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Industrial Electrical Engineering and Automation

Reaching for Automated Stacking

A Preliminary Study on Automation of a Reach Stacker

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Cover figure: A reach stacker from Konecranes. URL: `http://www.konecranes.com/sites/default/files/main_image/smv4531tc5_front_low_preview_v02.jpg`

Abstract

This is the report for a master thesis work which concerns the challenge of automating a reach stacker. A reach stacker is a vehicle that lifts and moves containers. This report should be seen as a preliminary study which handles automation concepts, simulations and sensors. Research questions answered are: *Which areas would benefit most from driver assistance*, *What kind of control is needed for these systems* and *Can an automated system with this setup be faster than a human operator?*

The path leading up to the concepts regarding the automation follows Karl T. Ulrich and Steven D. Eppingers methodology for Product Development. The chosen concepts are evaluated with models built in Simulink, a Matlab plug-in. An automated reach stacker needs sensors for mapping its surroundings, suitable sensor technologies and placement are therefore presented.

Two concepts were chosen to be simulated, one picks a container up and the other drops it down. A reach stacker uses hydraulics to lift a container, therefore the simulation model contains both mechanical and hydraulic parts. The model calculates the new position by measuring the distance to the goal position and then moves there with the help of controllers. The simulation results are presented with times and travelled distance. These results was at first not as good as was hoped for, but after the work was finished new information was revealed which would lead to much better results.

Problems with the design of the Simulink model, such as not seeing the compiled hydraulic part and the affect the actuators has on each other are discussed.

Keywords: Reach stacker — Automation — Concept development — Simulink simulation — Simscape modelling — SimMechanics — SimHydraulics.

Sammanfattning

Det här är en rapport för ett examensarbete som handlar om utmaningen att automatisera en reach stacker. En reach stacker är ett fordon som lyfter och flyttar containrar. Den här rapporten ska ses som en förstudie som hanterar automationskoncept, simuleringar och sensorer. Frågeställningar som besvaras är: *Vilka delar skulle tjäna mest på förarassistans*, *Vilken typ av reglerteknik behövs för dessa system* och *Kan ett automatiserat system med denna uppsättning vara snabbare än då den styrs manuellt?*

Den väg som ledde till koncepten följer Karl T. Ulrich and Steven D. Eppingers metod för Produktutveckling. De valda koncepten är utvärderade med modeller byggda i Simulink, ett Matlab plug-in. En automatiserad reach stacker behöver sensorer för att kunna kartlägga sin omgivning, lämpliga sensorteknologier och placeringar är därför presenterade.

Två koncept valdes ut för simulering, ett plockar upp en container och det andra ställer ner den. En reach stacker använder hydraulik för att lyfta en container, med anledning av det innehåller simuleringsmodellen både mekaniska och hydrauliska delar. Modellen beräknar den nya positionen genom att mäta avståndet till målpositionen och sedan flyttas den dit med hjälp av reglerteknik. Resultatet av simuleringarna är presenterade med tider och förflyttad distans. Dessa resultat var först inte så bra som hoppats, men efter att arbetet hade avslutats kom det fram information som skulle leda till mycket bättre resultat.

Problem med designen av Simulink modellen, så som att inte se den kompilerade hydrauliska delen och effekten ställdonen har på varandra diskuteras.

Nyckelord: Reach stacker — Automatisering —Konceptutveckling — Simulinksimulering — Simscapemodellering — SimMechanics — SimHydraulics.

Preface

This is a preliminary study, the first step in a development process towards an automated reach stacker. It is also a master thesis which is the final criteria for a Master of Science in Mechanical Engineering.The work behind this thesis was carried out between February and August 2016 at Konecranes Lifttrucks AB in Markaryd and at Lund University in Lund. I would like to thank Miroslav Antolovic and Anders Nilsson and all the staff at Konecranes Lifttrucks AB for trusting me with this work, their help and providing me with a workplace during the work. A big thank you to Gunnar Lindstedt for being my supervisor at LTH. Finally thanks to Elias Durgé who has helped me with the mathematics in section 3.2.3.

Terminology and abbreviations

3D — Three dimension

Boom — The arm on the reach stacker that levitates the spreader

Container casting — Holes in the container corners used to lock the container

FoV — Field of view

GPS — Global positioning system

Lidar — Light detection and ranging

PID — Proportional, integral and derivative

Reach stacker — A vehicle used for handling containers

RFID — Radio-frequency identification

Spreader — The part of the reach stacker which connects to the container

ToF — Time of flight

WIFI — Wireless local area network

Contents

Chapter 1

Introduction

In the fall of 2014 Konecranes Lifttrucks AB performed tests on a prototype for reaching containers with the use of two 3D cameras. These tests were performed with a reach stacker. A reach stacker is used for example in harbours for moving containers that can weigh up to 45 ton.

By automating this the process of moving containers becomes safer since the human factor is removed. Reaching for a container 10 m above your head is a hard task due to difficulties seeing the container. Another advantage of automating this task is the requirements on noise levels that industries often are affected by. By automating the reaching, it is possible to have a more precise movement and less force and speed in the moment when the lifting spreader connects with the container.

This prototype could, however, only move the lifting spreader in one direction or around one axis at the time. Figure 1.1 illustrates the possible movements. The spreader can move in X, Y and Z directions, it can rotate around the Z and Y axis and finally it is possible to change the width of the spread. When the driver does this manually with the help of a joystick, can he move the spreader in all directions at the same time. The movement of the lifting spreader is performed with hydraulics, this means there is a delay in the movement.

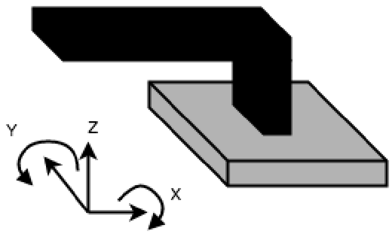


Figure 1.1: Gray block illustrates the spreader and the black blocks are the boom. Arrows illustrates possible movements and rotations.

1.1 Problem formulation

For the system to be ready for the market it needs to be as fast, or faster, as when a human is steering the reach stacker. In case the driver is faster than the system he/she will not be using it since it is not fast enough. The first prototype could only move in one direction at the time. By letting it move in several directions and rotate at the same time it will be more time efficient. To make it move in several directions simultaneously concurrent programming and control can be used.

The reach stacker used for testing the first prototype had on/off valves for the hydraulics. For an automated system that can be a problem, considering that the control algorithm, sensor input and hydraulic response need to be precise and fast. However, more advanced valves are available, allowing variable speeds.

Konecranes' reach stackers have technology for letting the driver know if there is a person or obstacle on collision course with the vehicle [1]. The possibility to remotely monitor vehicle data such as total lift load, hydraulic oil particles counter and alarm fault codes from engine or transmission [2]. However, the machines are not equipped with systems for automated driver assistance. By automating some processes it might be possible to increase the efficiency of the truck and at the same time increase the safety. The technology to let a vehicle assist the driver exists today [3], but automating the whole reach stacker is more time demanding than there is room for in this thesis. Therefore focus has to be on the most promising areas for driver assistance.

Hydraulics is a rather slow method to generate movements, comparied to using electric motors, and also rather imprecise [4]. Therefore the control algorithm does not need to be so advanced. Thus a PID (proportional, integral, derivative) controller is a proposed solution. Although a PID controller is simple, compared to many other controllers, more than 95% of the controllers used world wide in 2000 were PID controllers [5].

1.2 Purpose and research questions

The purpose with this thesis is to develop automated driver assistance for a reach stacker by using 3D cameras or other distance sensors. The driver assistance must be faster than when a human is manually operating the vehicle. Since Konecranes' first prototype in this area was reaching for a container this will be one of the driving assistance areas that will be of interest in this thesis. Three research questions will be answered in this study.

- Which areas would benefit most from driver assistance?
- What kind of control is needed for these systems?
- Can an automated system with this setup be faster than a human operator?

1.3 Focus and delimitations

The work will contain brainstorming on how automating the reach stacker can help the driver. Later a study following Ulrich and Eppingers development methodology will be performed to select which of these automation processes to further develop.

A suitable control algorithm which can handle the delay in the hydraulic system will be designed. As a result of impreciseness in the hydraulic a PID controller is proposed as a solution. The PID controller might need to be combined with some other controller, e.g. a Fuzzy controller, which is a common combination when it comes to hydraulic control [6] [7].

Due to the limited time no test on a real reach stacker will be performed, which would otherwise be an advantage for testing and validating both the speed of the system and also the noise level.

Chapter 2

Methodology

This chapter handles theories and tools applied in the report. Since this thesis handles several problems the following chapter are divided into three sections, Concept development, Automation of the spreader and Sensors.

2.1 Concept development

Since the timespan of this work was not big enough for developing a fully automated reach stacker focus was directed to the most promising movements for automation, here called *Processes*. To decide which of all processes to automate the work followed Karl T. Ulrich and Steven D. Eppingers methodology for *Product Development* [8]. By following their methodology the course of deciding which processes to further work with becomes scientific and structured.

Their methodology for concept development follows the steps seen in figure 2.1. The figure also illustrates how the steps follows each other, the doted arrows symbolises the possible need to go back in the chain.

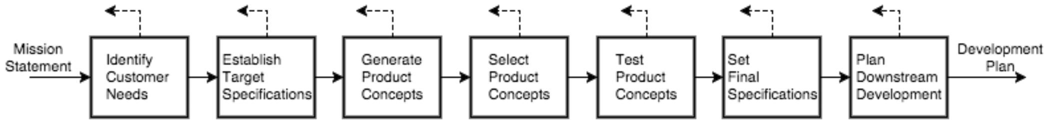


Figure 2.1: The steps in Karl T. Ulrich and Steven D. Eppingers Product Development methodology.

After the mission statement is established it is time for *Identifying Customer Needs*. The identification starts with gathering of raw data from the customers. This information was collected through interviews with customers, by watching the the reach stacker in use and meetings with the technical department at Konecranes Lifttrucks AB. This raw data was then translated into customer needs, where it is important to define what the product should do and not how it should do it. The needs are later organized in a hierarchical order, with primary and secondary needs. With a hierarchical order completed the needs are then ranked against each other.

Next step is to *Establish Target Specifications*. Here a list of measurable units is generated which contains ideal and acceptable values. These values were composed through benchmarking and discussions with operators and the technical department.

After *Establish Target Specifications* is it time to *Generate Product Concepts*. Concepts are generated in several steps, the first is to clarify the problems, then solutions to these are searched for both externally and internally. Searching externally in this case means to search for existing solutions for the problem and consulting experts and users, while searching internally the knowledge and creativity of the team is used while brainstorming for solutions. The last step in the concept generation is to explore the combinations of all concepts systematically. This is carried out by categorizing the subsolutions.

Figure 2.1 shows that the next activity is *Select Product Concepts*. According to the method this phase should be implemented in one or two steps, which are concept screening and concept scoring. In both these methods the concepts are rated but in the concept scoring the rating is also weighted depending on the importance of the criteria. These criteria are selected based on the customer needs and the needs from the company, e.g. low production cost. For both the screening and scoring a reference concept is used to rate the concepts to each other. Due to the complexity with comparing totally different concepts with each other neither the screening nor scoring were used in this thesis. The selection was instead made as a discussion around the pros, cons and possibilities for the concepts.

Then the *Test Product Concepts* phase begins, which in this thesis was the testing carried out in *Matlab* and *Simulink*, see section 2.2.

When the testing is completed is it possible to continue with *Set Final Specifications*. These specifications are based on what values could be reached in the testing phase.

The last step in the Karl T. Ulrich and Steven D. Eppingers product development methodology [8] is *Plan Downstream Development*. The purpose of this activity is to facilitate the further development of the product. It contains a development schedule with time frames for further development and identification of resources needed to finish the project.

All of the above mentioned steps, the steps in figure 2.1, involve three activities that they all have in common. These are economic analysis, benchmarking of competitive prototypes and build and test models and prototypes. The work of these three should be carried out along side the concept development. Reflection over the result is also important at the end of every step.

2.2 Spreader automation

The process of developing a suitable algorithm for the container reaching started with a model built in *Simulink* [9], an add-on to *Matlab* [10]. *Simulink* is a graphical programming environment for modelling, simulating and analysing. Building a model in *Simulink* and then simulating the process, rather than testing with a real reach stacker, made it easier and faster to test and change parameters in the control algorithm.

The model was built with the library *Simscape* [11], This library contains sublibraries. The skeleton of the model was constructed with the sublibrary *SimMechanics*, this contains the solid parts and joints that allow the arm and spreader to move.

The real reach stacker uses hydraulics to move the spreader to the desired location. To imitate the behaviour of hydraulics *Simscape* has a library called *SimHydraulic*. This library makes it possible to simulate the whole hydraulic system with pumps, vents and moving parts. The hydraulic system is connected to the mechanical parts and enables movements of the arm and spreader.

For tuning of the actuator speeds the times in table 2.1 were the limit. The actuator was not allowed to be faster than times specified by Elme, appendix B.2, and Konecranes. These times are for when the actuator is under the maximum allowed strain, when it is lifting a 45 ton container. In this table *Spreader rotation* is the actuator which allows the spreader to rotate around the Z axis in figure 1.1. *Spreader sideshift* moves the spreader in Y direction and *Spreader width* makes the spreader longer in the Y direction. *Boom lift* lifts or lowers the boom and furthermore moves the spreader in Z direction and *Boom telescopic* makes the boom longer which allows for movements in both X and Z direction. The tuning of the actuator was made by changing the hydraulic parameters for that actuator. These parameters did not have to correspond with their real value, the important part was to get the speeds right. The maximum pressure allowed in the system is 245 bar according to Konecranes.

Actuators	**Distance**	**Time**
Spreader rotation	$+105^\circ - (-195)^\circ$	< 42 sec
Spreader sideshift	± 800 mm	< 26 sec
Spreader width	$12.2 - 6.1$ m	< 25 sec
Boom lift	$0^\circ - 62^\circ$	< 32 sec
Boom telescope	$0 - 7$ m	< 31 sec

Table 2.1: Speeds for all actuators presented in time and distance moved during that time. Data for spreader rotation, spreader sidshift and spreader width is gathered from Elme, which is the supplier of the spreader. Data for boom lift and boom telescope is gathered from Miroslav Antolovic at Konecranes.

