Investigation of hydraulic interference in a loader crane

Spring progress report for PROJECTH3

Authors:
Robert Axelsson- Sjöblom
Anton Dahlqvist
Alexander Gratner
Johan Kuylenstierna
Hjalmar Lundin
Ludvig Michaelsson

Daniel Ohlsson
Robert Regula
Jitin Thomas
Isak Westin
Yantong Zhang

Supervisors:
Björn Möller
Tahir Qureshi

Last revised on May 25, 2015

Abstract

This project is conducted by a team comprised of students undertaking their M.Sc. in Mechatronics at the Royal Institute of Technology (KTH). The project is a collaboration between KTH and Hiab, a company seated in Hudiksvall providing load handling solutions , wherein a team of 11 students work over three study periods (between March and December 2015). The aim of the project is to verify already existing models of the Hiab XS 022, followed by the design and implementation of a velocity controller to obtain linear input-to-output signal relation. If these goals are achieved, a tip point controller will be developed and implemented on the Hiab XS 022.

This report is prepared after one period of work, and contains mainly details of pre study and state of the art (SOTA), the project plan, the requirements and the critical function prototype. A high level plan for the Autumn semester (September to December 2015) is also mentioned in this report.

Acknowledgements

Acronyms

This section presents all the acronyms used in this report along with their respective meaning. The list is ordered and grouped alphabetically (i.e. all acronyms that start with the same letter are grouped together).

AFC acceleration feedback control

AIDC adaptive inverse dynamics control

CAD computer aided design

KTH Royal Institute of Technology

LQG linear-quadratic-Guassian

LQR linear-quadratic regulator

MBC model based control

MIMO multiple-input-multiple-output

MPC model predictive control

MRAC Model reference adaptive control

NMBC non-model based control

NMPC non-linear model predictive control

ODE ordinary differential equation

PFF passive feed-forward

PID proportional-integral-derivative

PPC pole placement control

RGA relative gain array

RMS root mean square

SIMO single-input-multiple-output

SISO single-input-single-output

SMC sliding mode control

SOTA state of the art

VSC variable structure with sliding mode

WBS work breakdown structure

WCB WiFi CAN Bridge

Nomenclature

This section presents the nomenclature used, i.e. the symbols used and the explanation of these.

$\mathcal{H}$ The Hardy space, a space of distribution, originally defined as values of harmonic functions

ρ Density of the hydraulic oil

C_d Discharge coefficient, ratio of actual discharge to theoretical discharge

C_f Vascular resistance, flow divided by pressure differentiate

p Pressure of the hydraulic oil

q Flow rate of the hydraulic oil

Contents

Chapter 1   Introduction

This chapter serves as a general introduction to the project presented. It includes the background, the purpose and problem description, the project scope as well as methods used.

1.1   Background

The project is conducted as a collaboration between the Royal Institute of Technology (KTH) and the Swedish company Hiab. It features a team of M.Sc mechatronic students tasked to improve the operation of a loader crane (specifically, model Hiab XS 022) that is manufactured by the company.

Loader cranes are also known as knuckle-boom cranes or articulating cranes. These names stem from the fact that there are jointed boom sections which together forms an articulated arm. This form factor allows the crane to be mounted on a truck (see fig. 1) and occupy little space when it is in its folded position.

Figure 1. A Hiab XS 022 loader crane mounted on a small truck

The lifting capacity of these type of cranes is denoted in tonne-meters ($\mathrm{t\,m}$). This is because the varying distance from the base to the load produces different stress. The Hiab XS 022 has a capacity of $2.2\,\mathrm{t\,m}$ to $2.6\,\mathrm{t\,m}$. (Cargotec, 2015)

The loader crane consist of four actuators in the form of hydraulic cylinders. There are two approaches to supplying hydraulic oil to the actuators. Option one is using closed center valves and variable displacement pumps which can adapt the flow from the pump. Option two is using open center valves with fixed displacement pumps, which instead deliver a constant flow of hydraulic oil.

The open center valves are cheaper and more reliable. For this reason, Hiab would like to keep offering their clients this type of solution. However, due to the constant oil flow from the pump, the various functions may interfere with each other. This interference occurs when multiple actuators are enabled at the same time and since the flow is constant, the oil will choose the path of least resistance. This may result in one or more functions stopping until the remaining ones are finished with their movement. The goal of this project is to investigate the ability to counteract these interferences.

An earlier project was conducted by a team of M.Sc students in mechatronics regarding open-center valves during 2014. The project produced non-verified models of the hydraulics and mechanics of one of Hiab cranes. These models will serve as a starting point when approaching the task concerning this project.

1.2   Purpose

The goal of the project carried out in 2014 was to derive a model of the whole crane, with an open center valve and use that to create a velocity controller. Since these final goals were not reached, the goals are inherited into this project.

In order to reach those goals the model has to be verified such that it corresponds to the physical crane. Specifically, parameters and constants that are estimated has to be evaluated.

