutions
RGV	simplified control procedures compared to AGVs	failure sensitive, in case one component fails the system stops working
MTS	most efficient transport mechanism when distance between quay and stack is over 1 km	vehicle requires more space to drive compared to other solutions

Chapter 3

Control of Individual AGVs

The previous chapter concerned the types of equipment used at automated container terminals. The most frequently used type of equipment for horizontal transportation at automated container terminals is the AGV. This chapter emphasizes the control of individual AGVs. The first section discusses the architecture of the AGV along with the controlled basic variables of the AGV. The second section covers the types of localisation procedures that can be used on AGVs. The third section discusses the models that are used by controllers to control the individual AGVs. The fourth section discusses the methods that are used to increase the energy efficiency of the AGV. The final section concludes this chapter with a summary. After the needs of the individual AGV controller is determined, control of AGVs at a system level is discussed in the next chapter.

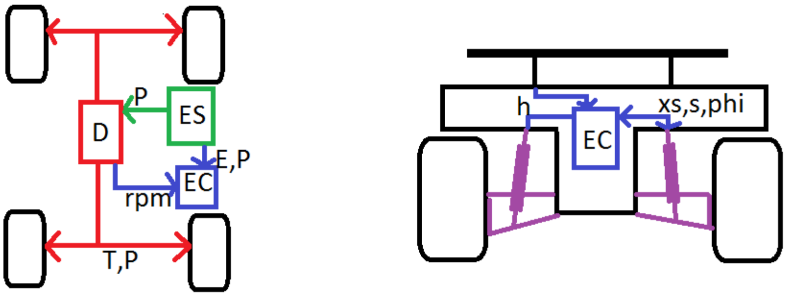
The goal of a controller of an AGV is to complete the transportation task that will be assigned by the AGV system controller. A transportation task is an order to transport a container between the stack and the cranes handling the trains and vessels.

In order for the controller to be able to reach its goal, it must measure and actuate several variables. The next section gives an overview of these variables.

3-1 The Architecture of an AGV

A general description of an AGV (including the specification of an AGV used at container terminals) is given in Chapter 2. The detailed architecture of the AGV is outlined in this section. The AGV consists of several subsystems; chassis, suspension, drivetrain, electronics and energy storage. These subsystems are covered along with their basic measured and actuated variables.

The connections between the different elements are shown in Figure 15. The variables that are exchanged are labeled at the connections.



D: drivetrain
ES: energy storage
EC: electronics/controller
T: torque
P: power
rpm: rotational velocity of powertrain
E: energy
accy: lateral acceleration
accx: longitudinal acceleration
h: height of platform (in case of lift-AGVs)
xs: spring deflection
s: wheel slip coefficient
phi: steering angle

Figure 15: The connections between the different elements of the AGV [22].

3-1-1 Chassis

The chassis provides the necessary amount of stiffness to the vehicle. The chassis will also distribute the load towards the suspension. The load consists of the weight of the vehicle as well as the transported container. Almost 30 percent of the total handled 20-foot containers are twin-lifted onto the AGV [38]. This is the most severe loadcase which the chassis of the AGV must be able to accomodate. The variation of the weight of the containers influences the dynamics of the AGV, because the mechanical loads on the wheels change. The change in mechanical loads changes the cornering and acceleration behaviour of the vehicle. These changes must be considered by the AGV controller [39].

Actuated variables on the chassis are found on lift-AGVs. These variables are the height of the platform with respect to the vehicle and the power delivered by the hydraulic cylinder which lifts the platform.

The measured variables on the chassis of AGVs are the accelerations in longitudinal and lateral direction. These variables are used by the controller in order to determine the torque that should be provided by the electric motors.

3-1-2 Suspension

The suspension distributes the load from the chassis onto the wheels. This system consists of springs, linkages (to connect the chassis and the wheels) and dampers. The suspension makes sure that the wheels remain in contact with the ground.

The geometry of the suspension system comes in many different forms. Double-wishbone, McPherson struts, trailing arms, swing-axles, beam-axles and multi-link suspensions are common used geometry concepts. McPherson struts are applied to AGVs, creating suspension kinematics that support four wheel steering. Figure 16 shows the concept of a McPherson strut suspension. The measured variables on the suspension of an AGV are spring deflections and wheel slip. The spring deflection is used to calculate the normal loads on the wheels of the vehicle. The spring deflection is also used in order to determine the weight of the container that is transported. These variables are important when a dynamic model of the vehicle is used by the controller in order to determine the torque that should be delivered to the wheels. The wheel slip variable serves to calculate the required steering angle for the AGV.

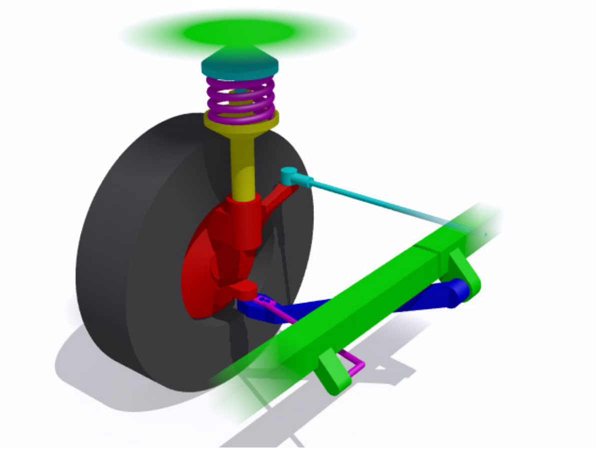


Figure 16: Concept of a McPherson strut suspension (source:en.wikipedia.org)

The actuated suspension variable is the steering angle of the AGV. The AGV has symmetrical four wheel steering. The steering angle at the front of an AGV is equal to the steering angle at the back of that AGV. In order to be able to increase the velocity while cornering the vehicle Ackermann steering is applied, which can be provided with a mechanical linkage [40].

3-1-3 Drivetrain

The drivetrain consists of the motor (also called powertrain) that delivers a drive torque and the elements which transmit the torque and power to the wheels (such as gears and axles). The AGV has electric motors, which are powered by a battery or a diesel-driven generator. These motors can be placed inboard as well as outboard.

Inboard electric motors need to be connected to the wheel by means of a driveshaft. With inboard motors it is possible to drive two wheels using one motor. Outboard electric motors are directly coupled to the wheels; the disadvantage of this method is the increased unsprung mass of the vehicle. The advantage is that the torque supplied to each wheel can be controlled seperately.

The actuated variables of the drivetrain are the torque of the electric motors and the power that is supplied by these motors. The variables that is measured is the rpm of the electric motors. This variables is used by the controller to calculate the velocity of the AGV after correction for wheel slip.

3-1-4 Energy Storage

The energy storage delivers energy to the drivetrain. The energy storage is either a fuel tank (for diesel powered AGVs) or a battery pack (for electric powered AGVs). Electric power is advantegeous because the other types of equipment used on container terminals are driven electrically as well.

The measured variables of the energy storage is the amount of energy that is left as well as the rate of usage of electric power. The controller uses this information in order to determine whether or not the battery should be recharged.

3-1-5 Electronics

The electronics on the vehicle processes the measurements and accounts for computing the actions that should be performed on the vehicle. The communication systems are a part of the electronics that are located on the vehicle. The electronic system consists of the controllers, sensors, actuators and the wiring linking these components.

Except for the variables that are already presented in this section, the electronics obtain information on the transportation task as well. Information on the transported container and the trajectory of the AGV are received from the AGV system controller.

The information on the trajectory of the AGV is used as a reference, in order to be able to determine the drive and steering commands. The commands are calculated by evaluation of a model describing the behaviour of the vehicle.

3-2 localisation Methods for AGVs

localisation systems are important in AGVs. The function of the localisation system is to determine the location of the AGV. The AGV controller uses the location and velocity of the AGV to determine the required heading and velocity of the vehicle. This section covers different localisation principles used on AGVs.

Table 10 lists the different types of localisation principles. There are two types of localisation methods, on-board and outboard localisation. When an on-board localisation system is used, the vehicle is able to determine the location and velocity without communication with external systems. Outboard localisation methods communicate with seperate systems in order to locate the vehicle. One off-board localisation method consists of a wire buried below the surface transmitting a radio signal. A sensor on the AGV is able to determine the distance between the AGV and the radio signal. The position of the AGV relative to the wire is known. The location of the wire is known to the AGV, so the position of the AGV can be calculated.

Table 10: Several types of localisation principles

localisation method	**measuring principle**	**type of system**
buried wires	doppler-effect	off-board
colored tape	difference in reflectance	off-board
gyroscope	resistance against change in rotational velocity of spinning wheel	on-board
radar	reflectance of radio waves on foreign objects	on-board
optical systems	image processing software	on-board
GPS	triangulation	on-board
wheel encoders	rotational velocities	on-board

The same concept can also be applied using colored tape on the ground, this is also an off-board method. The position of the AGV with respect to the tape can be determined using a camera or a set of light diodes. These localisation principles create an AGV system that lacks flexibility; hence these methods are not used at container terminals anymore.

On-board localisation on the AGV can be performed using gyroscopes. The gyroscope is able to detect even the slightest deviation in heading of the vehicle. The gyroscopes that are in use are electrostatic gyroscopes and the floated gyroscope, both having a high accuracy. The accuracy is measured by the value of random drift, which is the amount of degrees shift per operating hour. High accuracy systems have a random drift below 0.001 degree/hour [41]. Research is done at new gyroscopes, for instance the ring laser gyroscopes, the hemispherical resonator gyroscope and the MEMS-gyroscope. The accuracy of the gyroscopes is already sufficient for implementation on the AGV running on a container terminal.

Another on-board localisation method is radar. The vehicle sends a signal and determines how long it takes for the signal to return to the vehicle. The distance towards several objects can be calculated by multiplying the travel time of the signal and the velocity of the signal. High precision systems with an operational range of 10 m. and a sampling period of several milliseconds are designed for localisation of indoor vehicles [42]. This system can be expanded for use outdoor as well by magnifying the operational range. Radar systems are also able to identify obstacles.

Optical systems are able to be used in on-board localisation procedures. In this case, the image processing software on the AGV is supplied with images from cameras placed on the vehicle. The software is able to determine the distance to reference points in order to locate the vehicle. Obstacles and the distance to the obstacles can be determined as well. This method is already applied at indoor AGVs; this system is able to achieve a good tracking performance [43]. The architecture of the system is completely different compared to architecture that is used on outdoor AGVs. The outdoor AGVs need to be modified in order to be able to use this system.

Triangulation procedures are well-known examples of on-board localisation. One famous example is GPS, where at least three signals from satellites are used to determine the location of the vehicle. The signals can also be sent from several fixed points on the terminal. The distance from the receiver to the sender is determined by the Doppler phase-shift of the signal. The location accuracy depends on the receiver that is used and atmospheric effects. With the use of augmentation systems, accuracy of a few centimeters can be realized [44].

The European Union is currently involved in the process of creating a similar system with an even greater accuracy [45]. Unlike GPS or GNSS (A similar system developed by Russian authorities), which are military services; the European service will be under civilian control.

The disadvantage of GPS is that the signals can be subject to interference due to the presence of large obstacles at the container terminal. These obstacles are cranes, containers etc. [33].

The last on-board localisation method uses wheel encoders [39], these sensors measure the rotating velocity of the wheels. A separate sensor measuring the tire slip has to be incorporated as well, because the slip ratios of rubber tires are significant. When tire slip cannot be corrected for, this method is very inaccurate and cannot be used on AGVs.

The wheel encoders, radar, gyroscope and GPS systems are most suitable for use in AGVs [33]. The AGVs do not have to follow predefined lanes, making the AGV system flexible. The methods are accurate enough for implementation. Several different types of localisation methods can be used to provide redundancy in order to avoid failures of the localisation system.

Table 11 shows the strenghts and weaknesses of the aforementioned localisation methods.

Table 11: Comparison of different localisation methods

Localisation method	Strenghts	Weaknesses
Buried wires	relatively inexpensive, simple to construct	AGV system becomes inflexible
Colored tape	relatively inexpensive, simple to construct	AGV system becomes inflexible
Gyroscope	Accurate	Relatively expensive
Radar	Well-developed technology	Subject to interference effects from for instance communication equipment, electric equipment etc.
Optical systems	Method can be used for collision avoidance as well	Relatively expensive software and hardware
GPS	Proven technology, relatively inexpensive	Potential interference effects from large obstacles
Wheel encoders	Relatively inexpensive	Complicated control procedures are needed to make this method accurate enough

3-3 Models Used to Control AGVs

The previous section presents localisation techniques that are used to locate the vehicle. Together with the planned path this forms the most important input to the AGV controller. The number of other inputs that are required depends on the control method that is used. The models that are used to control AGVs are kinematic models and dynamic models.

The AGV is provided with the information on where it is planned to be. This information is compared with the actual location of the AGV and the deviation is calculated. This deviation is an important control criterion, because the AGV must be positioned accurately enough in order for the cranes to lower a container on the vehicle (or lift the container from the vehicle)

The required velocity of the AGV is often calculated by a controller using a kinematic model. A kinematic model only considers the motions (displacements, velocities and accelerations) of the vehicle. The variables of the kinematic model are acceleration, velocity, distance and time and these are used in order to calculate the reference velocity of the AGV.

Figure 17 shows the system and control cycle for the controllers using a kinematic model. The kinematic model is implemented in the controller in order to determine the actions that should be performed by the AGV. The system and control cycle represents the method of controlling the system. Measurements are performed on the system and subsequently fed into the controller. The controller then calculates the required actions that should be performed on the system. This process is then repeated until the goal is reached.

The state of the AGV consists of the position, velocitiy and heading. These variables are measured on the AGV. The actions that can be performed are applying a drive torque to the wheels or change the heading of the vehicle.

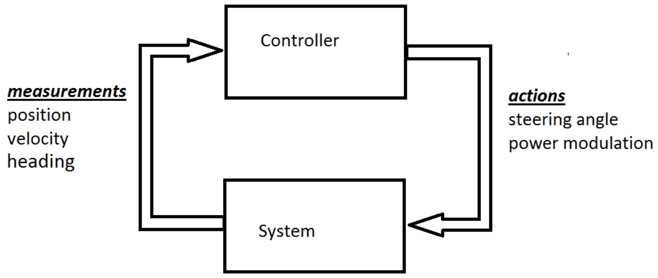


Figure 17: System and control cycle for kinematic models.