Data of the dimensions for the model was taken from brochures from Elme see appendix B.2 and Konecranes B.1.

To be able to monitor pressure and movements different sensors are used and connected to scopes that presents graphs. The evaluation of the model was performed by comparing three values. When the first prototype was tested the spreader was placed 30 cm away from its goal position in X, Y and Z directions. This took around 9 seconds to correct which also was the time the operator estimated it would take to align the spreader without an automated system. Therefore the model was evaluated by placing the spreader as the first prototype, that is 30 cm away from its goal position in X, Y and Z directions and measuring the time to move into the correct position. It was also evaluated by maximizing the moved distance within 9 seconds. The last evaluation was made by comparing the time it took to align the spreader when the stack was one container high and when the stack was three containers high. The moved distance of the spreader was the same in both these tests. The last evaluation was performed to examine if the height of the spreader would affect the time.

2.2.1 Control

The sensor information is fed to controllers, figure 2.2, which calculate the difference between the desired position and the actual position. The difference is called control error and for the rotary actuator controller it is $e = Reference - Angle$.

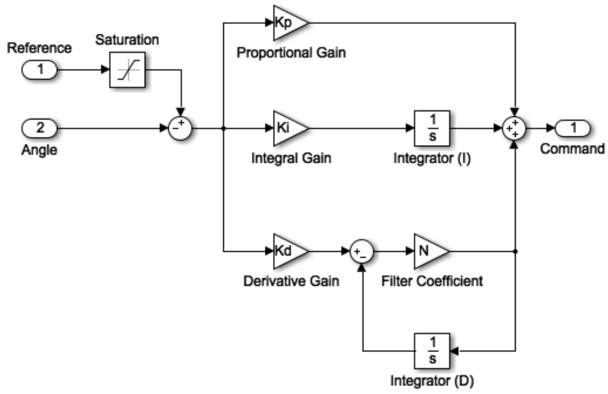


Figure 2.2: Schematic of the PID controller.

The output signal from the controller u, called *Command* in figure 2.2, is a product of a proportional part, equation 2.1, an integral part, equation 2.2, and a derivative part, equation 2.3.

$$u = k_p \cdot e \tag{2.1}$$

$$u(t) = k_i \int_0^t e(\tau) d\tau \tag{2.2}$$

$$e(t + T_d) \approx e(t) + k_d \frac{de(t)}{dt} \tag{2.3}$$

The proportional equation, 2.1, represents the present error and multiplies the control error with a desired value. This gain allows for tuning the speed of the response, however if the response is too fast there will be oscillations in the output signal. Since the present error is a part of this equation, u will be great when there is a great error and small if the error is small.

The future, e, T_d units head is predicted with the derivative equation, 2.3.

By combining these three equation, retrieved from Karl Johan Åström and Richard M. Murray book Feedback Systems [12], the control algorithm observes the past, the present and the future. The final control equation then becomes 2.4 which in *Simulink* looks like figure 2.2.

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d \frac{de(t)}{dt} \tag{2.4}$$

2.3 Sensors

The controllers need reference values for the desired location they are moving towards. Since the reach stacker is working with external objects these reference values can not be hard coded, they must be fetched from the surrounding. Inputs to computerised systems from the real world can come from sensors of different sorts. Therefore an evaluation on sensors was performed. Also this process followed Ulrich and Eppingers methodology for product development.

Since this thesis is a feasibility study the sensors were not tested. The result presented further on in this report is only recommendations worth thinking of when building a prototype. The recommendations are based on information about the sensors.

The sensors send values to a State Machine, which is built with a *Simulink* library called *Stateflow* [13]. The state machine is acting based on where the spreader is in relation to its goal position. It calculates new reference values for the controllers to act on.

Chapter 3

Results

This chapter contains the results of the Concept development, section 3.1, and the information that led to the result. Section 3.2, about the Simulink model, contains a subsection about the Mechanical and Hydraulic model, section 3.2.1, and a subsection for the Control, 3.2.2. The results about the Sensors are presented in section 3.3 which contains both sensor technologies and placement.

3.1 Concept development

3.1.1 Customer statements

To better know the customer needs a meeting was held at one of Konecranes customer.

During the meeting four questions were discussed. These were:

- What part in the reach stackers driving cycle can be improved by automation?
- What must be thought of if a process is automated?
- Situations where automation should not be used?
- How can the operator steer the process and what information does he/she need?

The summary of this meeting can be found in appendix A.1.

3.1.2 Customer needs

The translation from customer statements to customer needs, table 3.1, is divided into three categories, *Safe*, *Robust* and *Use*. *Use* is what the automation is supposed to do, *Safe* and *Robust* is how it should to this. The statements are translated into needs that later can be measured, table 3.2.

Costumer Statements		**Costumer Needs**
Safe	The operator has utter control of the movements	Semi automated, still an operator in the process Output to operator Input from operator
	Smooth handling	Few major and fast changes in movement directions
Robust	Reliable	Can be repeated without any problems
	Accurate	No error in movements
	Seapeatable	No deviation in repetition
Use	Fast	As fast or faster than without automation
	Quiet	More quiet than without automation
	Low wear and tear on equipment	Longer lifetime on equipment than without automation
	Environmentally friendly	Less impact on the environment
	Easy to use	Easy and intuitive interface

Table 3.1: Customer statements translated to customer needs.

There are two reason to let the operator have the utter control of the movements. The first is that making the system fully automated means a higher degree of safety must be reached, described in appendix A.1. The second also has to do with safety, allowing the vehicle to move fully automated may have devastating consequences. For example, if the reach stacker is operating with a levitated container and the automated system stops the vehicle due to a nearby object it may result in a vehicle rollover. Smooth handling is due to the same reason, with a heavy container levitated can fast movements in a new direction results in great forces which ought to be avoided.

The system is supposed to deliver on the same level every time, it should be *Robust*. This category consists of statements that it should be reliable, accurate and able to repeat the same movement several times.

The *Use* category is what will be the improvements with the new system. It should be faster, make less noise, be kinder to the equipment and finally be easy for the operator to use.

Table 3.2 is also divided into these three categories. The information in this table allows for measuring the needs generated in table 3.1.

Costumer Needs	**Measurable Units**	**Unit**
Semi automated, still an operator in the process		Binary
Output to operator		Binary
Input from operator		Binary
Few major and fast changes in movement directions	Times of changes in movement directions greater than rad/sec	Times
Can be repeated without any problems	Number of repeated cycles	Times
No error in movements	Deviation from target	mm
No deviation in repetition	Deviation from last cycle	mm
As fast or faster than without automation	Percentage of seconds faster than a human operator	%
As quiet or more quiet than without automation	Percentage of decibel lower than a human operator	%
As long or longer lifetime on equipment than without automation	Percentage of hours longer lifetime than a human operator	%
Less impact on the environment	Precentage of liters of petrol used for a drive cycle	%
Easy and intuitive interface		Binary

Table 3.2: Customer needs translated to measurable units.

Binary here means yes or no, either the need is met or not. The other units generated is for distance [mm], how many times a specific event occurs and percentage of a new value compared to a value without automation.

3.1.3 Target specifications

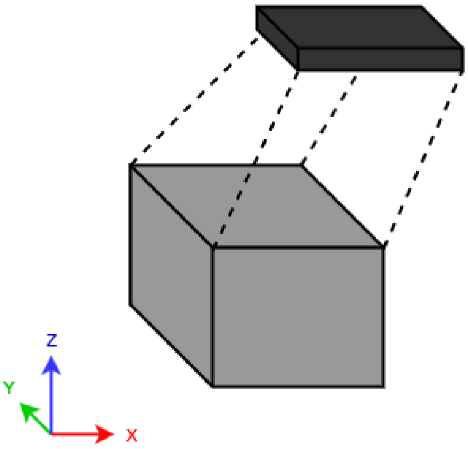
A final product should contain all the costumer needs with a binary unit. The costumer needs within the robust category is affected by the sensors which are presented in section 3.3. The target specification regarding speed is that a movement of 0.3m in all three directions (X, Y and Z) should take less than 9 seconds. The accuracy of the spreader alignment must be within 5 cm to allow for a lock between the spreader and the container. Comparing the sound, the lifetime and the impact on the environment is not within the span of this thesis.

3.1.4 Generate concepts

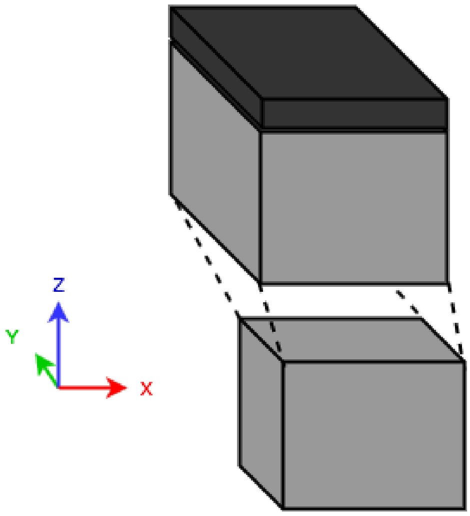
After discussing possibilities, studying of reach stackers in action and benchmarking a few concepts were generated.

- Concept *Pick Up*: Automatic spreader alignment when reaching for a container, figure 3.1a.
- Concept *Drop down*: Automatic spreader alignment when releasing a container, figure 3.1b.
- Concept *Warning system*: Warning system with possibility to see around corners, figure 3.2a.
- Concept *Spreader height*: Lifting of empty spreader, in Z direction in figure 3.2b.
- Concept *Automated driving*: Automatic driving of the reach stacker, figure 3.3.

Concept *Pick up* and *Drop down* in figure 3.1 are similar to each other, both are about spreader alignment. The difference is reference area. In *Pick up* the reference is the container and in *Drop down* it is the area where the container will be placed. The black block in the following figures illustrates the spreader, the gray block is the container. In figure 3.1b there is two grey blocks, the lower one is a container that the upper container will be placed upon. The dotted lines are how the reference points should move to finish the task. The spreader can move in X, Y and Z directions, and it can rotate around the Y and Z axis.



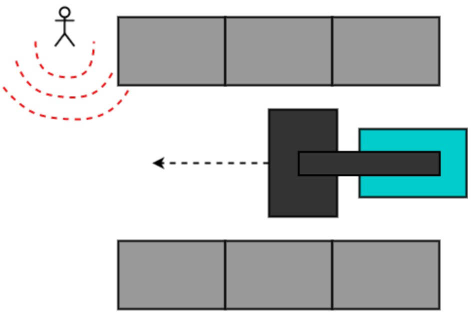
(a) Concept *Pick Up*, spreader alignment.



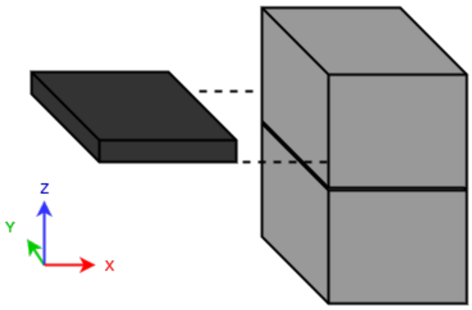
(b) Conceptt *Drop down*, container release.

Figure 3.1: Concept *Pick up* and *Drop down*.

Concept *Warning system*, figure 3.2a, is not in itself an automatic system but it is a safety system that can see around corners. This is necessary if the reach stacker should drive longer distances in automatic mode. The six gray blocks are containers and the blue/black blocks are the reach stacker. The black dotted arrow is the driving direction of the reach stacker and the red dotted lines are a warning signal emitted from a transmitter located on the person. Figure 3.2b illustrates concept *Spreader height*. This concept automatically lifts the spreader to a desired hight. In the case that the figure illustrates the spreader is empty but the same concept also works while lifting a container. The dotted lines are the reference lines that should be above the container.



(a) Conceptt *Warning system*, see around corners.



(b) Concept *Spreader height*, lifting spreader.

Figure 3.2: Concept *Warning system* and *Spreader height*.

Concept *Automated driving*, figure 3.3, represents automatic driving or driving assistance depending on how it is implemented. This figure illustrates reach stacker alignment with a specific container.

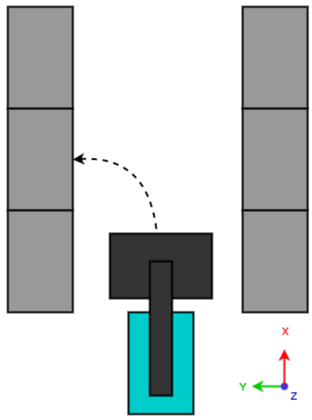


Figure 3.3: Concept *Automated driving*, automatic reach stacker steering.

3.1.5 Concept selection

The *Pick up* concept has been tested earlier, as mentioned in the Introduction. The tests were satisfying but needed further improvements, including the possibility to move in multiple directions. This concept was also the most appreciated by the customer, appendix A.1. This process has the possibility to lower fuel consumption, pick up time, and sound levels.

A closely related concept to the above is the *Drop down* concept, which has the same possibilities as well. But this concept is more challenging to implement due to difficulties with the sensor readings and placements, more about this in section 3.3.2.

As described in section 3.1.4 the *Warning system* concept is not a system for automating the reach stacker, but it is a necessary system if the reach stacker should be fully automated. This concept will not change the fuel consumption, working time or sound levels, but it does improve safety. The *Safety warning* would possibly be relatively easy to implement, transmitters and receivers using triangulation can be used for this. By measuring the time it takes for a signal to travel to three receivers with known positions can the location of the emitter be calculated. Possible solutions for this could be GPS, RFID and WIFI. Fixed objects like container stacks and buildings could be hardcoded into the map, another solutions is real time mapping by the vehicles.