Moreover, the overall goal is to use the model to create a linear velocity controller so all cylinders can actuate simultaneously. This is to be accomplished by controlling the open center valve so that the oil flow is shared amongst the functions, proportional to the user input. If this is achieved, the next step is to design a tip point velocity controller. This controller should make it possible to, from a single input, move the tip point in a straight line with a constant velocity, i.e. a Cartesian reference signal.

From the team's aspect, the goal is to carry out a project from start to finish and to gain knowledge and experience while doing so. In the spring period, focus is on planning of the project. The goals are to define verifiable requirements, deliver a state of the art report and implement an interface for the communication with the crane i.e. reading sensors and sending reference signals. Later in the fall, the goals are to verify the old model and also design and implement a velocity controller. From a learning perspective and for the interest of the project group, another goal is to learn hydraulics and different methods of hydraulic control.

1.3   Scope and delimitations

The delimitations chosen on the project are mostly based on the availability of hardware at the premises of KTH. Additionally, the scope will be limited by time restrictions. The main delimitations regarding the project goals are presented below.

- The project will only consider modeling and controlling the Hiab XS 022, it will not focus on making a general model applicable for all loader cranes. This delimitation comes from time restrictions as well as that there is only this specific model available for testing and verification. This limitation includes the valve model and other hydraulic peripherals mounted on the crane.

- The project will only consider the interference in regards to different loads and three of the four functions available on the test crane. The slew will be disregarded. This delimitation comes from the risks of using the slew given the crane's position in the lab hall.

- The project will focus on the crane in the lab hall, it will not consider eventual differences to the models that may occur when the crane is mounted on e.g. a truck.

Further, delimitations regarding which theories and literature to study will be influenced by the project goals. The main delimitations regarding these aspects are presented below.

- The project will not consider black box models of the crane. Because of the system complexity and multiple input-output characteristics, black-box models of the entire crane will likely not be accurate enough to base controllers on.

- The project will not consider aspects such as energy consumption, e.g. making a controller that will regulate the truck motor.

1.4 Method

The project is approached by the agile Scrum methodology complemented with a more in-depth organizational structure where the group members are allocated to seven areas of responsibilities. A work breakdown structure (WBS) is completed to facilitate the procedure of creating the tasks related to the development process. Moreover, the WBS constitutes as a foundation for a risk analysis aimed at bringing forth potential hazardous scenarios related to the project. The aforementioned topics are further expanded upon in the project plan which can be found in Appendix A.

This project report is divided into two main parts. One part comprises a state of the art (SOTA) research within the field of hydraulics control theory. This research focuses heavily on literature studies within the field. The other part is mainly focused on understanding the structure of previous year's models and developing criteria and test cases from which these models can be verified. It also contains improvements of last years hardware mounting. This part is titled the critical function prototype.

Chapter 2   State of the art analysis

This chapter describes the state of the art analysis performed in the beginning of the project. An introduction and several control theories are presented.

2.1   Introduction

The main scope of the state of the art (SOTA) is to find the best control strategy applied to hydraulic systems with multiple inputs and outputs. It will cover different control strategies for both model based control as well as for non model based control. The result from the following research should provide the right knowledge to decide which control strategy that best fits this application.

The literature review will not cover hydraulic modeling. The previous Hiab project focused their research mainly about modeling and therefore this material will instead be used if any further improvements have to be done with the model.

2.2   Model-based control

In model based control (MBC), control approaches stem from process models. From these, the control signals and variables to be controlled can be identified and studied.

There are several different approaches for MBC. Overall, it's about first designing a model for the plant to be controlled. This model dynamics is mainly described by suitable mathematical equations. The MBC structure relies heavily on the effectiveness of modelling. A controller based on an inadequate model will not work as expected all the time. MBC works well when plants are relatively easy to model but as the plants get too complex these control strategies drop in effectiveness. (Wang, 1997, p. 837)

Using this approach, control methods include proportional-integral-derivative (PID) control, lead-lag control, linear-quadratic-Guassian (LQG) control, $\mathcal{H}_\infty$ control, and model predictive control (MPC). All of these will be described below..

2.2.1   PID control structures

The proportional integral derivative (PID) control structure is one of the most commonly used feedback control structures in the industry today (REF). The ideal version of a PID controller in time domain can be described as

$$u = \underbrace{k_P e(t)}_{Proportional} + \underbrace{k_I \int e(\tau)d\tau}_{Integral} + \underbrace{k_D \frac{d}{dt}e(t)}_{Derivative}, \tag{1}$$

where u is the control signal and e is the error signal defined as the difference between the reference r and the output signal y according to

$$e = r - y. \tag{2}$$

Moreover, the constants k_P, k_I, k_D represent the proportional, integral and derivative parts respectively.