A controller using fuzzy logic is able to reduce the tracking error (deviation of current state from the desired state) [46]. The controller in this paper outperformed PID-control of the AGV. The reason for this is that an increase in load on the AGV led the PID control to perform badly whereas the fuzzy control was unaffected.

The PID as well as the fuzzy logic controlled AGVs only measure the position of the AGV in order to calculate the required control actions. The actuated variables on the AGV are the power delivered to the drives as well as the steering angle of the AGV.

When the AGV is travelling at high speeds, vehicle dynamics play a vital role in the handling, vehicle stability and performance of the AGV. Therefore, a model incorporating the dynamics of the vehicle in order to calculate the actions of the AGV is developed [39]. A dynamic model is a study on the interaction between forces and motions. This dynamic model is implemented in the controller in order to determine the actions by evaluating the states. With the use of a vehicle dynamics model (a model describing the transient behaviour of the AGV) of the AGV it is possible for the AGV to travel at high velocities while keeping the tracking error to a minimum. A dynamical model is different with compared to a kinematic model. Kinematic models consider the motions of the system under study. Dynamic models consider the interaction of the forces that are applied to the system.

The information need of the controller increases when vehicle dynamics models are implemented; the position of the AGV, the rotational velocities of the wheels, change of heading, the accelerations along the longitudinal and lateral axis of the vehicle, steered angle of all wheels and wheel slip need to be known. An estimate for the maximum tire-road friction coefficient needs to be provided as well.

The tire forces are calculated at vehicle dynamics models. A simple linear tire model can provide a good approximation of the tire forces (when they are not in saturation). This model is suited for implementation in a controller. The nonlinear "Magic Formula" tire model (developed by Pacejka) is an exact model describing tire loads. However, due to the model being nonlinear it is not suited for implementation in real time control and a linear approximation of this model is implemented in controllers.

Torque vectoring can be applied to the AGV using the output of the vehicle dynamics model. The drive torques provided to all wheels differ in order to maximize the traction forces that can be generated by the tires. The tire model is used to calculate the magnitude of these required drive torques.

Dynamical models can be implemented in MPC-structures. MPC stands for model predictive control, the MPC controller is able to optimize the current timestep while taking future timesteps into account. A fixed number of timesteps are evaluated at each interval, the MPC controller uses a fixed planning horizon. The advantage of this method of control is that is able to anticipate on the events within the planning horizon when determining the action for the current timestep.

The AGV is able to check for obstacles that are not accounted for by the path and trajectory planning procedures. The method described in [47] can be used in order to avoid obstacles. The path that was generated by the traffic control system is a large attractive potential, so the AGV follows this path. When an object is spotted, there is a repulsive potential, leading the AGV away from the object. Once the AGV has passed the object, it will continue along the originally planned path. Information regarding eventual obstacles can be obtained by radar or laser range finders.

The AGV controller has to make sure the boundary conditions, like the maximum velocity of the vehicle, are not violated.

Table 12 shows the strengths and weaknesses of the diffent control methods that are in use to control the AGVs

Table 12: Comparison of different AGV control methods

Control methods	Strenghts	Weaknesses
Kinematic models	Relatively simple method compared to vehicle dynamics modelling	Method is not able to achieve higher velocities of the AGV
Fuzzy logic	Control method is able to achieve satisfactory performance regardless of weight container and velocity of AGV	Method is not able to achieve higher velocities of the AGV
PID control	Well-developed technology	Large changes in the variables (weight of container) causes this method to perform poorly
Controller using Vehicle Dynamics modelling	Control method able to achieve relatively high velocities of the AGV, enables torque vectoring	Relatively complex method compared to the other methods

3-4 Energy Efficiency of AGVs

This section presents the methods used to increase the energy efficiency of the AGVs. These methods can be implemented in the control procedures.

With electric powered AGVs, it is possible to implement regenerative braking. Regenerative braking recovers the kinetic energy of the vehicle when it's braking. Under braking, electric motors will operate as brakes, slowing the vehicle down. While these motors operate as brakes, they generate electric energy, which can be stored by means of batteries, super capacitors [31] or by driving a flywheel [32].

The advantage of supercapacitors is that the power density is higher compared to batteries. Supercapacitors can be charged and discharged faster than batteries. The energy density of supercapacitors is smaller than batteries, therefore supercapacitors are used alongside batteries to store the regenerated energy only [48]. Flywheel systems add a significant amount of mass. The power density (in W/kg) of a flywheel is in the same order of magnitude as the supercapacitors while the energy density (Wh/kg) is significantly greater [49].

The recovered energy can be used when the vehicle accelerates again. The recovered energy is used in order to power a part of the energy peak that is required at acceleration, increasing the energy efficiency. Four-quadrant motors (also called motor-generators) can be connected to the wheels in order to drive and brake the AGV by means of the same devices.

Another configuration is having a separate drive (for instance a diesel engine connected to the wheels by means of a transmission) and connecting an electric motor to the drive shafts in order to provide extra power during peak demands. The main advantage is that the diesel engine can operate at its most efficient operating point. The complexity of the system and the controller will increase significantly, so this configuration is generally not preferred.

The AGV will experience a reduced amount of drag when travelling at a lower velocity. It is therefore beneficial to drive as slow as possible with respect to the energy efficiency of the equipment. However, the container handling performance cannot be compromised. This means that the AGVs should travel as slow as possible without becoming a bottleneck in the container handling process [50]. This method can be retrofitted to an existing fleet of AGVs and does not require the installation of extra components on the AGV.

Table 13 contains the comparison between the different energy saving methods.

Table 13: Comparison of different energy saving methods for AGVs

Energy recovery method	Strenghts	Weaknesses
Flywheel	High power density	System adds to the complexity of the AGV architecture
Supercapacitor bank	High power density	Low energy density
Batteries	In current situation already installed at AGVs	The mass of batteries needed to store sufficient amounts of energy is significant
Hybrid drive-trains	Diesel engine can be operated at its most efficient operating point	System adds to the complexity of the AGV architecture
Minimize the velocities of the AGVs	Method does not require installation of extra components, can be retrofitted to existing fleet of AGVs	The AGVs need to be coordinated well in order to fulfill all transportation tasks on time

3-5 Conclusion

The architecture of individual AGVs and their relations are considered in this chapter. The localisation methods are discussed in this chapter as well. The performance of the AGV is influenced by the accuracy of the localisation method that is used in order to measure the location and velocity of the AGV.

The mainstrain ways for localisation of AGVs are radar, gyroscopic systems, GPS systems and wheel encoders. Several of these measuring principles are used simultaneously in order to provide redundancy in case one sensor fails.

The most suited modelling method for AGVs is the method of dynamical modelling the AGV. The relation between the drive force and the velocity of the AGV is modeled. Dynamical methods are therefore better than kinematic models that estimate the required drive force by evaluating the motions of the AGV.

Dynamical modelling accounts for higher velocities of the vehicles, which can increase the productivity of the AGV system. The productivity is increased because a larger number of boxes can be transported in the same amount of time. A fuzzy control implementation is suited to control the AGV when the velocities are relatively low. The AGV is not able to achieve high velocities, contrary to an AGV utilizing a controller which makes use of a dynamical model of the AGV.

Torque vectoring and regenerative braking are used in order to increase the performance of the AGV and reduce the energy requirements of the AGV. Torque vectoring is used to supply only the necessary amount of power to each wheel, regenerative braking is used to recover the kinetic energy when the AGV is slowing down.

There are still open problems that need to be adressed in the future AGVs are nowadays powered electrically, electric AGVs have the potential to recover the kinetic energy at braking events. There are few papers on energy recovery at AGVs, while the possible gains are large due to the large mass that is accelerated and decelerated. Research should be performed in order to assess which of the energy saving methods is best suited for implementation on AGVs.

Also, applications of vehicle dynamics models at AGVs are not listed in literature, this is an open problem which needs to be adressed. The potential gain is an increase in the velocity of the AGV, which implies that less AGVs are needed at container terminals compared to the current situation. In order to calculate the wheel loads in the vehicle dynamics models, the center of gravity needs to be known, based on this survey one method is designed which is able to do this. This method is explained in Appendix A.

Chapter 4

Control of AGVs From a Container Terminal Perspective

The previous chapter provided an outline into the control of individual AGVs. At automated container terminals, there are a number of AGVs performing transportation tasks. The movements of these AGVs need to be coordinated in order to make sure that all containers are transported and the AGVs do not collide with each other. Coordination of the movements is performed at a system level, where the system consists of the entire fleet of automated guided vehicles. The first section covers the dispatching of the AGVs. The second section spans the trajectory planning as well as avoidance of collisions between AGVs. The third section considers the link between the individual AGV controllers and the AGV system level controller, before heading to the conclusion in the final section.

The goal of controlling the fleet of AGVs is to coordinate the motions of the AGVs as well as distributing the transportation tasks evenly across the entire fleet of AGVs. The control process of the system of AGVs contains three elements: dispatching, trajectory planning and collision avoidance.

The relation between the different processes is outlined in Figure 18. Typically, the AGV system control architecture consists of the dispatching controller and a trajectory planning controller.

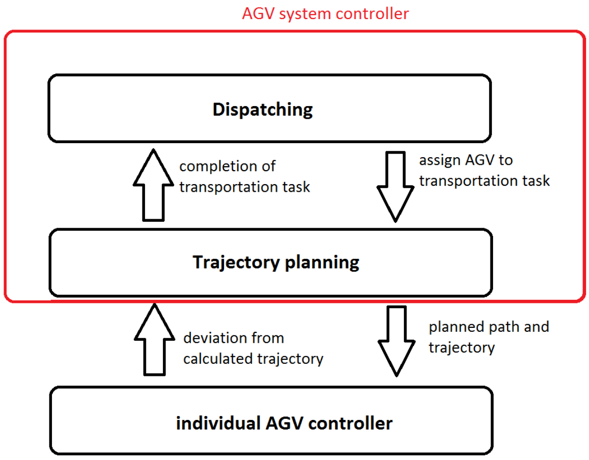


Figure 18: Schematic representation of the different levels of control.

The dispatching controller assigns a vehicle to a transportation task. Typically, the dispatching procedure provides the locations that the AGV should drive to in order to collect and deliver a container [47]. After the AGV is assigned to a transportation task, the route is calculated by the trajectory planning process. The trajectory planning process calculates the route of the AGV in two stages. First, the trajectory from the current position towards the pick-up location of the container needs to be calculated. Subsequently, the trajectory between the pick-up and drop-off location is calculated.

Collision avoidance is a very important issue with autonomous vehicles; the AGVs must stay clear of each other as well as obstacles. The information from the trajectory planning phase is used in order to detect collisions of paths of several AGVs, which are subsequently resolved. Collision avoidance is considered being a part of the trajectory planning process. Due to its importance to container terminals, it is explicitly mentioned in this chapter.

These processes are covered in detail in the next sections. The processes are covered from the top level to the lower levels. This means that dispatching is discussed first before heading onto trajectory planning and collision avoidance.

4-1 Dispatching of AGVs

This section covers the dispatching of AGVs. The methods are briefly discussed here for the sake of completeness. The dispatching methods have been investigated extensively and an overview of these studies can be found in [47]

In some procedures, dispatching is preceded by scheduling [51], [52]. The goal of scheduling in this case is to minimize the turnaround time of the vessels and trains. The cranes are scheduled in order to minimize the turnaround times and the AGV system adheres to the schedule created by the cranes. The AGVs follow the transportation requests coming from the quay cranes, RMGs and stacking cranes. The cranes give orders to the AGV system, a transportation task is a request to transport a container to or from the crane.

The cranes are scheduled in order to minimize the turnaround time of the vessels and trains. This process is explained in the next chapter. In most cases the AGVs only follow the orders from the cranes, the AGVs themselves do not need to be scheduled. Another set of approaches exist where AGVs are scheduled. The scheduling process and the dispatching process are combined in these approaches [47].

The goal of the dispatching process is to select an AGV that will conduct the transportation task according to a specific objective (e.g. minimizing the travelled distance). A transportation task is a container which needs to be moved from the origin to the destination location. For each transportation task, only one AGV must be selected among the set of AGVs that is assigned to the vessel or train to which the transportation task belongs. The dispatching process selects an idle AGV and assigns it to a transportation task. The parameter describing the state of the vehicles (the vehicle being idle or conducting a transportation task) has the largest influence on the outcome of the dispatching process.

Dispatching of an AGV occurs when an idle AGV is assigned a transportation task. Two kinds of dispatching problems exist: workcentre and vehicle initiated dispatching [47]. When the dispatching is workcentre initiated, an AGV is selected among a set of idle vehicles. Dispatching is vehicle initiated if an AGV has to select a transportation task from a set of transportation requests. Figure 19 shows a number of AGVs that are dispatched and are driving towards their assigned transportation task.

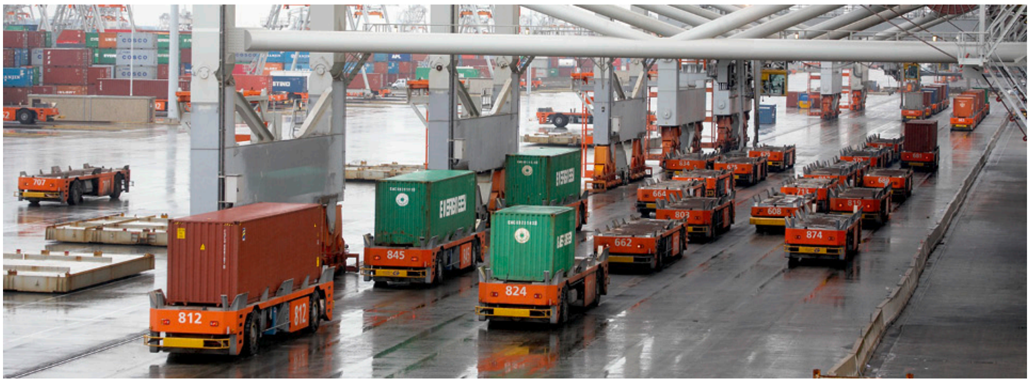


Figure 19: Dispatched AGVs driving towards their task (source: www.demagcranes.fr)

Dispatching of AGVs is performed according to rules. Currently there are several rules in existence that are used on terminals. These rules are listed in Table 14 [47].