The *Spreader height* concept can with small modifications be implemented on both the *Pick up* and the *Drop down* concepts. For the *Drop down* the spreader height must be increased compared to the *Pick up* since a container is connected to the spreader. Automating a process like this does not necessary help the operator, lower the fuel consumption or give any other advantages, but it is a natural step to improve the pick up and drop down concept. The implementation of such a system can be made in two ways. The first is by using sensors but in that case it is not possible to raise the spreader before the container is seen by the sensors. If the sensors see the container too late the vehicle might have to stop and wait for the spreader to get in place. The second one is using the container information system, where the location of the container is stored and also the height of the stack. If the height of the stack is known it is an easy task to lift the spreader to the desired height while the vehicle is driving towards the container.

The last concept is *Automated driving*. It takes the automation all the way and automates the steering. This could be done in small steps, not every movement must be automated at the same time. A start could be to align the reach stacker to a selected stack or reversing after a container pick or drop. However, as discussed in A.1 this concept introduces problems. Making the reach stacker drive in automatic mode puts a whole new level of safety risks on the process. A self driving vehicle takes the legal responsibility away from the operator, leading to a higher safety level required on the area where the vehicle is used, which in turns leads to higher investments. This could however work, but it is a much bigger concept than automating parts of a reach stacker and use it in the same safety areas as defined today. By letting the parking break be activated while in automated mode there would not be a requirement on a higher safety level on the operating area.

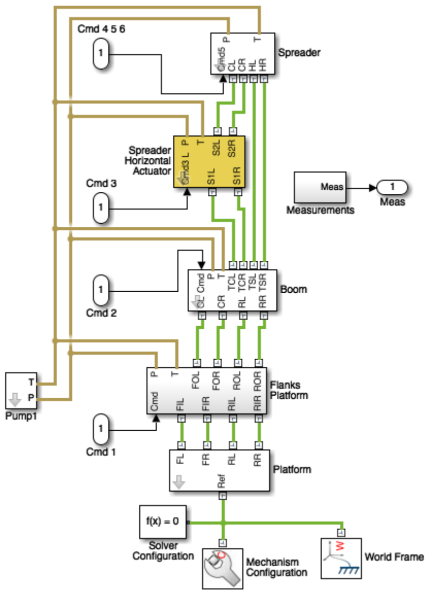
The concepts *Pick up* and *Drop down* were chosen for further work. *Automated driving* was eliminated due to the demand on higher safety levels on the area and since concept *Safety warning* is in fact a help system for *Automated driving* it was also eliminated. The *Spreader height* concept was not chosen for simulations since it is a relatively easy task and does not need any simulations. If the stack height is know the spreader is lifted to the desired hight before the reach stacker gets in front of the container.

3.2 Simulink model

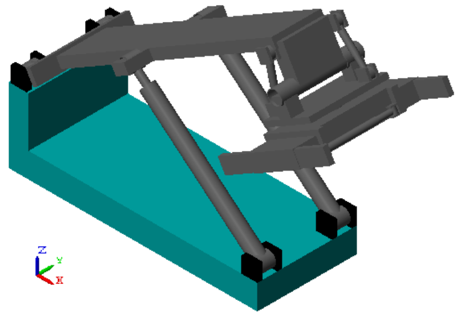
3.2.1 Mechanical and hydraulic model

The representation of the mechanical and hydraulic objects was built in a tree structure, with the major parts at the top, which figure 3.4 illustrates, and in the bottom of the model there are blocks with only one purpose, e.g. figure 3.5.

The top part of the model regarding the mechanical and hydraulic parts is seen i figure 3.4a, the compiled model is seen in 3.4b. Figure 3.4a contains several subsystems, *Platform*, *Flanks Platform*, *Boom*, *Spreader Horizontal Actuator*, *Spreader*, *Pump* and *Measurements*, which are explained below. This subsystem also contains the *World Frame*, *Mechanism Configuration*, that represents the gravity, and a *Solver Configuration*.



(a) The reach stacker in *Simulink*.



(b) The compiled reach stacker.

Figure 3.4: a) Model blocks representing mechanical and hydraulic parts, b) The visual model of the reach stacker.

The input to this subsystem is the Command signal *Cmd*, seen in figure 3.4a. This signal is the output from the controller. It is a vector of six signals that is sent forward into four subsystems. Deeper into the model the correct signal for that specific actuator is collected, in figure 3.11 this signal collection is made in the *S-SP* block.

Figure 3.5 is a screen shot from *Simulink* over the platform on which the reach stacker is built. In this part three different types of objects are used. These are *Solid* objects, representing the solid part, *Rigid Transform*, which changes the local coordinate system and *Connection Port*, used for connection with other subsystems.

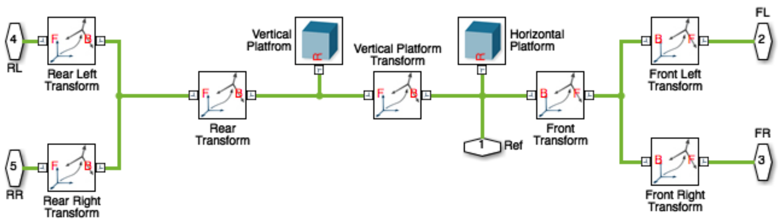
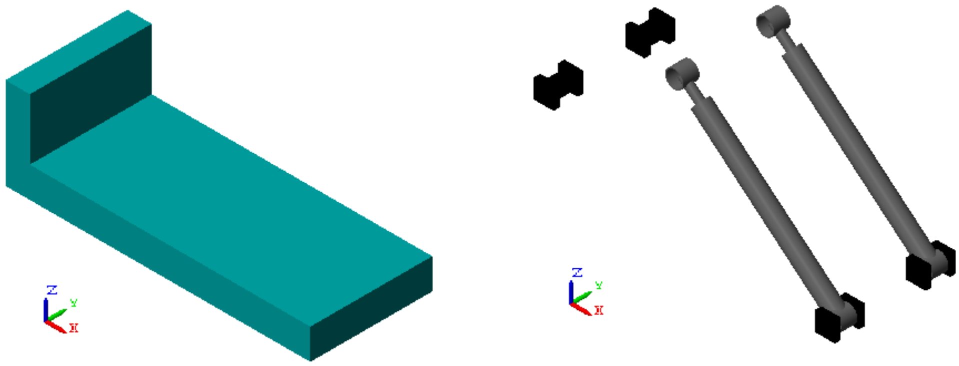


Figure 3.5: The platform on which the reach stacker is built.

The compiled equivalent to figure 3.5 is seen below in figure 3.6a. To the platform are four flanks and two actuators connected, figure 3.6b. The construction of the actuators is described later, figure 3.9.

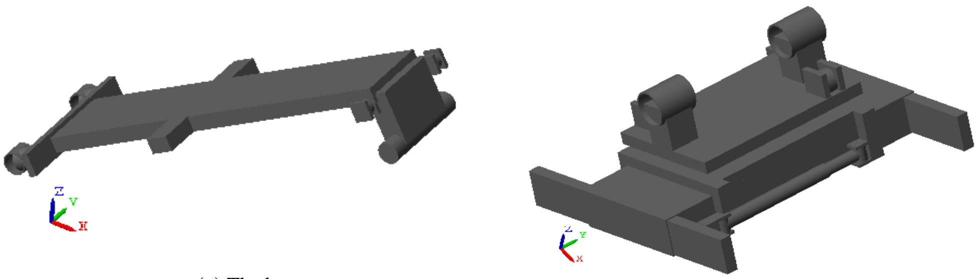


(a) The platform.

(b) Flanks connected to the platform and actuator between the platform and the boom.

Figure 3.6: Platform, flanks and actuator compiled.

The compiled subsystems to *Boom* and *Spreader* in figure 3.4a is illustrated in figure 3.7.



(a) The boom.

(b) The spreader.

Figure 3.7: The boom and the spreader compiled.

Both figures 3.7a and 3.7b are built with more subsystems inside them. For example the spreader has three kinds of actuators built inside it, one for changing the width of the spreader, one for rotating it and one for moving it longitudinal.

The real reach stacker uses hydraulics to move the spreader to the desired location. To imitate the behaviour of the hydraulics *Simulink* has a library called SimHydraulics. SimHydraulics makes it possible so simulate the whole hydraulic system with pumps, figure 3.8, vents and moving parts, figure 3.11. The hydraulic system is connected to the mechanical parts and enables movements of the arm and spreader.

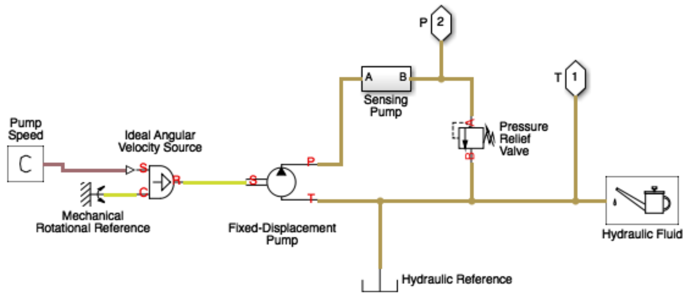


Figure 3.8: The hydraulic pump.

The pump block, figure 3.8, is built of a *Fixed-Displacement Pump*, the real pump, an *Ideal Angular Velocity Source* which drives the pump and the *Pump Speed*, which feeds the velocity source with a constant speed. A *Pressure Relief Valve* controls the hydraulic pressure which must be kept below 245 bar, see section 2.2. The *Hydraulic Fluid* allows for simulating with different oils and the *Hydraulic Reference* represents a connection to the atmosphere.

The pump is connected to actuators which are built from a mechanical part and a hydraulic part or only the hydraulic part if the actuator is located inside another part. The actuator which was seen as a subsystem in figure 3.4b, called *Spreader Horizontal Actuator*, is illustrated in figure 3.9 below. Worth paying attention to here is the connection between a mechanical and a hydraulic subsystem.

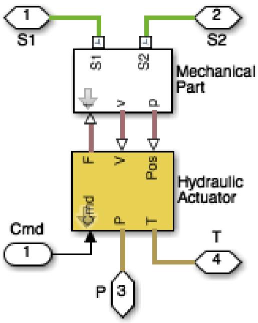


Figure 3.9: Actuator containing both a mechanical and hydraulic subsystem.

The interweaving of the mechanical and the hydraulic actuator in the figure above, 3.9, is described in figures 3.10 and 3.11. The mechanical subsystem contains a *Prismatic Joint* which allows the actuator to move along the Z axis. It also has an input, *f*, that contains the size and direction of the force acting on the joint. Beside the input there are two outputs, the position *p* and the velocity *v*.

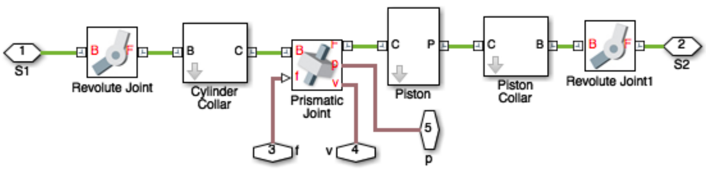


Figure 3.10: Mechanical part of the actuator.

The force, position and velocity are then in- and outputs to the hydraulic block, figure 3.11, via what is called *Subsystem*. It contains two parts, an *Ideal Force Sensor* and an *Ideal Translational Velocity Source*. The force sensor converts the force from a mechanical signal (green line) to a physical signal (brown line) and sends this as an output to the mechanical block. The velocity source does the same but acts as an input to the hydraulic system. Apart from the block called *Subsystem*, the hydraulic actuator is built from four major objects, figure 3.11. The *4-Way Directional Valve* allows for steering of the oil flow, a *Double-Acting Hydraulic*

Cylinder that creates the motion of the actuator, a *Translational Friction* object representing the actuators inner friction and a *Mechanical Translational Reference* that locks one end of the actuator in space. The hydraulic cylinder translates the hydraulic signal (yellow line) to a mechanical signal (green line). The control signal to the actuator is *Cmd* (described above) which is connected to the valve.

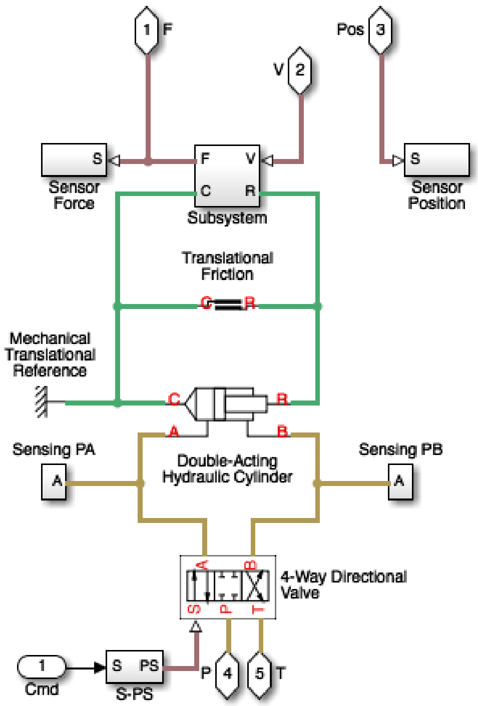


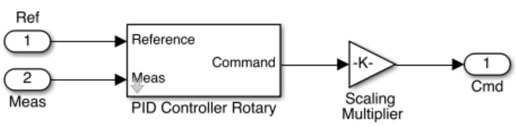
Figure 3.11: Hydraulic part of the actuator.

The output from the reach stacker model is a signal called *Meas* that contains measurements of angles and positions of different parts in the model. The measurement signal is fed back to the controller.

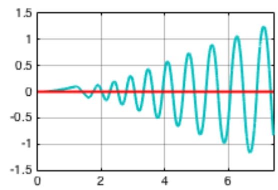
3.2.2 Control

Figures 3.12b to 3.15 illustrate the measured signal (blue line) and the reference signal (red line). Degrees of rotation can be seen on the Y axis and the X axis represents the time.

Tuning the control started with scaling the output signal, figure 3.12a illustrates how the multiplier is connected to the controller. In figure 3.12b the output is shown when the signal is to strong. It starts to oscillate without no apparent reason while the reference signal is zero. In this simulation the scaling multiplier was set to 0.001 and the proportional gain $k_p = 1$.