Table 14: Overview of different dispatching rules.

type of dispatching rule	**dispatching rule**	**goal of the dispatching rule**
workcentre initiated	random vehicle rule	distribute transportation tasks evenly
workcentre initiated	nearest vehicle rule	minimizing total travelled distance
workcentre initiated	farthest vehicle rule	minimizing idle time of the AGVs
workcentre initiated	longest vehicle idle time rule	distribute transportation tasks evenly
workcentre initiated	least utilized vehicle rule	distribute transportation tasks evenly
vehicle initiated	random workcentre rule	distribute transportation tasks evenly
vehicle initiated	shortest travel time rule	minimizing total travel time
vehicle initiated	shortest distance rule	minimizing total travelled distance
vehicle initiated	maximum outgoing queue size	prevent blockages at parts of the terminal

A multi-attribute rule combines several dispatching rules [47]. A multi-attribute rule considers several criteria; for instance the unloaded travel distance of the AGV to the pick-up point, the remaining space in the buffers at the pick-up and delivery points and the idle time of the vehicle. Each criterion is assigned a weight which changes depending on the current status of the system. It has been shown that this kind of rule performs better than single-attribute rules or multi-attribute rules with fixed weights.

It has been determined that workcentre initiated dispatching outperforms vehicle initiated dispatching when container terminals are considered [47]. Performance increases when the dispatching controller is supplied with pre-arrival information of transportation requests. The dispatching controller is able to assign a vehicle before the transportation task becomes available. The vehicle in the mean time is able to drive up to the pick-up location. This is important at quay cranes, because the AGV needs to be at the crane as the container is lowered in order to enable the crane running at its maximum capacity.

Fuzzy logic, neural networks and Markov decision processes hardly outperform heuristic rules. This makes that in the dispatching controller of an AGV system heuristic rules are most often applied.

Another distinction in dispatching processes exists: off-line or on-line dispatching. Off-line methods use the information at the start of the transportation processes in order to assign the AGVs to the tasks in an optimal manner. All transportation requests at a container terminal are not known in advance, that is why an on-line method to schedule the AGVs is preferred in most cases. On-line methods are able to assign vehicles when transportation requests become available, allowing for more scheduling flexibility.

The dispatching of AGVs at container terminals is workcentre initiated. The AGVs are dispatched by applying heuristic decision rules which are able to select the AGV which is best suited to fulfill the transportation task. The AGV that is best suited to fulfill this transportation task can be the AGV that is closest to the pick-up location or the AGV that is least utilized (as is already displayed in Table 14).

4-2 Trajectory Planning and Collision Avoidance

Once the AGV is dispatched as described in the previous section, it has to be determined how to get from the pick-up to the delivery location. The trajectory that the AGV has to execute needs to be calculated. Several methods exist already which are capable of doing so. This section gives an overview of several methods that are able to plan the trajectory of an AGV. Collision avoidance procedures are often integrated in the trajectory planning process, these are discussed in this section as well. This section is divided into the subsections distributed control and centralized control.

The trajectory of the AGV is calculated in two steps. The path planning procedure provides a path that is optimized to some criterion (for instance: minimizing the total length of the path). The path spans from the current location of the vehicle via the pick-up point to the destination point of the container. The trajectory planning procedure provides the schedule of the movement of the AGV along the planned path.

Table 15 shows an overview of different trajectory planning methods. There is a distinction between centralized and distributed control. Distributed control is a control structure at which each AGV plans its own trajectory. Control of the system of AGVs is in this case performed by the AGVs themselves. The AGVs communicate with each other in order to calculate the trajectories and to prevent collisions. Centralized control is a structure at which a centralized controller determines the trajectories of all the AGVs. The central controller sends the information regarding the paths to the AGVs. The AGVs in turn send information regarding the achieved progress of the transportation task to the central controller.

Table 15: Overview of different trajectory planning methods.

trajectory planning method	**goal of controller**	**control structure**	**used model**	**ref.**
local path planning method	limit change of acceleration	distributed control	fifth order polynomials	[53]
Splitting terminal up into nodes	minimize the travelled distance	distributed control	Dijkstra's algorithm	[54]
zone-control method	prevent collisions and deadlocks	centralized control	partition of terminal into zones	[55]
repulsive/attractive potentials	prevent collisions	distributed control	social pedestrian dynamic model	[56]
petri nets	balancing tasks across the fleet	centralized control	petri net	[57]
dynamic routing method	minimize travelled distance	centralized control	kinematic model	[58]
time-constrained routing	minimize energy requirement	centralized control	kinematic model	[59]
potential fields	prevent collisions	distributed control	potential fields	[60]
rerouting AGVs	prevent deadlock	distributed control	kinematic models	[61]

4-2-1 Distributed Control of AGV Systems

This subsection concerns distributed control of AGV systems. The trajectories of the AGVs are calculated by the individual AGVs. The AGVs communicate with each other in order to prevent collisions from occurring.

The local path planning algorithm tries to limit the change of acceleration in order to create a smooth ride for the AGV [53]. The velocity and curvature of the trajectory are continuous functions, in this case 5th order polynomials. This method is one of the first established methods that enable the AGV to plan its own route.

Another distributed control method uses the Dijkstra's algorithm in order to solve the problem of minimizing the total distance that has to be travelled by the AGV [54]. The terminal is split up in a set of nodes. Some are fixed in order to be able to assign driving lanes. Others will move, like for instance the quay cranes. Every quay crane can be seen as both an origin as a destination node (depending on whether the crane is unloading or loading containers) and these nodes are able to move along the quay wall. The shortest path between the origin and destination nodes is calculated by Dijkstra's algorithm. The AGV that is closest to the origin node will be assigned in order to reduce the length of the total travelled path. Dijkstra's algorithm is used in order to obtain the optimal solution to the scheduling problem.

A method based on the social pedestrian dynamic model is also a distributed control method [56]. A repulsive potential is generated that increases when the distance between the AGV and the other AGVs (or other obstacles) becomes smaller. Points of interest (like checkpoints) provide a attractive potential in the same way. The AGVs are able to drive around each other by evaluating the potential functions that are programmed in the controllers of the AGVs.

Potential fields (a virtual field consisting of attractive and repulsive forces) are also used in order to avoid obstacles [60]. This control method is also a distributed approach towards trajectory planning. The attractive forces try to "pull" the AGV towards the target while the repulsive forces try to "push" the AGV away from obstacles. The AGV scans the surrounding area and assess the potential field. In case an obstacle is present, the path is altered in a way that prevents the AGV from colliding while keeping the extra amount of distance to be travelled to a minimum. Because the functions are non-linear, genetic algorithms are used to find a solution to the routing problem. The advantage of the potential fields is that the AGV is able to navigate through areas with a large number of (unknown) obstacles without having to supply the AGV with information on the location and size of the objects. The AGV is able to detect the obstacles by itself and is also able to calculate a path avoiding the objects. Potential fields can be calculated in real-time, so the system is able to react to fast changing conditions.

The final distributed approach of trajectory planning of AGVs is rerouting the AGVs in case deadlock occurs. The algorithm described in [61] is able to avoid both deadlocks and collisions by rerouting the AGVs. The terminal must have a lay-out with several connected undirected circuits. This approach can be implemented, but a study of the effect of rerouting AGVs on the handling capacity of the system must be performed in order to make sure the capacity of the transportation system is maintained.

Table 16 shows the strengths and weaknesses of the different distributed control methods used to plan the path and trajectory of AGVs.

Table 16: Comparison of differend distributed control methods

Distributed trajectory planning method	Strenghts	Weaknesses
Local path planning	Method able to produce smooth path and trajectory	Method is not able to prevent collisions with other AGVs
Dijkstra's algorithm	Method able to calculate optimal solution to shortest-path problem	Method is not able to prevent collisions with other AGVs
Social pedestrian dynamic model	Method able to produce smooth trajectory while avoiding collisions	Future movements of other AGVs needs to be known in detail in order to gernerate the potentials
Potential fields	Method able to provide a trajectory free of any collision	Next to the equipment that is able to localise the AGV, the AGV needs to be equipped with sensors with sufficient range in order to scan the environment
Rerouting AGVs	Method is able to prevent collisions	Method is not able to generate a path that is guaranteed to be optimal

4-2-2 Centralized Control of AGV Systems

This subsection concerns centralized control of AGV systems. The trajectories of the AGVs are calculated by a central controller. The AGVs communicate only with the controller, communication with other AGVs becomes unnecessary.

Zone-control methods are centralized approaches to trajectory planning [55]. Zone-control methods are developed in order to prevent collisions as well as deadlock from occuring. Deadlock occurs when the buffer at the destination node is occupied. The vehicle remains occupied as well because the container cannot be unloaded. Another form of deadlock occurs when an AGV cannot proceed along its path because it is blocked by another AGV. The AGVs cannot resolve the deadlock by themselves, for they are only instructed to follow a certain path and they are not able to determine which AGV should give way. A special case of deadlock is livelock, where an AGV cannot continue due to a large queue of AGVs passing in front of him. They may pass in a way that does not enable the AGV to move in between the other AGVs [62].

Most of the central controlled AGV systems are zone-controlled; the AGVs cannot enter a zone unless they have the permission of the traffic control system to do so. The container terminal is divided into zones. The deadlock prediction looks ahead to the future zones that the AGVs will cross and lists the zones that will be crossed by more than one AGV [58]. These deadlock situations will be resolved by the planning algorithm, one AGV will let the other AGV pass. This can be done in two ways, slowing the conflicting AGV down or delaying the departure time of this AGV so it still is able to travel at constant velocity along the path.

Dynamic algorithms are able to incorporate forecasts of the traffic in order to avoid congestion of the terminal. When a zone is occupied, the interval between the arrival of the vehicle at the zone and the vehicle leaving the zone will be listed. This time window is used as a planning parameter for the other AGVs [63].

A dynamic approach to the scheduling and route planning of AGVs outperforms the static approach [64]. This is in the case the transit times for the AGVs on each arc are constant, acceleration and cornering effects are not yet modeled. The computation time is low enough in order for this system to be implemented at automated container terminals. Reference [64] applied a dynamic scheduling approach to trajectory planning of zone-controlled AGVs.

Another centralized control method is based on Petri nets. Petri nets are often used when solving scheduling or routing problems of various types of equipment. This method of scheduling routes is explained in detail in [57]. This method is used in order to balance the load across the system. The transportation tasks can be distributed evenly to all the AGVs.

A dynamic routing method is another centralized control method which is developed to avoid collisions [58]. The paths of the AGVs are calculated, these paths are the shortest route between the origin and destination nodes. The AGVs will only drive away from the origin node when the path is not crossed by other AGVs. It waits as long as it takes to have a free path. The AGVs do not travel along paths that are fixed on the terminal; decreasing the average traveled distance. The system operates in real-time and uses information on the planned trajectories of the other vehicles in order to determine the routes for incoming transportation requests.

The final important centralized control method is the time-constrained trajectory planning method [59]. This trajectory planning method takes the other AGVs into account as if they are moving obstacles. The AGV has a time constraint; the actions that will delay the arrival of the AGV beyond its arrival window are penalized. High velocities are penalized as well in order to maintain stability of the vehicles and to reduce the energy consumption. All constraints available in the model are designed to create an AGV that arrives on time while driving at the minimum velocity required for the AGV to arrive on time.

Table 17 lists the weaknesses and strengths of a central controlled AGV system.

Table 17: Comparisong of centralized control methods

Centralized trajectory planning method	Strenghts	Weaknesses
Zone-control	Prevention of deadlock	In order to determine trajectory of AGV, detailed information on the trajectories of all other AGVs in the system needs to be taken into account
Petri nets	Method is able to distribute transportation tasks evenly across fleet of AGVs, thus reducing individual peak loads	computational power required to solve problem is generally large
Dynamic routing method	Prevention of collisions, creating shortest path	Once paths become large, chance of free path becomes smaller, in this case certain transportation tasks can not be performed anymore
Time-constrained trajectory planning	Method capacle of preventing collisions while reducing energy consumption	In order to determine trajectory of AGV, detailed information on the trajectories of all other AGVs in the system needs to be taken into account

4-3 Connection Between System and Individual AGV Control

This section covers the interaction between the individual AGVs and the control at AGV system level. The interaction is governed by the exchange of data between the system controller and the controller of each individual AGV.

The transportation tasks are sent to a central task controller which is able to send this information to the AGVs. Due to the dispatching problem being NP-hard, the centralized dispatching of AGVs can only be done using heuristics. Because of the large amount of data involved in centralized dispatching of the entire fleet of vehicles at an automated container terminal, dispatching can also be performed by the vehicles themselves. Each AGV will pick one of the transportation tasks and communicates with the task controller in order to remove the task from the list of awaiting transportation tasks. This procedure prevents other AGVs dispatching themselves on the same task. The AGV system controller collects the data of the AGVs with respect to the progress of their assigned transportation task. This data is used in order to keep track of the productivity of the AGV system. The information on the productivity can subsequently be submitted to a terminal scheduling controller or be communicated to the controllers of the crane systems.

In the case of centralized control of AGV systems, the central controller must send the information with respect to the path and trajectory planning to each AGV-controller. The individual AGV-controller must make sure that the AGV adheres to the trajectory that is calculated by the AGV system controller. The disadvantage of centralized control is it having a single point of failure, this means that when the centralized controller fails all AGVs stop working. The advantage of a distributed control architecture is that the complexity as well as the amount of calculations that need to be performed by the AGV task controller are reduced. The routes are calculated by the AGVs themselves. Each AGV is informed by all other AGVs on their planned trajectories in order to avoid collisions from occurring.

The information exchange between the AGVs can either occur directly or indirectly. With direct communication between AGVs, each AGV will send its information to all other AGVs. Indirect communication occurs when the AGV sends its information to the AGV system controller, where the other AGVs can collect the data they need whenever they need to do so.