(a) Control scaling multiplier.



(b) The rotary control signal with a proportional gain $k_p = 1$ and a signal scaling multiplier of 0.001.

Figure 3.12: PID with control scaling multiplier and its output.

With a multiplier of 10^{-5} the signal is too weak, figure 3.13. The spreader does barely rotate even though the proportional gain was $k_p = 10$ in this simulation.

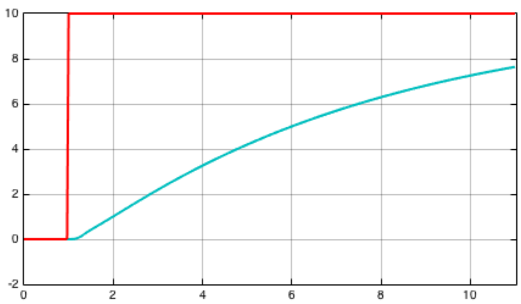


Figure 3.13: The rotary control signal with a proportional gain $k_p = 10$ and a signal scaling multiplier of 10^{-5}.

After a few simulations a scaling multiplier of 10^{-4} was found to be suitable. Then the proportional gain was tuned. If the proportional gain is too large it will overshoot and if it is even larger it will start to oscillate. If it is too small the measured value will not reach the reference value as can be seen in 3.14, where the gain is $k_p = 2$.

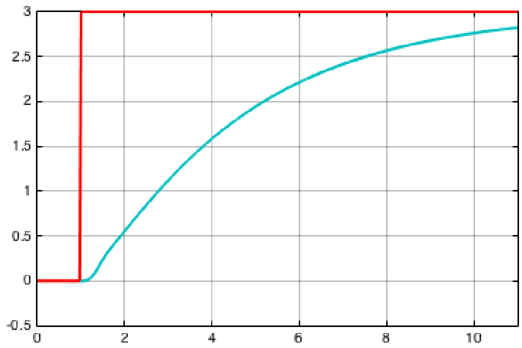


Figure 3.14: The rotary control signal with a proportional gain $k_p = 2$. The x-axis shows elapsed time [sec] and on the y-axis is the angle [degree].

Due to a too weak signal in figure 3.14, the proportional gain was set to 10, figure 3.15.

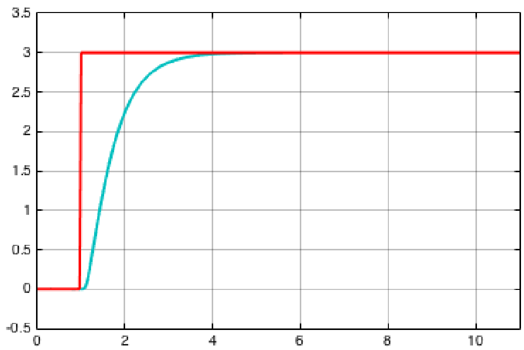
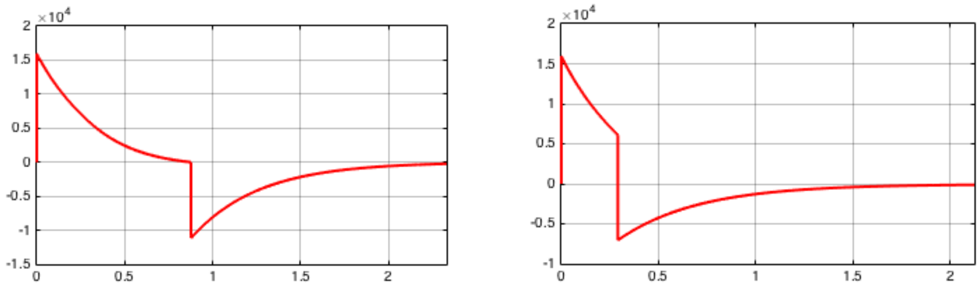


Figure 3.15: The rotary control signal with a proportional gain $k_p = 10$. The x-axis shows elapsed time [sec] and on the y-axis is the angle [degree].

In figure 3.15 looks like the reference value is reached within 4 seconds. However, in reality it should be a steady state error. Therefore is a integral part added. For the rotary actuator it is $k_i = 0.001$

The largest integral part for any of the controllers used in this model is $k_i = 0.01$ and none of them have any derivative gain.

The angular velocity for the spreader while rotating around its center is constant for a physical reach stacker. To get the movement of the model to correspond with the real reach stacker the PID controller in the Simulink model is only used when the spreader is 3 degrees, or closer, to the goal position. Before reaching the 3 degree limit, the spreader is set to reach 1000/-1000 degrees, depending on direction. This allows for a constant speed even when the spreader gets closer to its end position. However this controller is not suitable when the the initial error is just a few degrees.



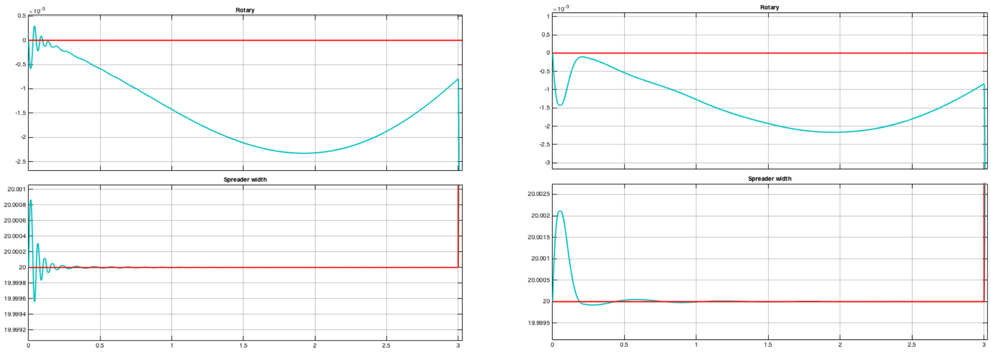
(a) Initial error of 8.5 degrees and with a breaking force of -11.2 kN at 0.85 sec.

(b) Initial error of 4 degrees and with a breaking force of -7 kN at 0.3 sec.

Figure 3.16: Forces on the rotary actuator. The x-axis shows elapsed time [sec] and the force [N] on the y-axis.

The forces applied to the rotary actuator when the initial error is 8.5 is seen in figure 3.16a. In this figure the tangent is close to zero at 0.85 sec and at that moment a negative force is applied, meaning that all the initial forces have been applied before the actuator starts the stopping process. The negative force applied is -11.2 kN. When the initial error is less than 8.5, the force tangent does not become zero before the negative force is applied, as seen in figure 3.16b. This figure illustrates when the initial error is 4 degrees, at 0.3 sec the force changes direction and becomes -7 kN. When comparing these figures it is seen that the negative force is greater and applied later in figure 3.16a, than in figure 3.16b. The result of this is that not enough force is applied before breaking for the rotation to be fast enough for the situation illustrated i figure 3.16b. To solve this two different PI controllers are used, *Controller 1* for initial errors below 3.6 degrees and *Controller 2* for errors equal to, or above, 3.6 degrees. The threshold of 3.6 degrees was found empirically. The 1000/-1000 degree goal position mentioned above is only used in combination with *Controller 2*. Initial errors below 3.6 degrees are not great enough for a constant speed.

While tuning the hydraulic actuators it was also needed to take into consideration how the actuators affects each other. Figure 3.17a shows the measured values from the rotary and the spreader width actuators. Both signals oscillates in the beginning. In the next figure, 3.17b, the signals are much smoother. The only parameter changed between this figures is the *Control scaling multiplier*, figure 3.12a, for the spreader width actuators. It is lowered from 0.1 to 0.005, resulting in a smoother output signal. As can be seen if a comparison is made between the rotary signal in figures 3.17a and 3.17b the output signal is changed. The output for the rotary actuator is therefore affected by the output from the spreader width actuators. This is due to mechanical vibrations.



(a) Rotary output and spreader width output with strong spreader control signal.

(b) Rotary output and spreader width output with weaker spreader control signal.

Figure 3.17: Rotary signal in the above graphs and spreader width in the lower graphs. The blue lines are the actual values of the actuator and the red lines illustrate the reference signals. Figures a and b have different values on the spreader control multiplicator.

3.2.3 Movement calculations

To move the spreader towards the goal position the reach stacker uses two simplified sensors. They measure the distances to two of the corner castings on the container. These sensors are placed on the two corners of the spreader which are closest to the reach stacker (point D in figure 3.19, which illustrates the boom and spreader from the side). These sensors tell the exact distances in X, Y and Z direction to the corner castings. The movements are then calculated in a state machine with the help of these sensor values. The state machine acts depending on the reach stacker's current position. It calculates goal values for the actuators and sends these values to the controllers. The state machine starts with checking if the spreader is a predefined distance above the container, figure 3.18. In these simulations this distance is 2 m above the goal position. If the spreader is above this distance it is lowered until the desired value is reached. After that the spreader is allowed to align itself. This 2 m limit is due to the sensors reach. The accuracy of the sensors are lower the further away from the object they are, see section 3.3.1, therefore the 2 m limit exists. While lowering the last 10 cm no alignments are allowed due to the locking between the spreader and the container. The state flow in figure 3.18 waits for the alignment to be completed before entering *Lower Z2*.

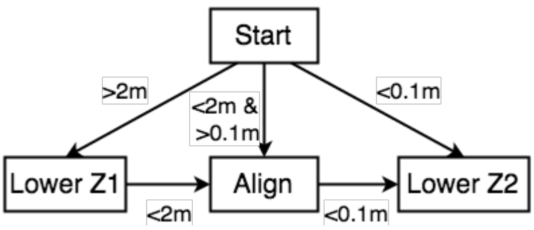


Figure 3.18: State flow chart over the movements. While in state Lower Z1 is it only allowed to lower Z. In Align movements in every direction are allowed. In state Lower Z2 the spreader is connected with the container and therefore only allowed to lower Z the last 10 cm between itself and the container.

Lowering the spreader is done by decreasing the boom angle, $\angle EAB$, in figure 3.19. The X coordinate of the spreader should end with the same value as it began with. This means that the length of line $\overline{AB}$ has to decrease. In this first stage in the state machine the boom angle, $\angle EAB$, and the length for $\overline{AB}$ are calculated. The new $\angle EAB$ is calculated in two steps, were the first step is to find $\angle EAC$ and the second is to find $\angle CAB$.

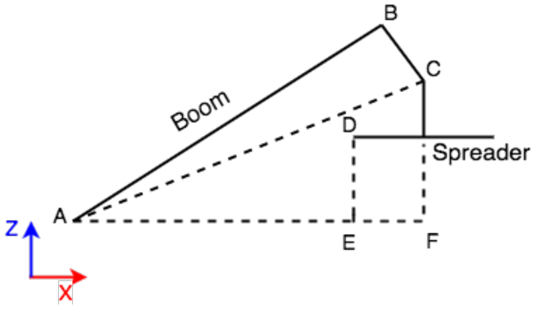


Figure 3.19: Boom and spreader from the side. Point A is placed in the joint between the boom and platform of the vehicle, point B is located on the uppermost point of the boom. The joint between the boom and the spreader is illustrated by point C and the sensors are placed in point D. Point E is a help point to D and point F a help point to C.

The process of calculating the new $\angle EAB$, starts with getting the current X coordinate of the sensor, $\overline{AE}$. In equation 3.1 α_a is equal to $\angle EAB$ and $\overline{AB}$ is the current boom length, figure 3.19. $\overline{TB}$ is the difference between measured sensor value and boom length in the X direction, figure 3.20.

$$\overline{AE} = (\overline{AB} - \overline{TB}) \cdot \sin \alpha_a \tag{3.1}$$

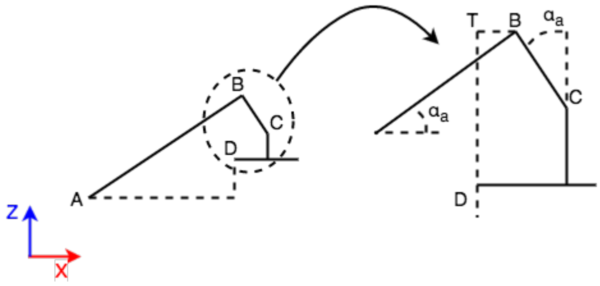


Figure 3.20: An illustration of the geometry between the boom and spreader. Points A, B, C and D follow the same convention as in figure 3.19. Point T has the same X value as point D and the same Z value as point B.

The sensors are placed in point D, figure 3.19, but the values for the boom are calculated from point B. The difference between the measured value in point D and point B is represented by $\overline{TB}$, in figure 3.20, calculated in equation 3.2.

$$\overline{TB} = \frac{(Spreader\ width/2) - \overline{BC} \cdot \sin \alpha_a}{\cos \alpha_a} \tag{3.2}$$

With $\overline{AE}$ known, it is easy to get $\overline{AF}$, equation 3.3. In equation 3.4 the opposite side to $\angle EAC$ is calculated. *Spreader height* is the total height of the spreader, that is the Z value between point C and D, $\overline{CD}_Z$.

$$\overline{AF} = \overline{AE} + \frac{Spreader\ width}{2} \quad (3.3) \qquad \overline{CF} = \overline{DE} + Spreader\ height \quad (3.4)$$

By using the Pythagorean theorem, it is now possible to calculate $\overline{AC}$, equation 3.5. By using the Pythagorean theorem again $\overline{AB}$ is found in equation 3.6 where $\overline{BC}$ is the fixed length on the boom.

$$\overline{AC} = \sqrt{\overline{AF}^2 + \overline{CF}^2} \quad (3.5) \qquad \overline{AB} = \sqrt{\overline{AC}^2 - \overline{BC}^2} \quad (3.6)$$

With all sides known it is possible to calculate the angels $\angle EAC$, α_b, in equation 3.7, and $\angle CAB$, α_c, in equation 3.8. From these two $\angle EAB$ is calculated in equation 3.9, where α_a is $\angle EAB$.

$$\alpha_b = \arctan \frac{\overline{CF}}{\overline{AF}} \quad (3.7) \qquad \alpha_c = \arcsin \frac{\overline{BC}}{\overline{AC}} \quad (3.8)$$

$$\alpha_a = \alpha_b + \alpha_c \quad (3.9)$$

For these trigonometric calculations to work the angle $\angle DEA$ in figure 3.19 must be right-angled. This means that $\overline{DE}$ can not be seen as the distance between the spreader and container, because the length is also affected by the height of the container stack. $\overline{DE}$ can also be seen in figure 3.21, which illustrates this problem further. The input for the height of the spreader is based on the distance called *Measured* in this figure. This is however not the length of $\overline{DE}$. The length of $\overline{DE}$ is $Container - Counterweight + Measured$.