A hybrid form is also an option for control of AGV systems. This form is called hierarchical control. With hierarchical control, the controllers are able to communicate with each other (like in the case of distributed control) but are supervised by other controllers [65]. The supervisory controllers are situated at a higher hierarchical level. The supervisory controller is able to intervene in case two controllers at a lower hierarchical level are in conflict with each other.

If for whatever reason the AGV is delayed, the AGV is able to calculate the amount of delay and can adjust the velocity planning in order to remain on schedule. This enables the AGV to reduce the error and track the velocity profile accurately. When the trajectory planning is changed or when the delay becomes too large, the AGV must inform the other AGVs, for their routes may need to be altered as well. The routes of the other AGVs may be altered in order to prevent collisions, queueing and deadlock from taking place.

Figure 20 shows the interaction between the AGV control at system and at individual level. The type of information that is exchanged is shown along with the direction of communication

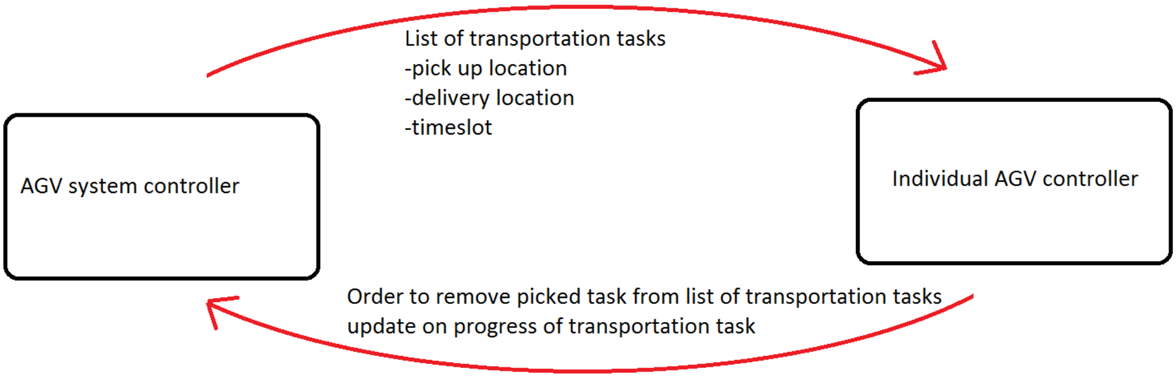


Figure 20: Interaction between AGV control at system and at individual level

4-4 Conclusion

The dispatching problem of AGVs is in general NP-hard, which means that centralized control of AGV systems at automated container terminals can only be performed using heuristics (as is done in zone-controlled AGV systems). Otherwise, calculation of the dispatching order would take too much time.

In order to overcome this, distributed approaches are implemented at automated container terminals in order to control the AGV systems. The method based on the social pedestrian dynamic model is one of the distributed control methods suited for trajectory planning of AGVs. The AGVs communicate with each other on both their routes and trajectories in order to avoid collisions between them. Each AGV needs to know the trajectories and paths of all other AGVs. The AGV must then determine if there are any conflicts.

Distributed control is able to provide satisfactory performance because the computation times are low compared to centralized control. The dispatching procedure can be solved in order to determine the optimal solution. The global optimum is the dispatching order with the lowest makespan of the vessels, trains and trucks.

In order to create an AGV system which is able to satisfy the demands of the container terminal at all times, a minimum number of AGVs is required. The minimum amount of vehicles that is necessary in order to achieve stable system performance can be calculated using for instance the method mentioned in [66]. This calculation includes the stochastic behavior of the arrival of containers and is able to calculate the minimum required vehicle number needed in order to prevent excessive queues from forming somewhere in the system. The reader is referred to [67] in order to obtain an insight into a multitude of methods and design guidelines for dispatching, vehicle positioning, battery management, routing and deadlock avoidance for AGVs.

In the current situation, the energy requirements are not taken into account during the planning of the trajectories. New research can be performed in order to come up with a trajectory planning method that minimizes the energy requirement while preventing collisions and deadlocks.

Another open problem concerns centralized control of AGV systems. Due to the large amount of data involved, the calculation time of the controller is too large. The problem is to find a way to obtain the optimal solution within a sufficiently small timeframe.

The last open problem concerns distributed control, the AGV controller needs to obtain information on the location and heading of the surrounding AGVs. The information can be information on AGVs within a certain range of the AGV or information on all the AGVs in the system. Both options create different requirements for the control of AGVs at system level as well as the control of AGVs at individual level.

Chapter 5

Individual Gantry Crane Control

The previous chapters concerned control of AGVs, this chapter will focus on the control of gantry cranes at individual level. The first section considers the control of gantry cranes in general. The specific control methods applied to quay cranes, RMGs and ASCs are covered in the second, third and fourth sections respectively. The penultimate section discusses the energy efficiency of the gantry cranes that are used at automated container terminals. The last section concludes this chapter.

Because all container cranes at automated container terminals are gantry cranes, the control procedures for these cranes are similar, because the cranes all share the same construction layout. The gantry cranes all have the same type of actuators and the control goals are similar. The control goal of the gantry crane is to transport a container from origin location to the destination location. The difference between the several types of gantry cranes is the distance and path that must be travelled in order to achieve the control goal. The first section covers the control methods for gantry cranes which are applicable to each type of container crane. The application of the types of cranes is different, this means that the control procedures for each type of container crane are slightly different as well. The control procedures for the different types of container cranes are outlined in their respective sections.

The assignment of tasks to cranes is the topic of the next chapter. The cranes are controlled at individual level in order to complete the handling tasks. The crane is supplied with information on the position of the containers to be handled, the crane controller must convert this information into actions. These actions are performed by actuators on the crane in order to handle the container.

5-1 Control of Gantry Cranes

The cranes that are deployed at automated container terminals are gantry crane types. The variables of the container handling cranes that need to be controlled are therefore similar. This section concerns control of gantry cranes in general.

The gantry cranes that are used at container terminals have three degrees of freedom. This means that there are three parameters that can be influenced independently. The cranes are mounted on rails along which they can travel. The second degree of freedom is the trolley movement, the trolley is able to move along the beam of the gantry crane. The last degree of freedom is the height of the spreader, which can be raised or lowered. The movement of the trolley is perpendicular to the movement of the crane itself. The control problem of gantry cranes is defined as moving a container from the origin to the destination location as fast as possible.

Figure 21 shows an RMG built by Konecranes, with arrows indicating the three degrees of freedom. The components of the crane are clearly visible in this illustration, the drives which hoist or lower the spreader are mounted on top of the trolley. The trolley is able to move along the boom by means of rails. The boom in this case is made out of two separate beams.

The methods that are used in order to coordinate the cranes at a system level are displayed in the previous chapter. This information is used by the container crane to determine the location the spreader should be moved to. The spreader must be moved to these exact locations either to load or unload a container. The spreader is brought into the correct position by moving the crane, the trolley and the spreader. The method of translating the information on the location of the containers into these locations for the crane is different for each type of crane. Once the locations are known the actuation of the drives on the cranes is the same for each type of container crane.

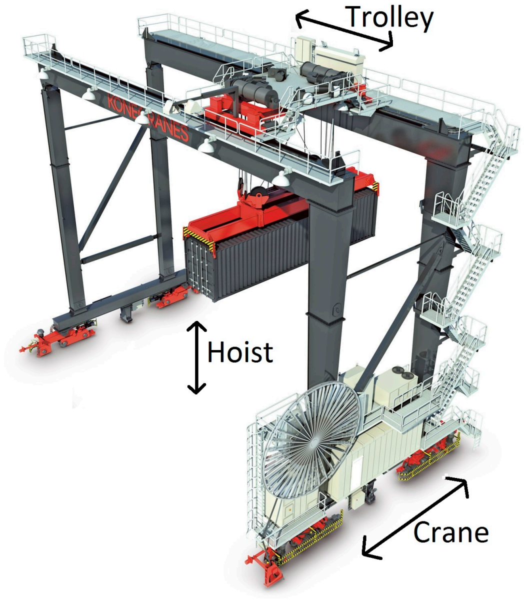


Figure 21: Example of a gantry crane; an RMG (source:www.konecranes.com).

Figure 22 shows an example of the system and control cycle. The system and control cycle relates the controller to the system that has to be controlled. In this case, the system under study is the gantry crane. Measurements are performed on the gantry crane in order for the controller to determine the actions that should be applied to the system.

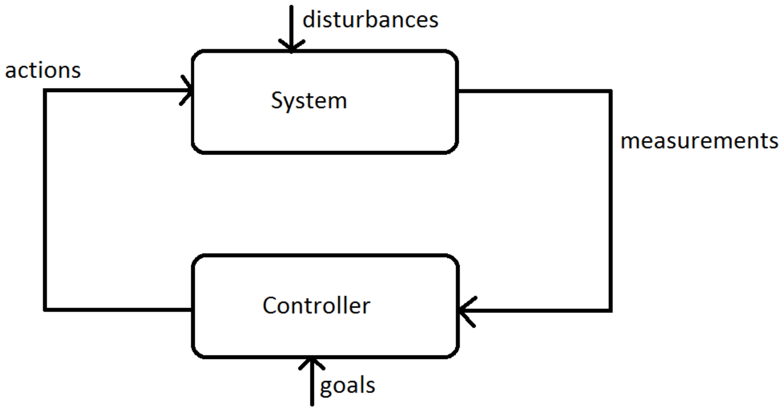


Figure 22: The system and control cycle for gantry cranes.

The measurements on gantry cranes are the position and velocity of the crane, the trolley and the spreader. The measurements of the crane position can be performed using RFID technology. Receivers located on the crane can determine the distance between the crane and the RFID transmitters. The position of the crane can also be measured using wheel encoders, which measure the angle of rotation of the wheels. In case several cranes are mounted on the same rail, they are provided with scanning lasers to measure between them.

The position of the trolley is measured in equal ways as the position of the crane is measured. But next to RFID technology and wheel encoders, laser range finders can be used [26]. The trolley is equipped with lasers which measure the distance between the trolley and a fixed plate on the boom. The problem of measuring the position of the spreader is not one dimensional, like the position measurement of the crane and trolley. The connection between trolley and spreader lacks the stiffness necessary to restrain the trolley in one direction.

The position of the spreader with respect to the trolley can be measured using laser scanners. The measured distance between the spreader and the trolley needs to be corrected for the orientation of the spreader. The spreader is able to rotate about three axes, the angle of the spreader can be measured using inclinometers, this angle is used when determining the exact location of the spreader [68]. The position of the spreader can be tracked by image processing systems as well. The spreader is equipped with markers, which are tracked by cameras mounted on the trolley [69]. The drive of the hoisting mechanism on the trolley can be equipped with an rpm sensor in order to determine the length of the cable between the trolley and the spreader. This information is coupled with the information on the position of the markers in order to accurately determine the position of the spreader.

The crane is supplied with three different actuators, the hoisting motors, trolley drive motors and crane drive motors. The spreader is put in the correct position with the use of these three actuators. The actions that are computed by the controller are the torques that need to be supplied by the drives.

Disturbances (like for instance windloads and frictional loads) act on the system. These disturbances cannot measured, the magnitude of these disturbances can be derived from the measurements on the position of the crane, trolley and spreader. The control actions are recalculated several times in order to compensate for these disturbances

The goals inside the controller change over time. Each time a container is handled, the controller is supplied with a new goal. This goal concerns a new handling task, to transport a container from a known origin position to a known destination position.

Control of a gantry crane is performed by evaluating a cost function. This cost function is a function of the deviation between the current and the desired state, the time available to perform the action, the boundary values (like maximum velocity and acceleration) and the energy required to reach the desired state. The minimum of this cost function is determined in order to find the optimal control for the gantry crane.

The controller of a gantry crane is supplied with equations describing the mechanical behaviour of the spreader. These equations are solved in order to obtain the required control actions [70]. The crane determines the optimal trajectory of the container and by solving the equations of motion the actions required to achieve this trajectory.

5-2 Control of Quay Cranes

This section concerns the control of quay cranes. This section concerns the positioning of the crane with respect to the vessel, twistlock handling and concludes with the control of skew and sway. This section is divided into subsections alignment of the crane, twistlock handling and sway angle control.

5-2-1 Alignment of the Quay Crane

The vessels that are handled by the quay cranes do not remain in a fixed place. When the vessels are moored at the berth, they are connected to the quay wall by cables. These cables allow for movements of the vessel. These movements are caused by the waves and wind loads that impact on the vessel.

Difficulties are caused by these relative movements of the vessel with respect to the crane. Because the container is fixed relative to the vessel, the container also moves with respect to the quay crane. The spreader must be able to follow the movements of the container in order to load or unload a container. The movements of the containers must be tracked in order to lift the containers on or off the vessel. The position of the containers on the vessel are known to the crane. This means that the movements of vessel itself can be tracked in order to determine the orientation and position of the container.

One way to do this is to use an automated mooring device. This device has been developed to automate the mooring process (which is not automated yet) and is already installed at a container terminal [71]. An example of such a device is depicted in figure 23. This concept contains several of these devices which are installed along the quay wall. Each vessel is moored using a number of these devices, which can be equipped with sensors in order to measure the motion of the vessel. This information can be send to the cranes in order to calculate the position of the containers.

Figure 23: Equipment used to automate the mooring process of a vessel (source: [71])

The alignment of the crane with respect to the bays of the container vessel is difficult due to the construction of the vessels being different. Currently, automated cranes are aligned by human operators which are in a control room at the container terminal. In order to automatically align the crane to the bay, the lay-out of the vessel along with an accurate measurement of position of the vessel needs to be known to the crane. The position of the vessel with respect to the quay wall is measured in three directions. The position of the vessel is measured at several locations along the length of the vessel in order to determine the rotations in three directions. The action that is undertaken in order to align the crane to the vessel is to move the crane along the quay wall.