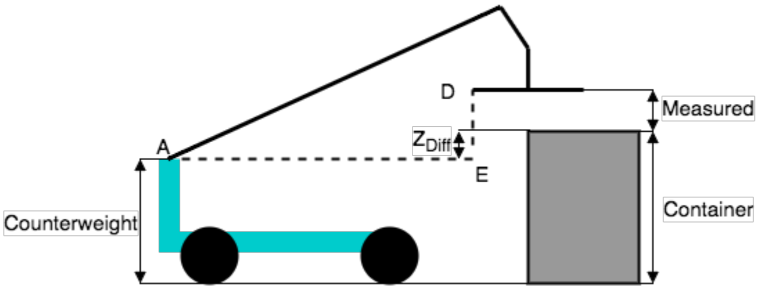
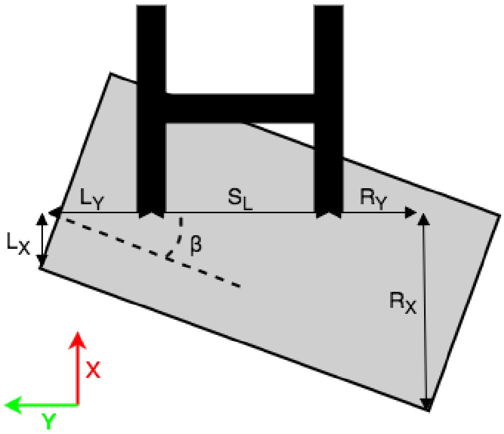
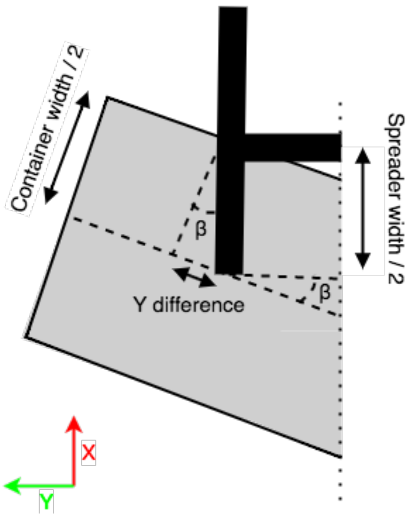


Figure 3.21: An illustration of the relationship between *Measured* sensor value, the height of the *Counterweight* of the reach stacker and the height of the *Container* stack. Points A, D and E follow the same convention as in figure 3.19.

Next step is to rotate the spreader so its aligns with the container, the angle β in figure 3.22a should be zero. The new angle of the spreader is calculated in equation 3.10. In this equation L_X, L_Y, R_Y and R_X are distances from the sensors to the corners of the container and S_L is the length of the spreader.



(a) The *Spreader* and the *Container* seen from above.



(b) The left half of figure 3.22a.

Figure 3.22: Spreader illustrated with wide black lines and the container as the gray rectangle. β is the angel the spreader has to turn to align with the container. In figure 3.22a are L_X, L_Y, R_Y and R_X distances from the sensors to the corner of the container and S_L is the length of the spreader. In figure 3.22b is the *Container width* and the *Y difference* are highlighted. *Y difference* is the difference in the *Y* direction which depends on the angle between the spreader and the container.

$$\beta = \arctan \frac{R_X - L_X}{L_Y + S_L + R_Y} \tag{3.10}$$

With the correct angle on the spreader it now has to be moved so the center of the spreader is coinciding with the middle of the container length and width. The distance from the current location to the new desired location in X axis is calculated by taking the average value of the two sensor values in X direction, L_X and R_X, figure 3.22a. The result is seen in equation 3.11. In the case illustrated in figure 3.22a the spreader will be moved along the negative X axis.

$$Horizontal\ X\ movement = (L_X + R_X)/2 \tag{3.11}$$

The Y movement also contains calculating the average of the sensor values but in the Y direction, L_Y and R_Y, figure 3.22a. But since the sensors are placed in the corners of the spreader and the movement is carried out around the middle of the spreader, the angle between the spreader and container also has to be taken into consideration. In figure 3.22b *Y difference* illustrates the distance affected by the angle. These two parts then makes up the equation for the movement in Y direction, and is seen in equation 3.12.

$$Horizontal\ Y\ movement = \frac{Spreader\ width}{2} * sin(\beta) - \frac{L_Y + R_Y}{2} \tag{3.12}$$

The spreader can also rotate around its Y axis. The reference angle between the spreader and the ground is set to 0°, meaning it will always stay parallel to the ground.

3.2.4 Simulation results

All these simulations are made with the *Drop down* concept.

Table 3.3 presents the time it takes to get to the goal position according to the simulations. In simulation 0.3 *m* the spreader is placed 0.3 m away from its goal position in X, Y and Z directions. The angle between the spreader and container is 45° and the time it takes to align the spreader is 11 seconds. The slow part here is the Y distance, the angle is great due to maximization of it within the time it takes to align the spreader.

In $0.3m\ mod.$ the first simulation is modified to speed up the process. The X and Z distances are the same but the Y distance and the angle are tuned not to take longer time than the X and Z movements.

For the simulation $> 2\ m$ the movements are tuned for maximum distance within 9 seconds. The Z distance is greater than 2 m and when the spreader is above 2 m it is only allowed to be lowered as explained in section 3.2.3. When the spreader gets below 2 m it starts to align.

To maximize X, Y and rotation movements the Z distance is below 2 m in $< 2\ m$. This means that X, Y and the rotation have almost 9 seconds to maximize their moves.

The $< 2\ m\ tele$ simulations are almost the same as $< 2\ m$ with only one difference, the container is placed further away from the reach stacker in the X direction. In the $< 2\ m$ simulations the telescopic actuator is being retracted and in $< 2\ m\ tele$ it is moved forward.

1 cont. and *3 cont.* have the same distances to the goal position, the difference is that in *1 cont.* the stack where the container is being placed on is one container high and in *3 cont.* it is three containers high.

	0.3 *m*	0.3 *m mod.*	> 2 *m*	< 2 *m*	< 2 *m tele*	*1 cont.*	*3 cont.*
X	30	30	72	126	262	50	50
Y	30	5	16	24	24	50	50
Z	30	30	320	199	199	70	70
Angle	45	1	27	45	45	0	0
Time	11.0	3.0	9.15	9.0	8.8	17.5	17.5

Table 3.3: Simulation results where 0.3 *m*, 0.3 *m mod.*, > 2 *m*, < 2 *m*, < 2 *m tele*, *1 cont.* and *3 cont.* are names of the simulations. X, Y and Z are the distances from the spreader's start position to its goal position in the three directions. These values are expressed in cm. Angle is the rotation angle (around the Z axis) between the spreader and the container, the angle is expressed in degrees. Time is the time it takes from the beginning of the simulation until the spreader has reached its goal position, the unit is seconds.

In section 2.2 it is mentioned that the first prototype did the 0.3 *m* movement in around 9 seconds. The operator estimated that also he could do the 0.3 *m* movement without the automated system in around 9 seconds. When comparing these times with the time it took for the automated system to do the 0.3 *m* movement, table 3.3, it is clear that the automated system is slower than both the first prototype and without any automation at all.

3.3 Sensors

3.3.1 Sensor technology

Both the *Pick up* and the *Drop down* concept demand sensors that can locate the container from a distance, therefore sensors like pressure sensors that needs direct contact are not an option. Not even proximity sensors that can see an object from a small distance (up to 120 mm) [14] will work because the range is not enough for this task.

A technical solution that can work is 3D cameras, which was used in the first prototype. There are few technologyies to achieve 3D vision with a camera. Time-of-flight (ToF) operates like a radar but uses light instead of sound. A source emits light with a specific frequency and a camera then measures the time it takes for the light to travel from the source to the object and back to the camera [15]. These cameras use a technology that allows for measuring the distance to each individual pixel. Possible environments for these cameras are many, for example both in- and outdoor, high speed or high accuracy. Another technology to get the distance to a object with 3D cameras is triangulation which can be achieved in two ways [15].

Stereo vision, which works like our eyes. It compares differences in two pictures taken at the same time from two cameras placed next to each other and calculates the distance to the object from this information. The second method is using one camera and a light projector, for example a light source that generates a dotted pattern. On a flat surface the dots will appear with a constant distance between each other. On a hemisphere the space between the dots will increase the further away from the center of the hemisphere they get. By measuring the distances between these dots it is possible to generate a 3D image. The accuracy with this technology increases the nearer the camera is to the object. With a distance of 0.15-0.3m the accuracy can be 10mm [16]. Several fields of view can be selected, for example $70^\circ x 52^\circ$ or $45^\circ x 34^\circ$ [16]. A disadvantage with 3D cameras is that they do not work well in fog and some cameras do not work in snow and heavy rain.

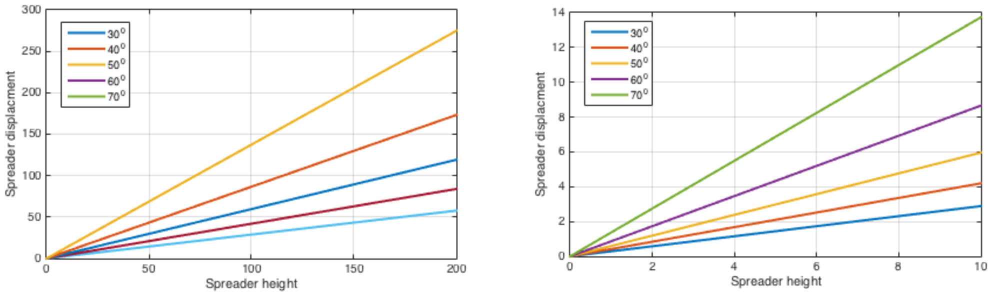
Lidar is a technology which also uses light for mapping. Lidar works like radar but with laser instead of radio waves. It enables mapping of objects up to 100 m away with an accuracy of $\pm 3cm$ [17]. This product has a vertical field of view of 15° and a horizontal field of view of 360°. With this range and accuracy a set-up with this technology has more options for placement of the sensor.

A technical solution enabling seeing through fog is ultrasonic. Ultrasonic sensors use the same Time-of-flight principle as the 3D camera above but with ultrasonic sound instead of light. The distance to the object is measured by the time it takes for the sound to travel to the object and back again. This sensor set-up usually consists of one transmitter and several receivers allowing for shape recognition of the object, different shapes and sizes gives different sensor outputs [18]. Unfortunately no company that sells a complete solution for this could be found, it has to be built from scratch. However there is a company called Toposens[1], which is in the process of developing a product that might work for this application. Ultrasonic sensors usually have a beam angle between a few degrees up to 80 degrees [19].

Sensors come with varying fields of view (FoV), which is described as the angle of the observable surrounding from the sensors point of view. How the FoV affects the maximum spreader displacement can be seen in figure 3.23. For the spreader to be able to move to the desired position this position must be within the sensors FoV. Otherwise the sensors can not see the goal position. FoV is defined as the total view angle for the sensor which means that it has half the FoV angle on each side of its center. For that reason the angles in figure 3.23 is half of what the legend says. The legend describes the FoV and the graphs illustrates the maximum

[1] http://www.toposens.com/

spreader displacement for that FoV at different heights.



(a) Sensor view 0-2 m.

(b) Sensor view 0-10 cm.

Figure 3.23: Sensor view with varying fields of view. The distance between the sensor and the container is found on the X axis. The Y axis shows the maximum horizontal distance between the container and the sensors for a specific field of view.

3.3.2 Sensor placement

When it comes to placement of the sensors some placements will work better with some sensor technologies than with other technologies. The first prototype used 3D cameras placed in two corners of the spreader. This placement works well for the concept *Pick up* where the container corners are fully visible trough the whole movement. If this placement is used for the concept *Drop down* the lifted container will conceal the corners of the lower container which the spreader is searching for. The concept could work if the spreader starts with finding the corners by moving in the X and Y plane, taking a picture and remembering the location, then align the container and lowering it blindly.

A way to solve the problem with moving blindly but still be able to place sensors on the spreader is to place sensors on extendable bars. Now the sensors can see around a levitated container. The drawback with extended bars is the risk of breakage of the bars since they will be extended on a moving spreader close to containers.

Sensors could also be placed on the boom. The drawback with that placement is that the spreader can be extended which makes it hard to find a good spot for a sensor on the boom. Instead several sensors placed on both the boom and on the forward edge of the reach stacker could be used. But sensors placed like this will not be able to guide the spreader if the goal position is behind the first stack. The first stack will block the view for the sensors.

Lidar has a long range which makes it possible to place it on the cabin roof. This gives a 360° view around the vehicle, but depending on the field of view the lidar might have to be tilted to be able to see when the spreader works high above the vehicle. This solution will not be able to see behind the first stack. In that case it is impossible for the lidar to guide the spreader.

Instead of placing sensors on the reach stacker they could be located on a drone. This could solve the drawbacks with the above mentioned placements of sensors. A drone can fly around the first stack and look from behind. A levitated container only blocks the view of the drone if the container is to be placed in a hole surrounded by containers on all sides. A drawback with a drone is the battery which has to be charged. But the drone will be in the air for maximum 1 minute for each pick up and drop down, the rest of the time it can be on standby on a platform on the reach stacker and be charged at the same time.

Chapter 4

Discussion and conclusions

The discussion and conclusions chapter is divided into four sections. First comes the discussion about the concepts. Then there is a section about the Simulink model, where possibilities and problems with Simulink are discussed. The third section contains the discussion about sensors and their placement. The last section in this chapter is about further work.