5-2-2 Twistlock handling

The containers are lashed on the vessel, upon arrival at the port the containers are unlashed. The containers remain fixed relative to each other with twistlocks while they are located at the vessel. When unloading the container, the twistlocks need to be removed from the container just before the container is put on the AGV. When the containers are loaded onto the vessel the twistlocks need to be attached to the containers before hoisting the container towards the vessel. The twistlocks are handled at the quayside. When the twistlock handling is automated, it needs to be incorporated in the quay crane operation directly.

The automated handling of twistlocks can be performed using a special platform. This is not applied a lot because the platform requires a lot of maintenance and the investment costs are substantial [72]. These platforms need to be mounted on the structure of the crane, which needs to be modified to accomodate the platform. The last reason that the platform is little used is that the supply of a sufficient number of twistlocks to the platform causes problems. Unlike containers, twistlocks are not standardized and a large variety of different types of twistlocks are in use. This makes the automation of twistlock handling difficult.

An Universal Container Locking System (UCLS) is developed in order to solve the twistlock handling problem. This system consists of special locking units that unlock when the spreader is engaged and lock when the spreader disengages. The need for twistlock handling is removed, reducing the handling costs. As twistlock handling is one of the most dangerous jobs at a container terminal, safety at the terminal increases when this system is used [72].

Measurements are performed by the quay crane in order to determine whether or not twistlocks are attached at the bottom of the container. One way to measure the presence of twistlocks is to use an optical system with image processing software. The actions that are performed are either attaching or removing the twistlocks.

5-2-3 Sway Angle Control at Quay Cranes

Due to the large length of the cables between the spreader and the trolley (which are around 50-60 m [25]) the spreader is able to move in two directions with respect to the trolley, these are called skew and sway. Figure 24 illustrates sway, this angle is represented with θ_3. With sway, the spreader moves back and forth with respect to the trolley in the direction of the boom. Skew is the movement of the spreader with respect to the trolley in the direction parallel to the quay wall. Because the container needs to be below the spreader in order to drop the container, the productivity of the crane is reduced. Before dropping the container off, the sway and skew motions needs to be damped out.

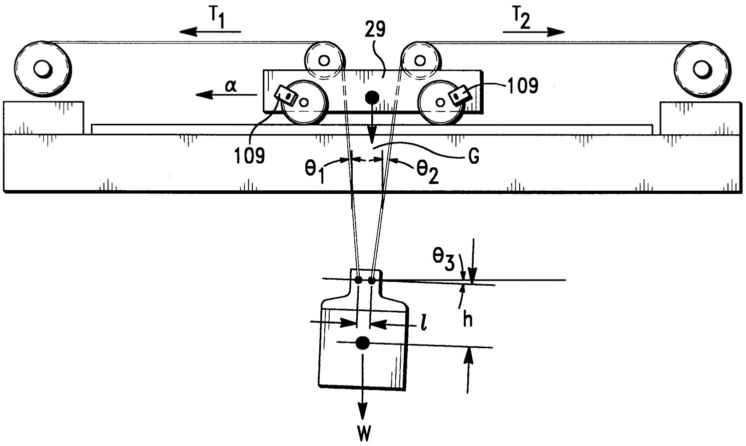


Figure 24: Illustration of sway at container cranes [source: patent US6250486 B1].

Reducing the angle of sway at automated container cranes is performed in order to increase the handling performance. Handling performance is increased because the crane does not have to wait until the sway motion is damped out before lowering the container onto the AGV or vessel.

Another important reason for reducing sway is safety near the container crane. When the angle of sway cannot be controlled by the crane the container might be able to swing around dangerously, hitting everything on its way. This may damage the AGVs or even the vessels, as well as creating a hazard for the people that are at work in the vicinity of the crane (for instance maintanance operators or people at work on the vessel).

Sway is a swinging motion of the load in the direction of trolley travel. Currently, the controller manipulates the inputs of the crane operator in a way that sway of the load is counteracted. It is reported that experienced crane operators currently are able to achieve a higher productivity when the anti-sway system is turned off [38]. This shows the difficulty in successfully automating a quay crane. As explained in [24], the cause for the lower productivity with the anti-sway system in action is significant non-linearities that are present in the crane-trolley interactions which are currently not accounted for.

One method that reduces sway uses an inclinometer to measure the inclination angle of the spreader itself [68]. The angle of the spreader with respect to the trolley is already measured (as discussed in the previous section). The evaluated state is composed of the parameters describing the states of the trolley and the spreader. Depending on the state of this system the controller calculates the required actions that reduce the sway angle. The angle of sway is reduced by changing the trajectory of the trolley. During acceleration and braking, the velocity of the trolley is controlled in a way that reduces sway. In case a large angle of sway occurs, the trolley can move against the direction of sway in order to damp this sway motion. The action that is performed is adjusting the velocity of the trolley in order to eliminate sway.

Another method designed to reduce sway makes use of an image processing system which is able to accurately track the spreader. Once the sway angle is determined, the crane controller determines which actions can be taken in order to reduce sway. Sway is reduced by an inertia damper mounted on top of the spreader. The inertia damper comprises of a mass which is connected to springs. This mass is moved against the direction of sway, damping this swaying movement [69].

The actions in the sway-reducing controllers are calculated from the equations of motion. The equations describe the sway angle as a function of positions, velocities and accelerations.

5-3 Control of RMGs

This section concerns the control of individual RMGs. The way RMGs handle the loadplan of the train is discussed as well as is the position control of the crane relative to the train. This section consists of the subsections aligning RMGs to trains and controlling sway.

5-3-1 Aligning RMGs to trains

The goal is to align the RMG to the train in a so the RMG is able to load and unload the containers. The position of the train with respect to the crane must be known in order to determine the location of the containers with respect to the crane.

The loadplan of a train is different compared to that of a vessel. The containers at trains are only categorized according to destination. Here, the destination of the containers is considered to be the train handling station at which they are lifted off the train again. The position of the containers on the train are detailed in the loadplan [73].

The position of the train and the rail cars which provide space for the containers can be determined in several ways. One possible way might be having a marker on each rail car which can be tracked by a camera system that is mounted on the RMG.

Another method might be to drive the train up to a fixed reference point (the end of the track for instance) and calculate the positions of the cars. The positions can be calculated using the dimensions of the locomotive and the used cars.

5-3-2 Sway Angle Control of RMGs

At automated RMGs, the sway angle is controlled using the methods developed for quay cranes. The control objective as well as the methodology remains the same. The rope length of the RMG is around 20 m [27], which is less compared to that of the quay crane. The hoisting and trolley travel velocities of the RMG are lower than the quay crane [25], [27]. The shorter rope length reduces sway somewhat, along with the lower velocities. The methods used at container cranes can thus be applied to RMGs as well.

Trains are still operated by humans, this means that the train handling process must be performed in a safe environment. The angle of sway needs to be restricted in order to prevent the container hitting the train or the personell that works in the vicinity of the trains.

When the RMG is aligned to the train, the crane is moved along the length of the train. After the handling of each container, the crane will move towards the next train car. The crane and the trolley movements must be coordinated in a way that minimizes the sway angle of the containers.

The sway controllers need to be supplied with dynamical models describing the sway angle as a function of the velocity and position of both the crane and trolley.

5-4 Control of ASCs

This section discusses the control regarding the ASCs.

The stacking algorithms that are used to assign the ASC to handling tasks are introduced in the next chapter. The stacking controller determines where the containers need to be stacked. When containers need to be taken out of the stack, the crane controller gets a signal to pick the container up and deliver it to the AGV or the truck. The positions of the trucks and the AGVs are known to the ASC controller.

The actuation of ASCs is covered in the fist section on the control of gantry cranes. At these cranes sway needs to be controlled because a container with a large sway angle is able to cause damage to the stacked containers, due to the spacing between the rows of containers being relatively small.

The velocity of an ASC is higher than that of an RMG or quay crane in order to stack and unstack the containers within a reasonable amount of time [28]. This is the reason that besides the control procedures that reduce the angle of sway, as mentioned in the section on quay cranes another method of controlling sway is developed. This method does not make use of controllers, it is controlled by a mechanical linkage.

This mechanical linkage contains a beam which is connected to the spreader. This beam adds sufficient stifness in order to diminish the sway angle. This concept is illustrated in 25.

Figure 25: An ASC equipped with a beam in order to counteract sway [source: www.terex.com].

5-5 Energy Efficiency of Container Cranes

This section concerns the reduction of the energy consumption of container cranes. Reducing the energy consumption of container cranes results in lower operational costs. This section is divided into the subsections scheduling and regenerative braking.

5-5-1 Increasing Energy Efficiency by Alternative Scheduling Procedures

The scheduling of the movements of gantry cranes influences the energy efficiency of the container handling process. Alternative scheduling procedures can increase the energy efficiency of the container gantry crane.

During the loading operation of a vessel, the crane moves the container to the vessel. The crane subsequently moves the spreader to the quay in order to start a new cycle. With the use of dual cycling, the spreader will transport a container to the quay. Unloading and loading operations are combined in order to reduce the amount of empty trolley moves [74].

Reducing the amount of empty trolley moves reduces the energy consumption of the quay crane. This procedure was designed in order to increase the container handling efficiency. The energy efficiency is implicitly improved because the amount of trolley moves is reduced. Moving a trolley requires energy, reducing the amount of these movements thus reduces the total energy consumption. The scheduling procedure becomes more complicated, the horizontal transportation and the stacking cranes must be able to keep up when the vessel is loaded and unloaded at the same time.

When waste energy is recovered (as mentioned in the next subsection), this can be supplied to the electricity grid. When the movements of the cranes are synchronized, the efficiency of the cranes can be further improved [75]. When one crane lowers a container it recovers energy, this energy can be directly supplied to a crane which hoists a container. The energy does not need to be temporarily stored in an energy storage, increasing the overall efficiency. This method requires a detailed scheduling procedure which determines which cranes need to lift and which cranes need to lower a container. When the cranes are scheduled in this way, the peak power demand is reduced. The scheduling procedure which is able to synchronize the movements of the cranes is a lot more complex compared to conventional scheduling procedures. All cranes (RMGs, ASCs and quay cranes) need to be scheduled simultaneously in order to synchronize the movements with respect to the simultaneous consumption and regeneration of energy.

5-5-2 Increasing Energy Efficiency by Regenerative Braking

When the potential energy that is released when a container is lowered is not dissipated across a braking resistor but instead is regenerated, the energy efficiency increases. The energy that is harvested using regenerative braking can be stored locally or supplied to an electricity grid.

When energy is stored local to the crane, the energy is used when the crane hoists another container. The energy can be stored using a flywheel [32], supercapacitor bank [31] or a large battery. The recovered energy reduces the energy requirement of the quay crane.

The energy required for one move of a quay crane is around 6 kWh [75]. The amount of auxiliary power of automated cranes is lower than human operated cranes because there is no need for an air-conditioning system, flood lights and walkway lights. Energy can be recovered to reduce the energy requirement. The maximum amount of recovered energy amounts to around 75-80 percent of the energy required to lift a container [75]. This percentage results from the efficiencies of the motor-generator system and energy storage.

The recovered energy can also be supplied to the electricity grid which the cranes are connected to. The energy can be used by other types of equipment, it can be stored in an energy storage system that is installed at the terminal or the energy can be used to charge the batteries of the AGVs.

5-6 Conclusion

The cranes are supplied with handling tasks by the crane scheduling processes which are described in Chapter 6. The location of the containers that need to be handled are known to the cranes. The spreader handles these containers by actuation of the crane drives, trolley drives and the hoisting drives. The position of the containers on the transport modality is known to the crane. In order to locate the container the position of the transport modality with respect to the crane needs to be known to the crane.

The quay cranes must be able to track the movements of the vessel in order to lift a container on or off the vessel. The position of the vessel needs to be measured in order for the crane to line-up with the container bays automatically. The RMGs need to know the position of the train in order to know the positions of the containers that need to be loaded or unloaded.

When moving the container, the sway angle needs to be minimized. This is done to maximize the container handling capacity as well as ensuring the safety of the lifting operations. The controller obtains data on the state of the trolley and the container and calculates the actions required to complete the handling task while keeping the angle of sway within acceptable limits. The actions that are considered are changing the velocities and positions of the trolley and the hoisting mechanism.

Automating container cranes gives an opportunity to reduce the energy consumption. The cost functions in the controllers are suited for implementation of energy consumption strategies. This can either happen in the scheduling process of the cranes or by applying regenerative braking.

The major open problem for quay cranes and RMGs is determining the position of the containers on the vessels and trains. The quay cranes and RMGs need to line up with the transport modalities, therefore they need to know their position relative to that transport modality. The position of the containers relative to the position of the transport modality need to be known as well in order to determine the position of the containers relative to the crane.

The previous problem highlights another open problem, communication between the transport modalities and the cranes. The transport modality needs to communicate the position of the containers that need to be handled to the crane. A standard communication protocol needs to be developed which enables the transport modality to communicate with automated cranes at different automated container terminals.

The position of the AGV relative to the crane needs to be determined as well in order to lift a container on or off the vehicle. This problem is equivalent to the problem of locating the transport modalities. However, because the AGV operates internal to the container terminal the AGVs can be modified in order for the cranes to determine their position.

Another open problem concerning automated operation of gantry cranes is the interaction of the automated equipment with humans. The transport modalities that are handled by the cranes are operated by humans. This means that they will inevitably operate in the vicinity of the automated equipment and measures have to be taken in order to ensure the safety of these people. Very few papers adress this issue regarding the automated operation of cranes, therefore more research should be performed in order to determine the measures needed in order to accomodate for people working in the automated environment.

Chapter 6

Control of Gantry Cranes at Container Terminal Level

The previous chapter concerns control of individual gantry cranes. The cranes at container terminals are also coordinated at a container terminal perspective. The cranes need to be scheduled in order to minimize the turnaround time of the vessels and trains. The cranes used on automated container terminals (quay cranes, RMGs and ASCs) are gantry cranes. The first section covers the scheduling of the gantry cranes for handling operations. The second section describes the process of stacking the containers. The last section contains the conclusion to this chapter.

Scheduling of quay gantry cranes is often considered alongside the berth allocation problem [76]. The berth allocation problem concerns the assignment of vessels to berths. The vessels all have a different size and they need to be scheduled along the quay wall in a way that minimizes the handling time for each vessel.

The berth allocation problem will not be revisited in this report, for it is out of the scope of this research. The reader is referred to [77] and [78] in order to get an insight into the berth allocation problem. The scheduling of the arrival of the vessels, trains and trucks at the terminal is not considered in this report.

6-1 Scheduling of Quay Cranes and RMGs

This section considers the assignment of gantry cranes to specific handling tasks. A handling task is a request to lift a container on or off the vessels, trains or trucks. The first subsection briefly introduces the assignment problem of quay cranes to vessels. The second subsection concerns the assignment problem for RMGs to trains.

6-1-1 Scheduling of Waterside Operations

Waterside operations are performed at the quay wall, the vessels are loaded and unloaded by the quay cranes. The problem of scheduling the quay cranes is to minimize the turnaround time of all the vessels while respecting the constraints. The sequence of handling operations for every quay crane needs to be scheduled according to these constraints. The major constraint arises from the rail on which the cranes are mounted, therefore the cranes cannot pass each other. Another constraint is the maximum crane travel velocity, which is generally low [25].

The crane scheduling problem is often formulated as a mixed integer linear programming problem. The mixed integer linear programming problem is formulated to determine the sequence of handling operations for the quay cranes and the vessels. The problem of scheduling the quay cranes is to find a (near) optimal solution to the assignment problem which satisfies the physical constraints. The objective of the controller is to find the optimal solution, the optimal solution is the solution with the minimum makespan of the set of vessels.

The quay crane assignment problem is defined as determining the sequence of handling operations (the order in which the vessels are served) as well as assigning the quay cranes to the vessels in order to minimize the total makespan of the set of vessels.

The minimum number of cranes that are assigned to a vessel is often defined by the contract between the terminal operator and the shipping line [79]. The assignment of cranes to vessels is not static, the assignment of cranes can change during the handling process of the vessels. This means that during the handling operation of a vessel, the number of quay cranes that are servicing it might be changing over time.

When more quay cranes are deployed on a vessel, the turaround time of that vessel is reduced. The relation between the number of assigned quay cranes and the turnaround time is not linear [79]. With every extra quay crane assigned to a vessel, the reduction in turnaround time of that vessel becomes smaller. The quay cranes interfere with each other, lowering the productivity of each crane. The maximum amount of assigned quay cranes is limited by this decrease in quay crane productivity [76]. This interference effect needs to be taken into account during the process of allocating cranes to vessels. The assignment of quay cranes to vessels should be performed in a way that maximizes the productivity of the system of quay cranes. Quay crane assignment is vital for handling performance of the vessels and is therefore taken into consideration during the berth planning process.

It is shown that assigning quay cranes to vessels should be preferred over assigning the cranes to berths [80]. The proposed procedure simultanously solves the berth assignment problem and the crane assignment problem. First, a ship sequence is created. Subsequently, the vessels are assigned to berths. After the berth assignment problem is solved, the cranes are assigned to the vessels in order to minimize the turnaround time. The model is formulated as a mixed-integer linear programming problem.

Another procedure of assigning cranes to vessels only consists of two steps [77]. The model assumes that the ship sequence cannot be influenced by the terminal. Therefore the model first determines the berthing position of the vessels before heading onto the crane assignment problem. The problem is formulated as a mixed-integer linear programming problem. This program is solved using a genetic algorithm with a fixed planning horizon.

An approach formulated as a mixed-integer linear programming problem is developed which assigns the cranes to holds [81]. This is because in practice, only one quay crane will be assigned to each hold on the vessel. The procedure looks for the holds that need to be handled and subsequently assigns the cranes to the holds in a way that minimizes the makespan of the entire set of vessels.

Another approach uses an integer programming model to assign the quay cranes to vessels [82]. Simultaneously, the berth assignment problem is solved in this approach. This procedure uses fixed time segments where the number of quay cranes for each vessel are determined. The assignment is stationary during one time segment.

The previous procedures divided the quay wall into discrete berths. The vessels can also be assigned to a position along the quay wall, instead of sectioning the quay wall into descrete berths. This position is determined by the size of the vessels, the distances between the berthed vessels and the length of the quay wall [83]. The quay cranes are assigned to the vessels based on the order of arrival, berthing position and the size of the vessels.

A simulation method that includes the horizontal transportation function in the crane assignment process is developed in [84]. The advantage of this procedure is that the productivity of the cranes and AGVs togehter can be calculated. The calculated productivity serves to calculate the optimal assignment of cranes to the vessels. This model is not yet implemented because the computation time is fairly large, compared to the control methods that were discussed previously.

The scheduling procedures use mixed-integer programming in order to provide the schedule of the quay cranes. The algorithms used to solve the scheduling procedures are not mentioned in this report. The reader is referred to [85] in order to obtain more information on most of the algorithms that are used to solve these mixed integer programs.

Table 18 shows the differences of the quay crane scheduling methods that are mentioned in this chapter. The methods of the assignment of vessels to berths are listesd in the column 'berth assignment'. The column 'vessel handling' lists the scheduling procedures that are used to determine the order of vessel handling. The methods that are used to assign the quay cranes to the handling tasks are listed in the column 'quay crane assignment'.

Table 18: Differences between the different quay crane scheduling methods

Method	Berth assignment	Vessel handling	Quay crane assignment	Type of programming method
Simultaneous berth and quay crane assignment	Discrete	Order of arrival and size of vessels	Berthing position and size of vessel	Mixed-integer programming problem
Two-stage method	Discrete	Order of arrival	Berthing position and size of vessel	Mixed-integer programming problem
Hold assignment	Discrete	Size of vessels	Berthing position and number of handling moves per hold	Mixed-integer programming problem
Fixed time segments	Discrete	Order of arrival	Berthing position and size of vessel	Integer programming problem
Continuous berth method	Continuous	Order of arrival	Berthing position and size of vessel	Mixed-integer programming problem

6-1-2 Scheduling of Railway Operations

The railway operations concern the handling of the trains that visit the terminal. This subsection introduces the assignment of RMGs to trains. The problem of scheduling of the trains and RMGs is equivalent to the scheduling of the vessels and quay cranes, the trains and RMGs need to be scheduled in a way that minimizes the makespan of the trains.

A mixed integer program is constructed which is able to schedule the handling of the trains [86]. The trains are assigned to one of the available tracks based on the time of its arrival at the container terminal. After the trains are assigned to a track, the handling operations on the trains are planned.

Another approach uses an integer programming based heuristic method that is able to schedule the RMGs in order to handle the trains. This scheduling method is able to construct an operating schedule for the RMGs which has a global optimum [87].

Heuristics can be used to schedule the trains and RMGs simultaneously [88]. This research showed that heuristics are able to be successfully implemented on container terminals. The heuristics are able to handle the complex operating environment of a container terminal.

Table 19 lists the train and RMG scheduling procedures that are mentioned in this section. The programming methods are listed in this table as well.

Table 19: List of train and RMG scheduling methods

Scheduling method	Programming method
Scheduling of trains and RMGs	Mixed-integer programming problem
Assign RMGs to trains	Integer programming problem
Simultaneous scheduling of trains and RMGs	Heuristics

The amount of models regarding the scheduling of trains and RMGs is low compared to the models that are created in order to schedule vessels and quay cranes. A limited number of publications on this subject are available. While the algorithm using heuristics to schedule the trains performs well, further research may need to be conducted to search for even better train and RMG scheduling methods.

6-2 Stacking of Containers

This section concerns the storage of the containers at automated container terminals. Storage of containers at automated container terminals is performed by automated stacking cranes. There are two problems; scheduling of ASCs and the reduction of unproductive stacking moves. Scheduling of ASCs does not only concern the stacking moves, also the truck handling moves are considered.

The daily operation of stacking the containers is governed by several decision making processes. These processes allocate space in the container stacking yard for the containers arriving with the incoming vessels and trains. Also, the decision making processes assign stacking equipment to container stacking tasks. Position control and velocity control of the stacking cranes is performed in real-time. When two or more ASCs are mounted on the same rail, they are not supposed to come into contact with each other. The operational decision making process uses a stacking strategy in order to determine when and where to stack a certain container.

The main objectives of a stacking strategy are [89]:

- efficient use of the available storage space
- avoidance of unproductive moves
- timely transportation of containers between the destination position (this is the outgoing transport modality) and the stack

The third objective implies that the containers that should be lifted onto a vessel should be stacked close to the berthing location of that vessel. The containers that should be lifted on a train should be stacked close to the scheduled arrival location of that train. The containers that are destined to leave the container terminal by truck should be stacked close to the planned arrival location of the truck.

The main inputs for the stacking strategy are the type of container (size, reefer, storage of dangerous goods), the modality with which the containers leave the container terminal and the date and time of departure [89]. The stacking strategy determines where to store the containers. The stacking strategy does not cover the assignment of ASCs to the individual stacking or unstacking tasks.

It is determined that on-line stacking rules are preferred over off-line stacking rules. "Online optimization can avoid suboptimal yard operations that might be caused by a predefined stowage plan" [89]. Some online stacking rules and their effects are simulated in [90], these rules are designed to find an optimum stacking strategy even when all of the information on the containers is not available

6-2-1 Scheduling of ASCs

Scheduling the ASCs makes sure that all handling requests are performed within a reasonable amount of time. Scheduling of the ASCs is required in order to prevent the ASCs from overloading. When the ASCs are overloaded, the amount of container handling requests are larger than the maximum amount of requests that can be handled by the ASCs. In this case the ASCs are not able to match the handling rate of the quay cranes. This means that they slow the container handling process down. Reducing the amount of reshuffle moves reduces the load on the ASCs. Reference [91] examines container stacking policies that distribute the workload between the available ASCs. Other variables that are considered are: the retrieval and stacking costs (distance that has to be travelled by the ASCs and eventual interference effects between different ASCs), a binary variable that indicates whether or not the container needs to be rehandled within the stack and the amount of occupied volume in stack compared to the maximum stacking volume (indication of space utilization).

The arrivals of vessels and trains are known some time in advance, this is generally not the case with trucks. The handling moves with respect to the trucks cannot be scheduled due to this reason. When the arrivals of trucks becomes known one half hour to 24 hours in advance, the performance of the stacking process can be improved [92]. Even when the arrival is known 4 hours in advance, a large improvement can be obtained. Assigning ASCs to trucks is nowadays scheduled on an ad-hoc basis, due to the arrival times being known only minutes in advance.

The containers can be put at an easy accessible location prior to the arrival of the truck. The ASCs can perform these relocation moves when they do not need to service other trucks or AGVs [92]. The moves are be performed when the stacking cranes become idle, thus these moves do not interfere with the other container handling processes on the container terminal. The majority of the shuffling moves can in this case be performed prior to the arrival of the truck. The unproductive moves are shifted from the peak hours to the off-peak hours.

The efficiency of the stacking process is even better when the information on the containers is available prior to stacking. The stacking decisions improve so the attempt to fix poor stacking decisions by having pre-arrival information on the trucks becomes not necessary anymore. Only when the information on the container is incomplete, this method improves the performance of the stacking process and scheduling of the ASCs [92].

6-2-2 Reducing the Amount of Rehandling Moves

Rehandling moves (also called reshuffling moves) are unproductive container handling moves that are performed in order to shuffle a container across the stack. This is performed in order to expose the container that has to be delivered from the stack. Rehandling moves happen in case the container that has to be picked up has other containers stacked on top of it. The total number of unproductive moves increases when the average stacking height increases.

Reducing the amount of unproductive reshuffling moves has a benificial influence on both the workload of the ASCs and the energy requirement of the stacking process.

Each vessel has a stowage plan, indicating the location of the containers on the vessel [89]. The shipping line first makes a rough plan, based on categories, which will be sent to the terminal. Somewhat before arrival, the detailed stowage plan is created. The containers that belong to each category are defined in detail. The stowage plan is important for the stability of the vessel. The heavier loaded containers are located at the bottom of the vessel, instead of on the deck. The stowage plan is able to serve as an input into the stacking process in order to reduce the amount of reshuffling moves.

The containers that need to be transported by trains are also grouped together. The position on the train does not influence the performance of the transport process, so the containers are not grouped according to categories (they are only grouped by train).

Unproductive stacking moves may arise just before the arrival of a vessel, containers are repositioned in the stack in order to create empty areas that can accomodate the containers that are unloaded from the vessel. The containers that will leave with a certain vessel are sometimes collected in one or more specific areas of the stack, the repositioning of these containers causes unproductive stacking moves as well [93]. These extra amount of moves can be reduced when the sequence at which the containers need to be loaded onto the vessel is known to the stacking cranes prior to stacking. This sequence can be determined from the information on the loading plan of the vessel.

The container handling efficiency increases with a reduction of reshuffling moves. A reduction of reshuffling moves also reduces the energy consumption of the stacking process. The energy consumption is reduced because the cranes perform less moves per handled container. The total number of reshuffle moves can be estimated for a given stack lay-out and calls (incoming vessels or trains) [**?**]. The stacking strategy needs to minimize the amount of reshuffling moves.

A stacking procedure using heuristics is proposed in [94], which sorts the goal containers at the side where the containers will eventually leave the stack. This is an attempt to reduce the average travelled distance for the handled containers. When a train or a vessel arrives, the containers that need to be loaded onto the train or vessel are grouped together. The heuristics sort the containers according to the vessel or train with which they will leave the container terminal in order to reduce the amount of shuffle moves.

A large reduction of shuffle moves is obtained in [89], where the amount of reshuffle moves is reduced by 80 percent with respect to the situation where containers are stacked at random. The improvement comes from stacking the containers according to categories. The categories are defined by mode and date of departure. The containers are stacked on top of each other when the top container is set to leave the container terminal prior to the container below. The amount of reshuffling moves is significantly reduced. The simulation considered catagorized stacking in different set-ups, including rules that control the workload of the ASCs.