4.1 Concept development

In section 2.1 *Select Product Concepts* among other topics is explained. In this case the selection was made as a discussion due to totally different concepts being evaluated. In cases like this it can be a hard task to find a suitable reference concept to which all others can be compared. When concepts such as *Warning system* is evaluated against *Spreader height* it is difficult to find a suitable reference object. That is why there was a discussion around the concepts instead.

The concept *Automated driving* was eliminated since it was not suited for automation. But by making it a guiding system instead of automated one there would not be any safety risks. This guiding system could show a live feed of the upcoming road on a screen, and on the same screen the direction of the vehicle and the most favourable route are also displayed. Today rear view cameras work similar to this with the exception that no route is proposed. Maybe such a system would not be used every time but it could work as a training system for new operators. However, the development of such a guiding system would probably be time consuming so it might not be worth it if the system would not be used on a daily basis. On the other hand a guiding system would be a perfect evaluation of a possible *Automated driving* concept.

One of the research questions was *Which areas would benefit most from driver assistance?* As described in section 3.1 *Pick up* and *Drop down* are the most promising concepts. If the sensor placement is also considered *Pick up* stands out as a winner. *Drop down* absolutely has potential but the sensor placement for that concept is more difficult. The concept *Spreader hight* also has potential if the hight of the stack is known in the container information system. If it should rely only on sensors it would probably be too slow from time to time, for example when the spreader can not see the stack in time for it to be raised before the vehicle reaches the stack. This concept does however not require any simulations because it is a relatively easy task. The equations used in *Lower Z1* in section 3.2.3 can be used for this movement as well.

4.2 Simulink model

A lot of time during this project went into the building of the model, both in the building itself but also in the understanding of Simulink. The author had only used Simulink once before starting this project and that time he got a finished model and only did tests with it. When the understanding of the program grew the possibilities seem endless. The author believes that if there was more time a reach stacker model could be built in Simulink for testing nearly every part of the vehicle, not only the hydraulic lifting system.

A problem that arose during the building of the Simulink model had to do with the actuators. The mechanical part of the actuator adapts itself to the starting position of the simulations. This means that the mechanical part of the actuator which levitates the boom will be more extended in the beginning of the simulation if the spreader's start position is high up, than if it was close to the ground. But unfortunately the hydraulic part of the actuator did not extend and this could not be seen in the compiled simulation. Suddenly the actuator did just stop for no apparent reason. A lot of thought and time were required to realize where the problem was.

While tuning the speeds for the actuators, see table 2.1, to correspond with reality the hydraulic parameters for the actuators were changed. The final parameter values did not have anything to do with reality instead they assured the speeds were correct. The size off the hydraulic pump was not taken into consideration while tuning the parameters and the motor that drives the pump in the model has a constant rpm. In reality the rpm is adapted to the real time need of the pump. The only constraints for the pump was the maximum pressure of 245 bar, see section 2.2. It might be that the pump in the model is too big and that in reality it can not handle all the actuators moving at the same time. That is something that has to be further investigated. This simplification in the model was made due to time constraints.

When tuning the hydraulic actuators there are a lot of parameters to take into consideration, described in section 3.2.2. One of these is how the actuators affects each other. Figure 3.17a shows the measured values from the rotary and the spreader width actuators. Both signals oscillates in the beginning. The movements created from these oscillations are very small, in the range of ± 0.0002 m for the spreader width actuator and ± 0.0006 degrees for the rotary actuator. These movements will therefore not be possible to detect with the naked eye so from that point of view the oscillations must not be removed since the values converges. However, these oscillations will possibly result in a marginally slower automated process, but the most important reason to remove the oscillations is the simulation time. When building a model like this there will be a lot of testing with different values for all parameters. Long simulation times because of unnecessary oscillations will lead to increased work time, therefore this tuning is important to do before time is wasted on long simulations.

Some times even the lack of control can be of help. To make the rotary actuator move in a linear fashion it is set to a goal position of -1000 or 1000 degrees when it does big movements, see section 3.2.2 about control results. The PI controller is only in use when the rotary actuator is within three degrees from its goal position. This is not how the rotary actuator was intended to be designed, the plan was to always go through the controller. However, when always going through the controller the rotary actuator did not work for both small and big rotations. This solution makes it linear but might not be the most elegant solution. The angle of 1000 was chosen due to the big number, the actuator will never get close to the angle and therefore not slow down for other reasons than the approach of the reference value.

The time it takes for a actuator to complete its movement depends on its speed and the control output. The combined movement pattern for the actuators is not linear. If several actuators move at the same time the fastest will complete its movement first. That means that when lowering the spreader it might look like it changes the X coordinate as well because the boom telescope actuator might be moving slower than the boom lift actuator. It is due to that the actuators are always moving at their highest speed and that could be a problem. If a container is to be placed in an area surrounded by other containers there might not be much room to play with and the movement has to be linear. A solution to this is calculating the time every actuator will need and adjust the speed of the faster actuators to the one that needs the most time.

When building this model the author used a substitute for the sensors. Instead of sensors the model measures the exact distance between the container placed on the ground and points fixed to the spreader. This is what a sensor would also do but in another way. In the *Pick up* concept simulation these fixed points are two corners of the spreader and for the *Drop down* concept the fixed points are located on two corners of the container. Since this is done in Matlab the distance measurement will be exact and the sensors can therefore be seen as ideal, which will not be the case for a real product. Bad sensor resolution could be a problem which is not considered in the simulations, more about that in section 4.3. It is also assumed that both sensors can see the container castings which does not need to be the case and it does not need to be a problem either. It could be solved with clever programming. If one sensor sees a corner and the other does not see anything the spreader can be moved just from the angles of the corner that is seen. If the angle between the container corner and the spreader is large, the spreader has to be rotated for the other sensor to be able to see its corner. If the spreader angle is near zero, relative to the container, the spreader must be moved sideways.

For the evaluation of the simulations the author chose to use the *Drop down* concept. This concept is the most demanding for the system since it lifts a heavy container that weighs up to 45 ton. While tuning the speeds for the actuators the slowest times was chosen, in other words, the time it takes to move the actuator when it is under the greatest strain.

One of the research questions that was presented in the beginning of the report was *What kind of control is needed for these systems?* In section 3.2.2 about the control it is stated that none of the controllers use a derivative gain and only a small integral gain is used. No fuzzy controller was actually tested because there was no need for it. The only controller which is a bit special is the rotary controller. It uses two different controllers depending on if the -1000/1000 reference angle is used or not. If it is used the controller is a bit weaker than if it is not used. The author believe a lot of this has to do with the proportional valve. If a classic on/off valve is used instead it would put higher demands on the controller.

Another research questions was *Can an automated system with this setup be faster than a human operator?* As can be read in table 2.1 about the actuator speeds the *Spreader sideshift* moves ± 800 mm in < 26 seconds or ≈ 3 cm/second. This data is taken from appendix B.2. However, when this was presented for the people at Konecranes they said that the spreader moved with a speed of 10 cm/second in that direction. If this is true the time for the 0.3 m simulation presented in table 2.1 be just over 3 seconds, if the angle of 45° is reduced. This would be a big improvement of the process. Before this information was revealed from Konecranes the author thought was to recommend them to talk to Elme about making the *Spreader sideshift* movement faster because it had an negative impact on the process. Unfortunately was the information in Elme's brochure trusted and the new information from Konecranes came after the work was finished, therefore the simulations are not updated with the correct speed. But if this is taken into consideration while discussing the simulation times in table 2.1 the results are very satisfying. The distance that in the first prototype took approximately 9 seconds takes just over 3 seconds with concurrent movements. In simulation $< 2m\ tele$ when the concurrent movement takes 9 seconds it can move approximately 260 cm in X direction, 200 cm in Z direction and rotate 45°. If the X distance travelled within 9 seconds also is calculated with the new speed it gets $10[cm/second] * 9[seconds] = 90[cm]$ instead of 24 cm. It can also be seen, if we compare simulation *1 cont.* with *3 cont.*, that the height of the spreader would not change the times.

4.3 Sensors

As mentioned in the target specifications, section 3.1.3, the alignment must be within 5 cm for a perfect alignment to work. In the section about sensor technology, section 3.3.1, resolutions for a few sensors using different technologies are presented. All these resolutions are within 5 cm when the sensor gets close to the object but some of them might not have high enough resolution if they are scanning the environment from a distance. This has to be considered while deciding sensor technology and placement.

In section 3.1.2 about customer needs it is mentioned that robustness is an important feature of a system like this. The author believes that the hardest obstacle to achieve this is the sensors. The environment in which the reach stackers will work can be harsh. The equipment will be exposed to heavy rain, fog, snow and cold weather which can have an impact on the accuracy of the sensors. Furthermore the placement also affects the robustness. Under the category *Robust* in table 3.1 it can be seen that the customer statement *Reliable* is translated to the customer need *Can be repeated without any problems*. This means that the system should always work. When it comes to sensor placement this customer need might be hard to fulfil. The sensor placement will influence which container placement is possible for the system to handle. For example a Lidar placed on the cabin roof will not allow for drop down and pick up behind the first stack. Therefore finding a good sensor placement and a matching sensor for that placement will be a crucial part in further development of this system.

With the robustness in mind the authors personal favourite for the sensor placement is the drone. The reason for that is the versatility of the drone. Depending on if the chosen container is in the first or the second stack, if it stands on the ground or 4 containers up the drone can hover in different positions. The drone concept is probably the concept which demands most pre-work since it has to be programmed and tested for several positions. Another concept that could fulfil the robustness need is sensors placed on the spreader that takes a picture and moves blindly when a levitated container is blocking the view of the final position. This solution sets high requirements on the system by not having any real time feedback of the distances to the goal position. A third possible solution is to combine several sensor placements and using different sensors depending on the location of the spreader.

4.4 Further work

There is still a long way to go before this system can be implemented on a real reach stacker. The author's recommendation is to start with getting all of the parameters right in the model and not just have the speeds and pressure as limits. By doing so there will be more understanding of the pump's possibilities. If the pump can handle movements from all actuators at the same time or if the speeds will be lowered.

Sensors in the model could also be designed to mimic how they work in the real world. The sensor field of view affects how far away from the container, in the X and Y plan, the sensors can be and still see the container castings. By implementing a sensor field of view in the model the largest spreader displacement could be tested. It might also be possible to add a filter on the sensors which allows for test of the sensor accuracy. In the model used for this thesis work the sensors measure the distance between the spreader and the container or between the container and the container, which a real sensor also would do. But this model does not care where the sensor is placed, it only uses these values which the real sensor would send to the system. The sensor placement could also be tested in the model, to better see the affect of the sensor shadow.

Sensors should also be tested in the physical world, not only in the Simulink model. Testing different sensors and placement will give a greater understanding of what is possible with the different techniques. If the choice is to use a drone that work itself could be an exciting MSc thesis.

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Appendix A

This appendix contains summaries from meetings held during the thesis work.

A.1 Customer interview

Here is a summary of a meeting held at the customer.

Automation of spreader alignment would be very appreciated. Due to difficulties with seeing the holes for the twistlocks while reaching for a high placed container, this process would be great to automate. Some reach stackers are equipped with a vertically movable cabin which allows for seeing higher placed containers and also seeing containers on the second row. With automated spreader alignment a vertically movable container would not be needed. It would also be useful to have an automated lowering process used while placing a container on a truck, railway wagon or on top of another container.

One advantage with a reach stacker compared to a container lift truck (which acts as a fork truck) is that the reach stacker does not need to be perpendicular to the container it handles. This gives a possibility to take shortcuts while grabbing or releasing a container, which is one thing that an automated process could take advantage of. Automating parts of the driving, such as turning the reach stacker when reaching the selected container, gives a few advantages. The vehicle would always be perfectly placed. A reach stacker is steered via the rear wheels and they can turn while the vehicle stands still which wears a lot on the tarmac. If this process would be automated, it can be programmed not to turn the wheels while standing still.

A system like this must always work, independently of weather and light, if it only works 80% of the time the operator will not use it. If it for some reason does not work or can not continue with a started task, the system needs to tell the operator about this. The time for a specific movement does not need to be faster than with manual steering, but the time for the whole process does, regardless if the automated system is kinder to the equipment. This means that an automated system that is cheaper to use compared to a manual movement due to lower wear and tear but is slower than the manual movement will not be used by the operator.

An important thing that has to be considered while designing a system like this is safety. Making the reach stacker drive in automatic mode puts a whole new level of safety risks to the process. A self driving vehicle takes the legal responsibility away from the operator, leading to a higher safety level required on the area where the vehicle is used, which in turns leads to a higher investment. This could however work, but it is a much bigger concept than automating parts of a reach stacker and use it in the same safety areas as to today. By letting the parking break be activated while in automated mode there would not be a requirement on a higher safety level on the operating area.

The operator has to be able to stop and terminate the process, but there is no need for the operator to be able to decide the speed or direction of the movements. The process could be started with a button and the process could be stopped when completed or when the operator moves anything. Allowing the operator to stop the process by moving anything and not demanding a stop button push is a much safer solution. In a situation where a fast decision is crucial it should be easy to stop the movement. Even though the system can work on its own when started some sensors guaranteeing that the operator still is in the seat is required. There should not be any reason to give the operator a lot of information while the automated system is active, except a light indicating that the system is working. If the sensors lose contact with the container the light will be turned off. On the existing reach stackers today, there is a light turned on when the twistlocks are in place, this would be enough even for indicating that the automated process is finished. If an error occurs, like sensors losing connection with the container, an error message tells the driver about the error.

A.2 Discussion of concepts and sensors

Below is a summary of a discussion about the concepts and possible sensors for these concepts. The meeting was held at Konecranes Lifttrucks AB in Markaryd and present during the meeting was Anders Nilsson, Technical and Quality Director, Kari Rintanen, Technical Manager, Miroslav Antolovic, Tendering Engineer, and Felix Grunert. Kari is the developer of the first Pick up prototype mentioned in the Introduction.

During this meeting the two concepts *Drop down* and *Pick up* were discussed and also sensors suitable for these concepts. Both these concepts will need three coordinates from the sensors to be able to reach there goal positions.