Table 20 shows an overview of the different stacking procedures that are discussed in this section along with a short description on the procedures

Table 20: Overview of the different stacking procedures

Stacking procedure	Description of procedure
Random stacking	Put the container on one of the available stacking positions
Category stacking	Sort containers by their position on the outgoing modality
Reverse sequence	Sort containers by the order in which they are loaded. the first ones to be loaded need to be stacked last (so they are on top of the piles)
Outgoing location sorting	Sort containers at the side at which they will leave the stack

6-3 Conclusion

The cranes are assigned to vessels by solving the berth assignment problem and crane assignment problem simultaneously. The vessels are scheduled in order to maximize the utilisation of the quay wall and to keep the waiting time of each vessel within acceptable limits. The cranes are scheduled simultaneously to the vessels in order to reduce the makespan of the vessels and make sure the handling time for every vessel remains within acceptable limits. The quay cranes are scheduled in a way that minimizes the makespan for the set of serviced vessels. Mixed-integer linear programming models are used to calculate the optimal assignment of cranes to vessels.

The rail mounted gantry cranes that service the trains are coordinated in a similar fashion to the scheduling of the quay cranes. First, the trains are assigned to tracks. Subsequently, the RMGs are assigned to the trains in a way that minimizes the makespan of the set of trains. Mixed-integer programs are used in this case as well.

The assignment procedures create a schedule for the quay cranes and RMGs. The schedules are sent to the individual cranes, which calculate the control actions that are necessary in order to execute the calculated schedule. These control actions are for instance the crane and trolley movements. These control actions are discussed in Chapter 5.

The process of stacking the containers is controlled by stacking strategies. These strategies minimize the amount of rehandling moves in order to maximize the efficiency and performance of the stacking process. The stacking strategy also calculates the required ASC movements in a way that does not overload the system of ASCs. Category stacking has the best performance compared to the other stacking strategies.

When a container needs to be stacked, restacked or unstacked, the location of that container is sent to the relevant ASC along with the required destination position of that container. The actions that the ASC performs in order to perform the required task are discussed in Chapter 5.

The major open problem regarding the control of gantry cranes at container terminal level is the communication between the types of cranes. Currently, there is no methodology available which is able to connect the quay cranes, RMGs and ASCs. All the container handling processes are connected to each other due to the containers temporarily being stored in the container stack. Therefore a method should be considered that coordinates these processes.

Another open problem is the stacking of refrigerated containers (reefers). These containers need to be connected to a power supply while they are stored in the stack. It is not clear if automating this process can be cost effective or how connecting the reefers to the power source can be automated.

Unproductive stacking moves still remain at the truck handling process, due to their arrival times being unknown at the time of stacking. This open problem should be adressed in the future. Ways to overcome this by changing the process which delivers containers to the trucks should be investigated in order to make their arrival times more predictable, thus creating an option to reduce the unproductive stacking moves at this end of the stack.

Chapter 7

Conclusion and Recommendations for Future Research

This chapter will provide the conclusions to this research. The first section discusses the answers to the research questions. The last section provides recommendations for future research on automated container handling.

7-1 Conclusions of the Literature Research

This section covers the answers to the research questions based on the research that is presented in the previous chapters.

The main research question was: "How can container handling equipment be automated?"

The main question involves by 4 subquestions. The 4 subquestions that support the main question of this research were:

- What are the current trends on containerized transporation and container terminals?
- What is the current state of automation of container handling equipment?
- What parameters are involved in automating container handling equipment?
- What models and control techniques are used in automated container handling equipment?
- What are the current limitations in automating container terminals?

The current trends on container terminals are the trend towards automated container handling and the trend towards an increase in energy efficiency with respect to the container handling process. Container handling is automated in order to reduce the terminal operating costs in areas where human labour costs are high. Automation is also performed in order to keep the turnaround time of the deep-sea vessels (which remain to grow in size gradually) within reasonable limits. The energy consumption is reduced in order to reduce the operating costs and to conform to the societal trend towards more energy-efficient processes.

Currently the horizontal transportation system and the stacking process are fully automated. The container cranes are currently unable to lift the containers on or off the vessels or trains due to difficulties in aligning the container spreader with the container slots. The cranes are able to transport the containers from the vessel towards the quay automatically.

The parameters that are involved in controlling an automated container terminal are listed in table 21. The parameters that are listed in this table only concern the global parameters. The parameters can be used at automated container terminals in order to schedule the movements of all the equipment. The detailed parameters like for instance the tire-road friction coefficient at AGVs is not taken into consideration in this table, for doing so would make for a very long list of parameters. The parameters presented here are the minimal requirements in order to plan the handling operations.

The control architectures that are applied at automated container terminals are centralized control, distributed control and hierarchical control.

A centralized control architecture must be able to process a large amount of data. This data consists of all the variables of all the pieces of equipment. Because the scheduling processes are NP-hard, an exact solution cannot be found. Heuristics can be used in order to make a centralized controller work. When one piece of equipment sends data that is in error, the actions calculated by the centralized controller may be in error as well. A centralized system is also vulnerable to failures, when the controller fails the handling process comes to a halt. The advantage of centralized control is that the movements of the individual pieces of equipment can be coordinated without any conflicts arising. Also, when equipment at an automated container terminal is replaced, the centralized controller needs to be updated.

The advantage of a distributed control architecture is that it provides redundancy. When one controller fails, the other pieces of equipment are still able to perform their functions. The only disadvantage is that the controllers must be enabled to communicate with each other. In case the controllers are in conflict which each other, the conflicts need to be resolved in order to continue the container handling operations.

An hierarchical control structure is able to assist in resolving conflicts between several controllers. It has the advantages of a distributed control architecture, but this control architecture is much more complex. When equipment is replaced, the other controllers do not need to be updated, equipment can thus be replaced while the other pieces of equipment remain in operation.

The models that are used to control the AGVs are kinematic models and dynamic models. Kinematic models are used in order to plan the trajectory of AGVs. Dynamical models are suited to control the individual AGVs. The models describing the dynamical interaction are able to accomodate for relatively large velocities of the vehicle. Dynamical models are currently used at cranes as well, in order to be able to reduce the sway angle of the container.

The challenge of modelling the types of equipment is that the models need to provide accuracy. With large displacements (for instance the angle of sway), the dynamic interactions become non-linear. Linear models are more suited for implementation in controllers, the challenge is to create a linear model that is able to estimate the influences the nonlinearities.

The main limitation in the process of automating container terminals is the difficulty of determining the exact location of the containers at trains or vessels. The quay cranes and RMGs need to line up with the containers in order to be able to lift them on or off the transport modalities. Also the cranes need to detect the exact location of the AGV in order to lift a container on or off the vehicle. Another limitation is the movement of the vessel during container handling operations, these movements make determining the exact location of the containers on the vessel a complex task.

Other open problems do exist as well, but these issues do not disturb the process of automating container terminals. The other open problems concern issues that limit the efficiency of the automated container handlig process only. Examples of these problems are the implementation of energy recovery methods or the implementation of vehicle dynamics models at AGVs.

The main research question: "How can container handling equipment be automated?" can now be answered. The main issue at automated container handling equipment is coordination. Coordination is performed in order to connect the container handling processes. For instance, the AGV must arrive at the quay crane just in time to collect a container. All the movements of the equipment need to coordinated in order to handle the containers. The planning and scheduling of the pieces of equipment is very important with respect to the performance of the entire terminal. Scheduling of the equipment needs to be perfomed automatically in order to automate the container terminal.

When the tasks of the equipment are planned, it is possible to determine the detailed actions that need to be performed by the actuators that are mounted on the equipment. These actuators are controlled in order to make the equipment adhere to the output of the scheduling process.

The actions that should be considered for satisfactory performance of an automated container terminal are the sequence of the handling operations on the vessels, trains and trucks and the assignment of equipment to these handling tasks. The RMGs and quay cranes are scheduled to the trains and vessels respectively. When containers are needed, they inform the stack controller that a container has to be delivered. The ASCs, RMGs and quay cranes send requests to the AGV system.

The individual performance of the AGVs can be increased using efficient routing algorithms and models describing the dynamics of the vehicle in order to maximize the velocities of the vehicles. The individual performance of the cranes is determined by the amount of information on the exact location of the vessels, trains and trucks. Models describing the dynamics of the cranes can increase the performance of these container cranes.

The performance of AGVs can be increased by reducing the amount of energy that is necessary in order to conduct the transportation tasks. The energy efficiency of AGVs can be improved using regenerative braking. The energy efficiency of the cranes can be improved by regenerating the energy when a container is lowered.

Table 21: Main parameters at automated container terminals.

equipment type	parameter	unit
AGV/ASC/RMG/QC	number of vessel handling operations	[-]
AGV/ASC/RMG/QC	expected arrival time of vessels	[hr]
AGV/ASC/RMG/QC	Queue of vessels waiting to be handled	[-]
AGV/ASC/RMG/QC	size of vessels	[m]
AGV/ASC/RMG/QC	required number of handling moves on the vessels	[-]
AGV/ASC/RMG/QC	maximum handling time of the vessel	[hr]
AGV/ASC/RMG/QC	number of train handling operations	[-]
AGV/ASC/RMG/QC	expected arrival time of trains	[hr]
AGV/ASC/RMG/QC	queue of trains waiting to be handled	[-]
AGV/ASC/RMG/QC	size of trains	[m]
AGV/ASC/RMG/QC	required number of handling moves on the trains	[-]
AGV/ASC/RMG/QC	maximum handling time of the trains	[hr]
AGV/ASC/RMG/QC	number of truck handling operations	[-]
AGV/ASC/RMG/QC	expected arrival time of trucks	[hr]
AGV/ASC/RMG/QC	queue of trucks waiting to be handled	[-]
AGV/ASC/RMG/QC	capacity of trucks	[TEU]
AGV/ASC/RMG/QC	size of trucks	[m]
AGV/ASC/RMG/QC	maximum handling time of the trucks	[hr]
AGV/ASC/RMG/QC	weight of container	[ton]
AGV/ASC/RMG/QC	center of gravity of container	[m]
AGV/ASC/RMG/QC	destination modality of container	[-]
AGV/ASC/RMG/QC	expected time of departure of container	[hr]
AGV	number of transportation tasks	[-]
AGV	destination location of containers	[m]
AGV	origin destination of containers	[m]
AGV	number of vehicles in the system	[-]
AGV	position of the RMGs	[m]
AGV	position of the quay cranes	[m]
AGV	number of idle vehicles	[-]
AGV	distance from AGV to the destination	[m]
AGV	reference velocity of the AGV	[m/s]
ASC	capacity of stacking yard	TEU
ASC	number of empty stacking positions	[-]
ASC	number of stacking requests	[-]
ASC	number of retrieving requests	[-]
ASC	forecast of retrieving requests	[-]
ASC	expected departure time of transport modality	[hr]
RMG	position of RMG with respect to train	[m]
RMG	instanteneous capacity	[moves/hr]
RMG	sequence of containers on the train	[-]
RMG	position of container relative to the quay crane	[m]
RMG	velocity of hoisting, trolley travel and crane travel	[m/s]

quay crane	loadplan of the vessels	[-]
quay crane	instanteneous capacity	[moves/hr]
quay crane	position of quay crane with respect to vessel	[m]
quay crane	position of container relative to the quay crane	[m]
quay crane	velocity of hoisting, trolley travel and crane travel	[m/s]

7-2 Recommendations for Future Research

This section concerns recommendations for future research in the field of control of automated container terminals. The recommendations concern research into control of individual pieces of equipment as well as control of the entire container terminal. This section is divided into sections covering recommendations at terminal level and at equipment level.

7-2-1 Recommendations for Research at Terminal Level

Coordination of the movements of container handling equipment at an automated container terminal is very important. Coordination is important because the different types of equipment depend on each other in order to function properly. The cranes cannot load the transport modalities without AGVs, to give an example. So far, the scheduling procedures are only applied to one type of equipment at a time. An improvement in the efficiency of the scheduling process might by the integration of all scheduling procedures. The various types of equipment might be better coordinated. The productivity of the quay cranes might be improved when the AGVs and ASCs are scheduled simultaneously with the quay cranes. These types of equipment can be scheduled simultaneously in order to obtain a constant flow of containers to and from the quay cranes. The quay cranes do not have to wait for the AGVs or for specific containers to load on the vessel. The implementation of this scheduling procedures in the controllers of the various types of equipment needs to be investigated. This research will focus on the control architecture and the relation between the different controllers at the container terminal.

Another recommendation concerns the velocity of the individual AGVs. The capacity of the AGV system that is needed to transport the containers changes over time. The necessary capacity of the system is a function of the number of handled trains and vessels and the time that is available to handle both the vessels and the trains. Although this subject concerns the velocity of individual AGVs, it is considered to be a decision at system level. The reason is that the velocity of AGVs is determined from the capacity requirement of the AGV system. The handling capacity of the system of AGVs is a function of the number of AGVs and their velocities. When few AGVs are deployed, they need to drive fast in order to handle the amount of containers. When more AGVs are deployed, the velocity of the AGVs necessary to handle the containers is reduced.

The total resistance in the situation with few fast-moving AGVs is large due to the large amount of drag that is experienced by the individual vehicles. The total resistance in the situation with a lot of slow-moving AGVs is large due to the relatively large amount of rolling resistance experienced by the individual AGVs. Somewhere in between these extreme cases, there is an optimal number of vehicles which reduces the total drag. Future research can be performed in order to evaluate this curve and the relation between this curve and the amount of handling operations on the terminal.

The handling of the twistlocks causes problems. The design of twistlocks is not standardized, so there are a lot of different twistlocks in use. Research can be conducted in order to determine an appropriate way to deal with these different types of twistlocks automatically. Another research can be performed in order to determine a plan to standardize the twistlocks which is considered feasible as well as attractive to the actors involved. When twistlock handling is automated, this feature can be integrated in the design of intelligent container crane controllers which enable the container cranes to operate without any human supervision being necessary.

When the distance between the berths or tracks becomes large, it might be beneficial to use a trailer system when the vessels or trains are unloaded [35]. These trailers should be pulled by AGVs and need to connect and disconnect automatically. The advantages of having such a system should be investigated along with their effects on the storage process.

Further research can be performed in order to increase the proportion of direct transshipment at automated container terminals. With direct transshipment, the containers are exchanged between a barge and deep-sea vessel without the container being lifted towards the quay. This reduces the number of requests for AGVs and ASCs, as well as increasing the energy efficiency. The effects of this concept on the load planning of vessels and scheduling of quay cranes need to be investigated. The control of the quay crane movements becomes more difficult, because both vessels move with respect to the crane and each other. The quay crane also needs to consider two load plans at the same time, adding to the complexity of this operation. These problems need to be overcome in order to enable direct transshipment at automated container terminals.

7-2-2 Recommendations for Research at Equipment Level

The energy efficiency of the individual AGVs is an area in which further research can be undertaken. Research can be performed in order to determine whether hybrid AGVs or electric powered AGVs should be used at container terminals. The control of these energy storage systems must be taken into account during this research. The AGV must be able to drive with the maximum efficiency in the operational conditions of a container terminal.

When handling the container vessels, the quay cranes need to take the movements of the vessel into account. Research can be performed in order to determine the movements of the spreader given the movements of the vessel. Another research topic might be finding a method able to damp or restrict the movements of the vessel in a way that these become insignificant to the control of the quay cranes. The movements of the vessel need to be considered in the control problem of the quay crane controllers.

When energy is regenerated at gantry cranes, the amount of regenerated energy can be very large. This holds especially for quay cranes because they are the largest cranes at a container terminal and the containers have a larger amount of potential energy when lifted. The storage of the harvested energy must be considered. It must be investigated whether or not the energy must be stored locally to the crane or supplied to the electrical grid which the cranes are generally already connected to.

When energy is supplied to an electrical grid, control procedures have to be designed which control the flow of energy through the network. When energy is supplied to the network, this can be taken into account in the crane scheduling process. For instance, one crane should lift containers when another one is lowering a container (the energy does not have to be stored, increasing the energy efficiency of the overall container handling process). Research can be performed in order to determine the best strategy to accomodate for these procedures.

ALVs (Automated Lifting Vehicles) are already developed, these are used to decouple the ASCs and the horizontal transportation function. Decoupling the processes at the quay cranes cannot be performed because the cranes move, so they are unable to place the container onto a rack. This can be overcome by fixing a rack to the structure of the crane. Another method is to find a suitable lifting concept which is able to lift the container from the ground.

Appendix A

Measurement Center of Gravity of Containers by AGVs

As mentioned in Chapter 3, the AGVs can be controlled using a model representing the dynamical behavior of the vehicle. An important variable in these models is the center of gravity of the container that is transported. Because each container is loaded differently, the center of gravity is different for each container. In current literature, no papers describe methods that are able to measure this. A method that is able to measure the center of gravity of the container is proposed in this appendix.

First, the equations of motion of AGVs are discussed, these are needed in order to measure the center of gravity of the container that is transported. These equations can subsequently be used to control the vehicle once the center of gravity of the container is known.

A-1 Equations of motion of AGVs

The dynamics of the AGV can be described by a set of differential equations describing the state of the system. These equations are called the equations of motion. The differential equations describe the steady-state tyre loads as a function of the vehicle parameters and accelerations of the vehicle.

During acceleration and turning, the vehicle will be subjected to load transfer. The load on the tyres differs when compared to the static situation. The spring and damper ratios have no influence on the amount of load transfer, they only influence the transient response. This process can be modeled linearly when steady state is reached, therefore linear models for longitudinal and lateral acceleration for the AGV are created.

The free-body diagram for longitudinal acceleration of the AGV is given in Figure 26. The center of gravity of the vehicle is assumed to be known, the position of the center of gravity of the container is assumed to be spaced randomly. The center of gravity of the container is assumed not to move during the container handling process.

The maximum traction force that can be obtained from the tyres is related to the normal force on the tyres. This relation is described by the coefficient of friction. The reference plane in the model is defined by the ground plane, this is shown by the black line in Figure 26. The forces that act on the tyres all act on the contact patch. Table 22 lists the abbreviations used in the model of Figure 26.

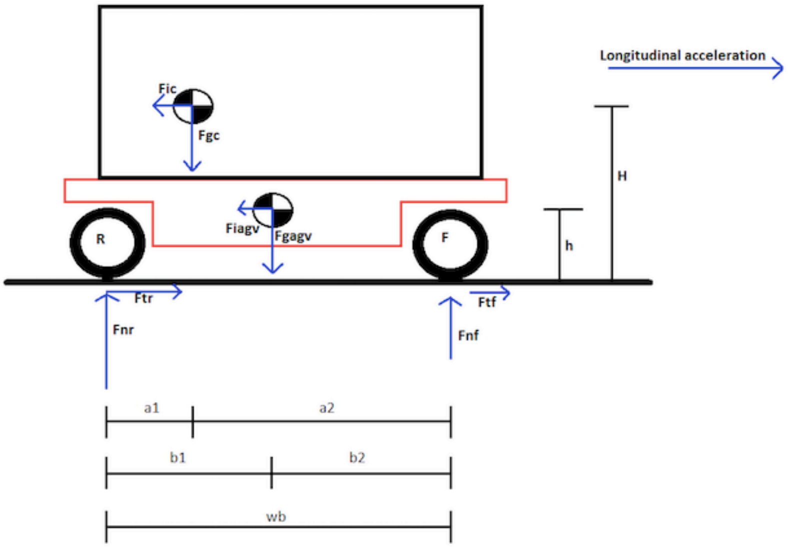


Figure 26: Model for longitudinal acceleration of a AGV

Table 22: Summary of the parameters used in the model for longitudinal acceleration of the AGV.

Symbol	Meaning
F_{ic}	The inertia load acting on the container during acceleration
F_{gc}	Gravity load that acts on the container
F_{iagv}	The inertia load acting on the AGV during acceleration
F_{gagv}	Gravity load that acts on the AGV
F	Location of the front axle
R	Location of the rear axle
H	Distance of center of gravity of the container with respect to the reference plane
h	Distance of the center of gravity of the AGV with respect to the reference plane
F_{nr}	Normal load acting on the rear tyres
F_{tr}	Traction load acting on the rear tyres
F_{nf}	Normal load acting on the front tyres
F_{tf}	Traction load acting on the front tyres
A_1	Horizontal distance of the center of gravity of the container to the rear axle
A_2	Horizontal distance of the center of gravity of the container to the front axle
B_1	Horizontal distance of the center of gravity of the vehicle to the rear axle
B_2	Horizontal distance of the center of gravity of the vehicle to the front axle
Wb	Wheelbase of the vehicle acclongitudinal Longitudinal acceleration

The static solution of the longitudinal distribution of the tyre forces is:

$$F_{nrstatic} = \frac{F_{gc} * A_2}{Wb} + \frac{F_{gagv} * B_2}{Wb} \tag{A-1}$$

$$F_{nfstatic} = \frac{F_{gc} * A_1}{Wb} + \frac{F_{gagv} * B_1}{Wb} \tag{A-2}$$

A check of the previous equations gives that the forces on the front and rear axles (F_{nf} and F_{nr}) combined are equal and opposite to the total gravity forces of the container and the AGV (f_{gc} and F_{gagv}). Under acceleration (the direction of which is being indicated by the arrow in figure 26), load transfer is described by:

$$\Delta Flong = \frac{F_{ic} * H}{Wb} + \frac{F_{iagv} * h}{Wb} \tag{A-3}$$

$$Fic = m_{container} * acclongitudinal \tag{A-4}$$

$$F_{iagv} = m_{agv} * acc_{longitudinal} \tag{A-5}$$

$$F_{nrdynamic} = F_{nrstatic} + \Delta F \tag{A-6}$$

$$F_{nfstatic} = F_{nfstatic} - \Delta F \tag{A-7}$$

When the AGV decelerates, the acceleration becomes negative and the load transfer reverses. When the acceleration is constant, the inertia loads are constant as well. Acceleration is achieved when the AGV develops a traction force. The traction force is the resultant of the traction developed minus the rolling resistance of the tyre. The traction force of the tyres equals the inertia load of the container and AGV, for it creates the acceleration of the entire mass. The inertia load is exerted by the vehicle in order to accelerate. It acts opposite to the direction of travel in this derivation because it is defined as the load that acts on the vehicle.

The free body diagram for the lateral acceleration of the AGV is given in Figure 27. In this case, the AGV is turning to the left. This model is similar to the model used to describe the longitudinal acceleration of the AGV. Table 23 explains the symbols used in the schematic model. The symbols for the inertia and gravity loads are the same as in the model for longitudinal acceleration. The magnitudes of these loads may differ due to differences in the magnitudes of the longitudinal and lateral accelerations.

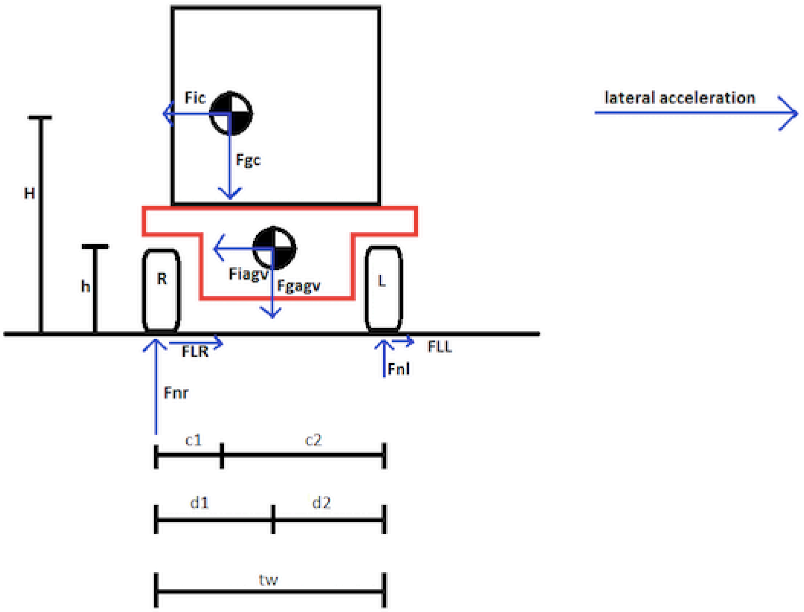


Figure 27: Model for lateral acceleration of a AGV

Table 23: Summary of the parameters used in the model for lateral acceleration of the AGV

Symbol	Meaning
F_{ic}	The inertia load acting on the container during acceleration
F_{gc}	Gravity load that acts on the container
F_{iagv}	The inertia load acting on the AGV during acceleration
F_{gagv}	Gravity load that acts on the AGV
L	Location of the left wheels
R	Location of the right wheels
H	Distance of center of gravity of the container with respect to the reference plane
h	Distance of the center of gravity of the AGV with respect to the reference plane
F_{nr}	Normal load acting on the rear tyres
F_{LR}	Lateral load acting on the right tyres
F_{nr}	Normal load acting on the left tyres
F_{LL}	Lateral load acting on the left tyres
C_1	Horizontal distance of the center of gravity of the container to the right tyres
C_2	Horizontal distance of the center of gravity of the container to the left tyres
D_1	Horizontal distance of the center of gravity of the vehicle to the right tyres
D_2	Horizontal distance of the center of gravity of the vehicle to the left tyres
Tw	Track width of the vehicle
$Acc_{lateral}$	Lateral acceleration

The static solution of the lateral distribution of the tyre forces is:

$$F_{nrstatic} = \frac{F_{gc} * A_2}{Wb} + \frac{F_{gagv} * B_2}{Wb} \tag{A-8}$$

$$F_{nfstatic} = \frac{F_{gc} * A_1}{Wb} + \frac{F_{gagv} * B_1}{Wb} \tag{A-9}$$

A check of the previous equations gives that the forces on the right and left sides of the AGV (F_{nr} and F_{nl}) combined are equal and opposite to the total gravity forces of the container and the AGV (f_{gc} and F_{gagv}). Under acceleration (The direction of which is being indicated by the arrow in figure 27), load transfer is described by:

$$\Delta Flat = \frac{F_{ic} * H}{Tw} + \frac{F_{iagv} * h}{Tw} \tag{A-10}$$

$$F_i c = m_{container} * acc_{lateral} \tag{A-11}$$

$$F_{iagv} = m_{agv} * acc_{lateral} \tag{A-12}$$

$$F_{nrdynamic} = F_{nrstatic} + \Delta F \tag{A-13}$$

$$F_{nldynamic} = F_{nlstatic} - \Delta F \tag{A-14}$$

A-2 Measuring the Center of Gravity of Containers

The equations decribing load transfer during lateral and longitudinal acceleration can be solved simultaneously in order to calculate the load transfer when a vehicle is subjected to both accelerations at the same time.

The mass of the container can be determined using the spring deformation. The spring deformation is the change in lenght between the state of the container being loaded on the AGV and the state of the AGV being unloaded. Using the spring deformations, the load of the container can be determined. The longitudinal position of the center of gravity can be determined using the difference in wheel loading between the front and rear axle. The load of the front axle and the rear axle is known, therefore the longitudinal position can be determined. The lateral position can be determined using the same approach.

When the AGV is loaded, it will drive away in order to deliver the container. When the drive force during the first acceleration procedure is fixed, the height of the center of gravity can be calculated. The accelerations in longitudinal and lateral direction need to be known. These accelerations can be measured using accelerometers at the front and rear axle of the vehicle.

A-3 Control of AGVs

The previous discussion concerned normal loads at the four wheels of the vehicle. The relation between the traction force of the tyres and the normal force on the tyres is called the friction coefficient. The friction coefficient between the tyre material and the surface of the terminal needs to be determined once (during the installation of the AGV system for instance).

Because of this relation, it is useful to be able to know the normal load on the tyres, so the appropriate amount of traction can be provided that enables the AGV to accelerate while minimizing wheel spin or lock-up. The parameters of the model are fixed, with the exception of the center of gravity of the container, the mass of the container and the accelerations. The torques of the electric motors can be regulated with the use of this model.

The torques can be calculated using a model of the tyre, representing the relation between normal force and traction force under certain circumstances. These tyre-models are non-linear. The most applied tyre model is the Pacejka "magic formula" tyre model [95].

In order to finalize this model, the rolling resistance needs to be measured at the terminal. This parameter is needed in order to calculate the resulting traction forces (in both directions). Aerodynamic loads are not yet accounted for, because both the magnitude of the loads and the center of pressure are unknown. In order to optimize the model, this can be included given that sensors can be placed to measure the relevant parameters.

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