As mentioned in the introduction the *Pick up* concept has been tested with a reach stacker. While doing these tests it was realised that on/off valves on a actuator will affect the movements created by another actuator if both are moved at the same time. If simultaneous movements should be made there is consequently a need for proportional valves.

The *Drop down* concept has been tested with a Rubber Tired Gantry Crane (RTG). Sensors used in this case were 3D cameras placed on the spreader. They took a picture of the container stack or trailer where the container would be placed and calculated the X, Y and Z directions for the movement. Since the cameras were placed on the spreader they were blinded when the spreader was lowered, therefore the movement had to be calculated by the first (and only) picture, then the spreader was moved blindly. This puts a demand on precise sensors and calculations.

When it comes to sensors both the *Drop down* and *Pick up* concepts used 3D cameras. The one used can see up to 4 m, the resolution of the camera gets better when the camera gets closer to the object and will finally reach a resolution of a few mm. The results produced with these cameras were very satisfying during the earlier prototypes. For the *Pick up* automation a camera could be placed in each corner. This could however be a problem if the selected stack is lower than the stack next to it. In a case like that there is a risk that one or several cameras will hit the higher stack and break.

Another solution could be to use lasers. Velodyne LiDAR develops a sensor that use 16 rotating lasers to build a 360° horizontal and 50° vertical map of its surroundings. The sensor resolution is ± 2 cm and it costs around 9 000 $.

Not all containers have the same height, so this can not be hardcoded. When placing a container on a stack or trolley the height must be a known parameter. This could be achieved by measuring the hight of a container while handling it, but that is harder than it sounds. If it is picked up from a stack there is no good reference point to measure from if the cameras are placed on the spreader. Sensors could be placed on the boom but then the question is were on the boom to place it since the boom can be extended. Today, well-organised harbours have systems knowing where all containers are placed and also its measurements. In the future all harbours will have systems like this and then no real time measuring of the container height will be needed.

Appendix B

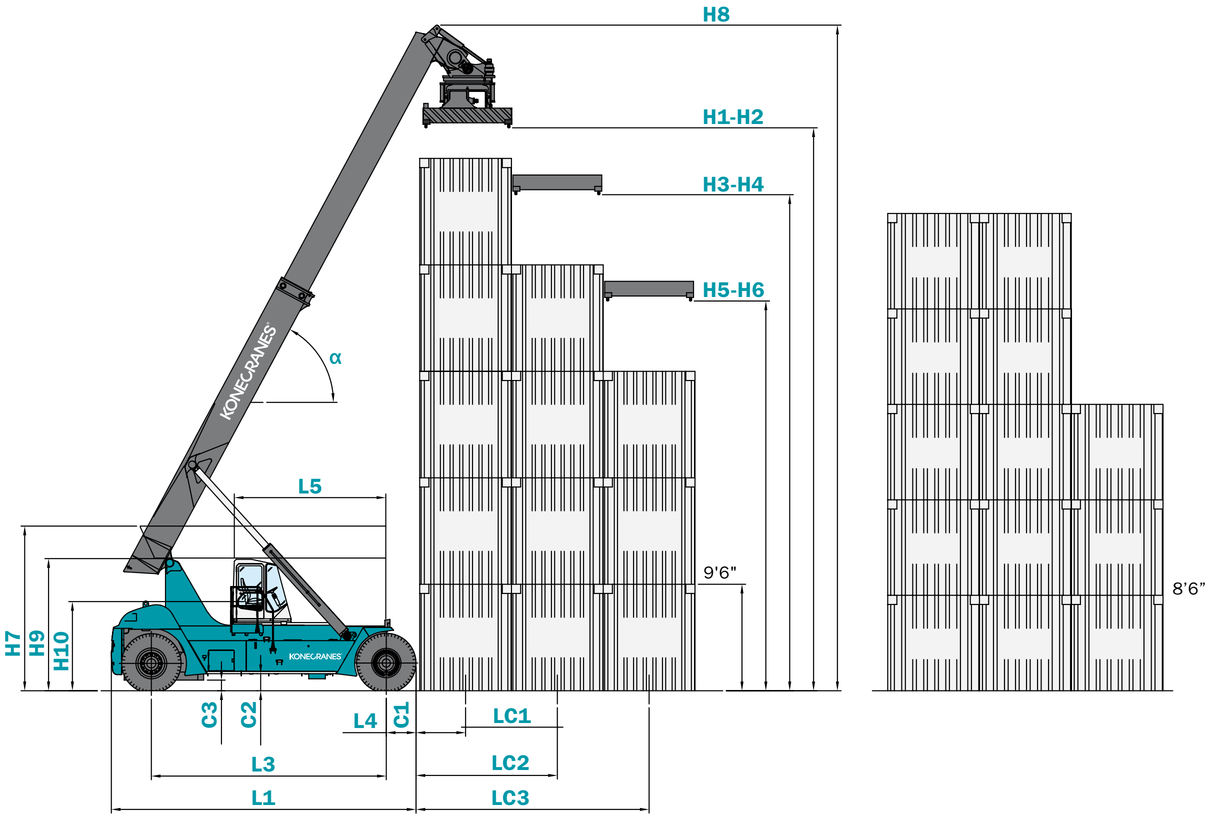
This appendix consists of parts of brochures containing data of dimensions and speeds used for the model.

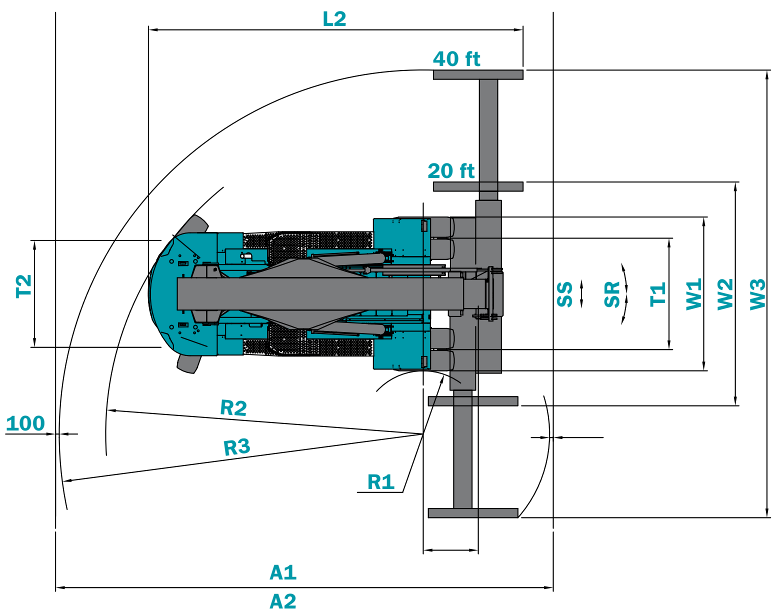
B.1 Konecranes, Reach Stacker

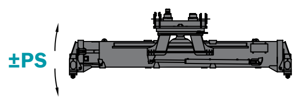
This section contains three pages from a brochure about Konecranes reach stackers. The selected pages have information about the dimensions of the reach stackers. The reach stacker used as a model for this project is *SMV 4535 TB5*[1].

[1] Konecranes. *Reach stackers with heart*. Last visited 17 September 2016. Page 19 - 21. URL: http://www.konecranes.com/sites/default/files/download/kc_rst_print_8809022_low.pdf

DIMENSION MEASUREMENT IDENTIFIERS







TECHNICAL DATA

Reach stackers for container handling, 41 to 45 tons

	MODEL			SMV 4127 TB5	SMV 4527 TB5	SMV 4527 TB6	SMV 4531 TB5
LIFTING DATA	**Dimensions**	**Identifier**	**Units**				
	Lifting capacity at load center LC1 / LC2 / LC3 (no jacks)		tons	41 / 27 / 14	45 / 27 / 14	45 / 27 / 14	45 / 31 / 16
	Lifting capacity at load center LC1 / LC2 / LC3 (with jacks)		tons	-	-	-	-
	Load centers in row 1 / 2 / 3	LC1 / LC2 / LC3	mm	2000 / 3850 / 6350	2000 / 3850 / 6350	2200 / 3850 / 6350	2000 / 3850 / 6350
	Stacking height in row 1 (9'6" / 8'6")			5 x 9'6" / 5 x 8'6"	5 x 9'6" / 5 x 8'6"	5 x 9'6" / 6 x 8'6"	5 x 9'6" / 5 x 8'6"
	Spreader type, telescopic, locking			Toplift with 4 x twistlocks, extension 20-40 ft, 4 lifting eyes, safety locking (ELME 817)			
	Lost load center to face of tires / jacks	L4	mm	800	800	800	800
	Wheelbase	L3	mm	6400	6400	6400	6400
WEIGHT	Service weight		kg	68500	68500	69200	71800
	Axle pressure front LC1 (unloaded / rated load)		kg	37500 / 96500	37500 / 102200	38200 / 104300	37500 / 102200
	Axle pressure rear LC1 (unloaded / rated load)		kg	42000 / 88600	42000 / 88600	42300 / 88900	42000 / 95500
	Axle pressure front LC2 (unloaded / rated load)		kg	31000 / 13000	31000 / 11300	31000 / 9900	34300 / 14600
	Axle pressure rear LC2 (unloaded / rated load)		kg	26500 / 6900	26500 / 6900	26900 / 7300	29800 / 7300
WHEELS	Tire type			Pneumatic	Pneumatic	Pneumatic	Pneumatic
	Tire dimension / ply rating, front & rear		Inch	18.00 x 25"/PR40	18.00 x 25"/PR40	18.00 x 25"/PR40	18.00 x 25"/PR40
	Rim dimensions, front & rear		Inch	13.00 x 25"	13.00 x 25"	13.00 x 25"	13.00 x 25"
	Tire pressure, front / rear		MPa	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0
	Number of wheels, front / rear (X = driven)			4X / 2	4X / 2	4X / 2	4X / 2
	Track width, front / rear	T1 / T2	mm	3030 / 2911	3030 / 2911	3030 / 2911	3030 / 2911
DIMENSIONS	Boom angle, min - max	α	deg	0 - 62	0 - 62	0 - 62	0 - 62
	Lifting height in twistlocks, min - max at LC1	H1 - H2	mm	1150 - 15300	1150 - 15300	1150 - 15300	1150 - 15300
	Lifting height in twistlocks, min - max at LC2	H3 - H4	mm	1150 - 13400	1150 - 13400	1150 - 13400	1150 - 13400
	Lifting height in twistlocks, min - max at LC3	H5 - H6	mm	1150 - 10500	1150 - 10500	1150 - 10500	1150 - 10500
	Boom height, min - max	H7 - H8	mm	4500 - 18200	4500 - 18200	4500 - 18200	4500 - 18200
	Truck height over cabin / seat height	H9 - H10	mm	3650 - 2450	3650 - 2450	3650 - 2450	3650 - 2450
	Sliding cabin stroke (manual / hydraulic)	L5	mm	1800 / 2900	1800 / 2900	1800 / 2900	1800 / 2900
	Overall length, with - without spreader	L1 - L2	mm	11500 - 8300	11500 - 8300	11700 - 8300	11500 - 8300
	Drive axle width	W1	mm	4160	4160	4160	4160
	Spreader width, min - max	W2 - W3	mm	6050 - 12175	6050 - 12175	6050 - 12175	6050 - 12175
	Spreader sideshift	SS	mm	± 800	± 800	± 800	± 800
	Spreader rotation	SR	deg	-105 / 195	-105 / 195	-105 / 195	-105 / 195
	Mechanical Pile Slope (side tilt / no power)	PS	deg	± 2	± 2	± 2	± 2
	Ground clearance, front / mid / steering axle	C1 / C2 / C3	mm	300 / 465 / 275	300 / 465 / 275	300 / 465 / 275	300 / 465 / 275
	Aisle width (with 20 ft / 40 ft container)	A1 / A2	mm	11500 / 13600	11500 / 13600	11800 / 13900	11500 / 13600
	Turning radius, inner	R1	mm	1500	1500	1500	1500
	Turning radius, outer 20 ft / outer 40 ft	R2 / R3	mm	8550 / 9850	8550 / 9850	8550 / 9900	8550 / 9850
PERFORMANCE	Drive speed forward, unloaded / at rated load		km/h	25 / 22	25 / 22	25 / 22	24,5 / 22
	Drive speed reverse, unloaded / at rated load		km/h	25 / 22	25 / 22	25 / 22	24,5 / 22
	Lifting speed, unloaded / at 40% load / at rated load		m/s	0.38 / 0.35 / 0.23	0.38 / 0.35 / 0.23	0.38 / 0.35 / 0.23	0.38 / 0.35 / 0.23
	Lowering speed, unloaded / at rated load		m/s	0.35 / 0.40	0.35 / 0.40	0.35 / 0.40	0.35 / 0.40
	Gradeability, at rated load, 0/2 km/h		% / %	29 / 22	29 / 22	25 / 20	25 / 20
	Towing power, at rated load, 0/2 km/h		kN / kN	315 / 251	315 / 251	300 / 246	300 / 246
DRIVELINE	Engine power (min - max)	**EU2 / EU3b**	kW	256 - 294	256 - 294	256 - 294	256 - 294
	Engine torque (min - max)	**EU2 / EU3b**	Nm	1640 - 2172	1640 - 2172	1640 - 2172	1640 - 2172
	Transmission, gears forward + reverse			DANA 4 + 4 / ZF 4 + 3			
	Transmission type, function, shifting			Automatic transmission, torque converter, reverse protection, powershift			
	Drive axle model			Kessler D102			
	Driving brake system, type			Oil-cooled multiple wet disc brakes (WDB)			
	Parking brake system, type			Dry single disc / spring release			
	Steering system / steering axle type			Hydraulic power steer / HD axle + double-acting cylinder			
OTHERS	Load-sensing hydraulics / power-on-demand			Yes / yes	Yes / yes	Yes / yes	Yes / yes
	Safety, Monitoring & Overload System			Yes	Yes	Yes	Yes
	Hydraulic oil pressure, boom / spreader		MPa	24 / 15	24 / 15	24 / 15	24 / 15
	Diesel / hydraulic tank volumes		Lit	650 / 850	650 / 850	650 / 850	650 / 850
	Noise level inside cab (LM) DIN 45635	**EU2 / EU3b**	dB(A)	68 / 66	68 / 66	68 / 66	68 / 66
	Noise level inside cab (LpAZ) EN 12053		dB(A)	75	75	75	75
	Noise level outside (LWA) 2000/14/EC		dB(A)	111	111	111	111

NOTE 1. TB models do not have support jacks / TBX models have support jacks for increased capacity and lower ground pressure
NOTE 2. Other lifting attachment combinations possible, check factory information
NOTE 3. Four lifting eyes on spreader are standard; extra ones can be provided plus container guides on one side of spreader
NOTE 4. Optional for laden handlers: Hydraulic Pile Slope ±6 deg and Powered Dampening Cylinders ±5 deg + tilt lock
NOTE 5. For available driveline combinations, see driveline chart and latest factory information
NOTE 6. BH = reach stacker for barge handling (other models available)

SMV 4531 TB6	SMV 4535 TB5 (TBX5)	SMV 4537 TB5 (TBX5)	SMV 4542 TB5 (TBX5)	SMV 4543 TB5 (TBX5)	SMV 4545 TB5 (TBX5)	SMV 4545 TB3 (BH)
45 / 31 / 16	45 / 35 / 20	45 / 37 / 19	45 / 42 / 24	45 / 42 / 25	45 / 45 / 37	45 / 45 / 35
-	45 / 37 / 24	45 / 41 / 28	45 / 44 / 30	45 / 44 / 34	45 / 45 / 45	45 / 45 / 35
2200 / 3850 / 6350	1900 / 3850 / 6350	2000 / 3850 / 6350	1800 / 3850 / 6350	1800 / 3850 / 6350	2275 / 3850 / 6350	1975 / 3875 / 6375
5 x 9'6" / 6 x 8'6"	5 x 9'6" / 5 x 8'6"	5 x 9'6" / 5 x 8'6"	5 x 9'6" / 5 x 8'6"	5 x 9'6" / 5 x 8'6"	5 x 9'6" / 5 x 8'6"	3 x 9'6" / 3 x 8'6"
800	930	930	930	930	1025	1025
6400	6400	6400	7250	7500	8000	9000
72500	79700	83000	83500	84500	107000	105200
38200 / 104300	38700 / 103400	42000 / 106700	42000 / 104400	42500 / 103700	51000 / 114600	52000 / 118300
42300 / 95800	43400 / 104400	46500 / 110100	46400 / 116000	47100 / 116000	54600 / 127200	57300 / 121200
34300 / 13200	41000 / 21300	41000 / 21300	41500 / 24100	42000 / 25800	56000 / 37400	53200 / 31900
30200 / 7700	36300 / 10300	36500 / 9900	37100 / 9500	37400 / 10500	52400 / 24800	47900 / 20100
Pneumatic	Pneumatic	Pneumatic	Pneumatic	Pneumatic	Pneumatic	Pneumatic
18.00 x 25"/PR40	18.00 x 33"/PR36	18.00 x 33"/PR36	18.00 x 33"/PR36	18.00 x 33"/PR36	21.00x35"/PR40	21.00 x 35"/PR40
13.00 x 25"	13.00 x 33"	13.00 x 33"	13.00 x 33"	13.00 x 33"	15.00 x 35"	15.00 x 35"
1.0 / 1.0	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0
4X / 2	4X / 2	4X / 2	4X / 2	4X / 2	4X / 2	4X / 2
3030 / 2911	3030 / 2911	3030 / 2911	3030 / 2911	3030 / 2911	3227 / 3420	3227 / 3420
0 - 62	0 - 62	0 - 62	0 - 61	0 - 59	0 - 55	0 - 62
1150 - 16300	1300 - 15400	1300 - 15400	1300 - 15400	1300 - 15400	1300 - 15400	1300 - 15400
1150 - 14200	1300 - 13500	1300 - 13500	1300 - 13500	1300 - 13500	1300 - 14600	1300 - 13500
1150 - 11500	1300 - 10500	1300 - 10600	1300 - 10400	1300 - 10400	1300 - 11600	1300 - 10500
4500 - 19300	4675 - 18350	4775 - 18400	4775 - 18500	4975 - 18500	5100 - 18800	4675 - 18300
3650 - 2450	3800 - 2650	3800 - 2650	3800 - 2650	3800 - 2650	4050 - 2900	3800 - 2650
1800 / 2900	1800 / 2900	1800 / 2900	1800 / 2900	1800 / 2900	1800 / 2900	1800 / 2900
11700 - 8300	11500 - 8450	11500 - 8450	12300 - 9300	12550 - 9550	14150 - 10600	11500 - 8450
4160	4160	4160	4160	4160	4600	4160
6050 - 12175	6050 - 12175	6050 - 12175	6050 - 12175	6050 - 12175	6050 - 12175	6050 - 12175
± 200	± 800	± 800	± 800	± 800	± 800	± 800
± 200	-105 / 195	-105 / 195	-105 / 195	-105 / 195	-105 / 195	-105 / 195
± 5	± 2	± 2	± 2	± 2	± 2	± 2
300 / 465 / 275	300 / 425 / 450	300 / 425 / 450	300 / 425 / 450	300 / 425 / 450	300 / 300 / 500	300 / 300 / 500
11800 / 13900	11500 / 13600	11500 / 13600	12650 / 13850	12900 / 14000	15200 / 15400	15900 / 15900
1500	1500	1500	2200	2600	2800	3250
8550 / 9900	8550 / 9850	8550 / 9850	9750 / 10400	10100 / 10750	11300 / 11300	12400 / 12400
24,5 / 22	26 / 23	25 / 22,5	25 / 22,5	25 / 22,5	24 / 20	24 / 20
24,5 / 22	26 / 23	25 / 22,5	25 / 22,5	25 / 22,5	24 / 20	24 / 20
0.38 / 0.35 / 0.23	0.38 / 0.35 / 0.23	0.38 / 0.35 / 0.23	0.38 / 0.35 / 0.23	0.37 / 0.34 / 0.22	0.35 / 0.33 / 0.17	0.35 / 0.33 / 0.17
0.35 / 0.40	0.35 / 0.40	0.35 / 0.40	0.35 / 0.40	0.35 / 0.40	0.25 / 0.35	0.25 / 0.35
25 / 20	24 / 18	24 / 18	23 / 17	23 / 17	22 / 16	22 / 16
300 / 246	260 / 214	260 / 214	260 / 214	260 / 214	260 / 214	260 / 214
256 - 294	256 - 294	256 - 294	256 - 294	256 - 294	256 - 294	256 - 294
1640 - 2172	1640 - 2172	1640 - 2172	1640 - 2172	1640 - 2172	1640 - 2172	1640 - 2172
			Kessler D106		Kessler D111	Kessler D111
Yes / yes	Yes / yes	Yes / yes	Yes / yes	Yes / yes	Yes / yes	Yes / yes
Yes	Yes	Yes	Yes	Yes	Yes	Yes
24 / 15	24 / 15	24 / 15	25 / 15	25 / 15	24 / 15	24 / 15
650 / 850	650 / 850	650 / 850	650 / 850	650 / 850	700 / 950	700 / 950
68 / 66	68 / 66	68 / 66	68 / 66	68 / 66	68 / 66	68 / 66
75	75	75	75	75	75	75
111	111	111	111	111	111	111

B.2 Elme, Model 817

This section is a brochure from ELME about their product *Model 817*[2] which is a spreader used on reach stackers.

[2]Elme. *MODEL 817*. Last visited 17 September 2016. URL: http://www.elme.com/wp-content/blogs.dir/1/files_mf/1446562773ELMELeaflet_Model817.pdf

MODEL 817

TOP LIFT SPREADER FOR LADEN CONTAINER HANDLING WITH REACH STACKERS

Standard supply includes:

- Mounting arrangement to fit the boom head.
- Mechanical pile slope (MPS).
- Four vertical pendular ISO twistlocks.
- Lifting eyes near twistlocks.
- Hydraulic telescoping.
- Hydraulic sideshift.
- Hydraulic rotation.
- Solenoid valves for all hydraulic functions.
- Electrical and mechanical twistlock protection and indication system.
- Electric telescoping protection system.
- Lift interrupt signal.
- LED-indication lights.
- LED-work lights.

ELME Spreader Model 817 is a telescopic top lift spreader for handling of laden ISO containers weighing up to 45 tonnes. 817 is designed for mounting on reach stackers.

The strong and basic concept offers distinct advantages, such as two parallel telescopic beams, assuring max overlap. Beam sections dimensioned to absorb not only the vertical, but also the very considerable horizontal forces.

TWISTLOCK SYSTEM

The twistlock system is manufactured in a rugged design and is well-proven since many years. 817 has hardened ISO quick exchange pendular twistlocks. Hydraulically activated and mechanical interlocking against faulty locking and unlocking.

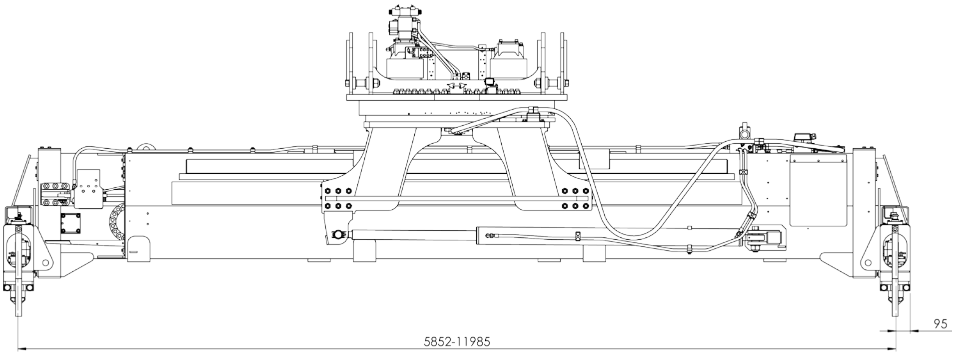
TELESCOPING, SIDESHIFT AND ROTATION SYSTEM

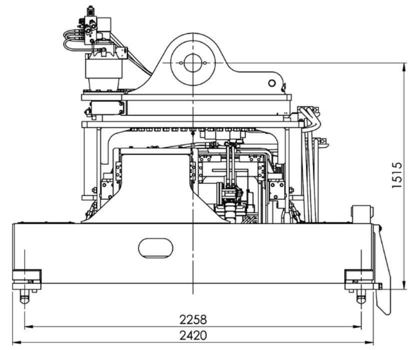
Telescoping is powered by one hydraulic cylinder inside each beam. Sideshift is executed by two hydraulic cylinders on the outside of the mainframe. Rotation is done by a slewing ring with double transmissions for turning and brakes for holding.

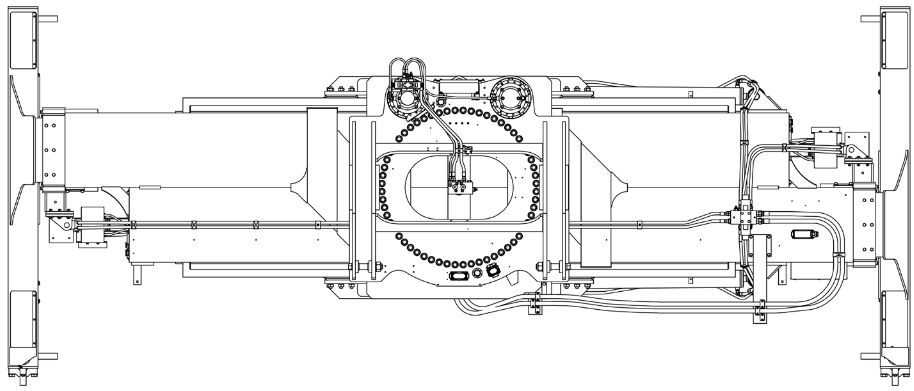
CONTROL AND PROTECTION SYSTEM

Electrical systems monitor the state of the spreader at all times. Indicator lights advise the operator when the spreader is correctly seated, locked or not locked. Each signal is a precondition for the important protection functions of the spreader. Such as twistlock activation, telescoping and lift interrupt.

MODEL 817







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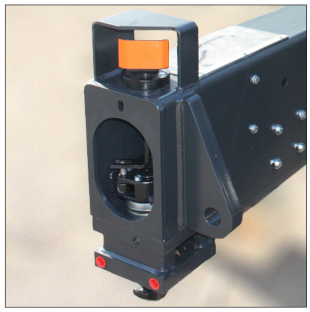
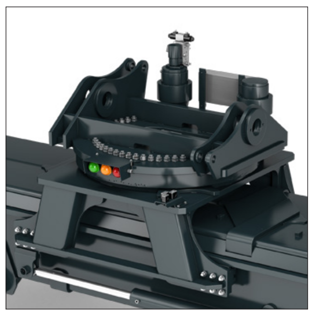


Twistlock and lifting eye.



Rotator.

Technical specifications

Type of lifting system		Four vertical twistlocks
Spreader weight (TW)		9 300 kgs without extra equipment
Lifting capacity (SWL), spreader		45 tonnes ± 10 % eccentric load
Lifting capacity (SWL), lifting eyes		4 x 11,25 tonnes
Twistlock		ISO pendular 20 mm
Telescopic positions		20 and 40ft
Telescoping speed	20-40ft	< 20 sec.*
	40-20ft	< 25 sec.*
Rotation	+105°/-195°	< 42 sec. between endpoints*
Sideshift	± 800 mm	< 26 sec.*
Mechanical pile slope (MPS)		± 2°
Hydraulics	operating pressure up to	140 bar
	flow	40-60 L/min
Electric - control voltage		24 VDC
Colour		Black grey RAL 7021
Paint thickness		150 µ

* Calculated speed at 20° C.

All specifications are subject to change without notice. A list of options enables you to adapt the spreader more precisely to your needs and further information is available on request.

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