The control loop associated with a PID controller can be designed using either one, two or three degrees of freedom. The one degree of freedom design is shown in fig. 2.
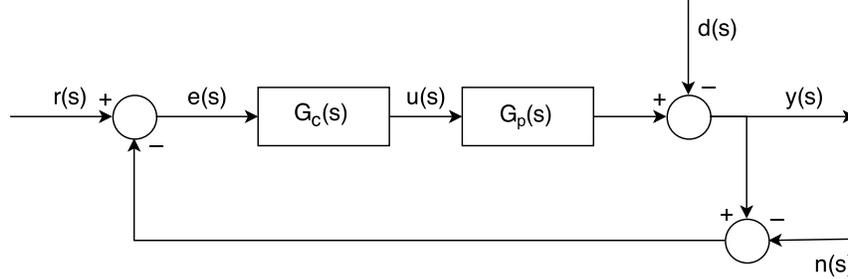
Figure 2. A one-degree-of-freedom PID controller design

The Figure shows the plant model G_p, the control model G_c, the measurement disturbance $n(s)$ and the noise disturbance $d(s)$. It also shows the reference signal r, output signal y and the error signal e. Although this one degree of freedom design is the most commonly used, it results in a control structure where the measurement noise can not be attenuated independently of the reference signal. The closed loop transfer function

$$y(s) = \left[\frac{G_p(s)G_c(s)}{1 + G_p(s)G_c(s)} \right] (r(s) - n(s)) + \left[\frac{1}{1 + G_p(s)G_c(s)} \right] d(s) \tag{3}$$

further illustrates the dependence between the reference signal and the measurement signal for the output, y. A two degree of freedom design solves this problem by providing the user with two different control components, one which is related with loop stability and another which can shape the closed-loop response. This design is shown in fig. 3.
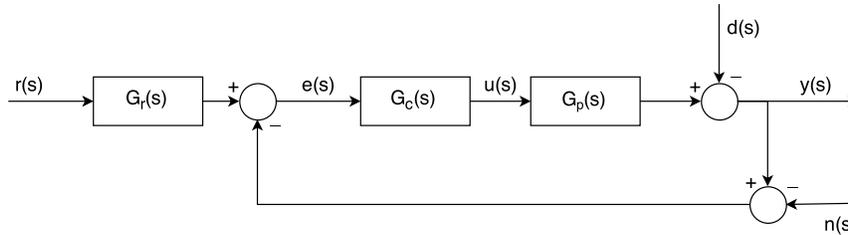
Figure 3. A two-degree-of-freedom PID controller design

The closed loop transfer function

$$y(s) = \left[\frac{G_p(s)G_c(s)G_r(s)}{1 + G_p(s)G_c(s)} \right] r(s) + \left[\frac{G_p(s)G_c(s)}{1 + G_p(s)G_c(s)} \right] n(s) + \left[\frac{1}{1 + G_p(s)G_c(s)} \right] d(s) \tag{4}$$

for this design shows how the added transfer function block $G_r(s)$ affects the closed loop response. Furthermore, a three degree of freedom model is shown in fig. 4.
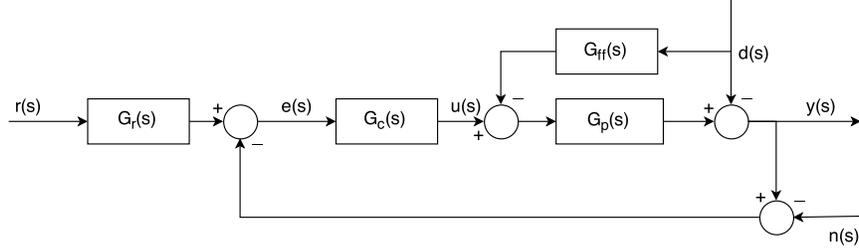
Figure 4. A three-degree-of-freedom PID controller design

This design has introduced yet another transfer function block G_{ff} which enables another degree of freedom. As the closed loop transfer function

$$y(s) = \left[\frac{G_p(s)G_c(s)G_r(s)}{1 + G_p(s)G_c(s)}\right] r(s) + \left[\frac{G_p(s)G_c(s)}{1 + G_p(s)G_c(s)}\right] n(s) + \left[\frac{1 - G_p(s)G_{ff}(s)}{1 + G_p(s)G_c(s)}\right] d(s) \tag{5}$$

shows, this block enables a more independent control of the noise disturbance affecting the system (Johnsson and Moradi, 2005, p. 57-59).

2.2.2 Lead-Lag controller

The Lead-Lag compensator is a control structure consisting of a Lead and a Lag term. The structure can be represented in many ways, below is one example (Ljung and Glad, 2006, p. 109).

$$F(s) = K \underbrace{\frac{\tau_D s + 1}{\beta \tau_D s + 1} \frac{\tau_I s + 1}{\beta \tau_I s + \gamma}}_{Lead \qquad Lag}. \tag{6}$$

By using a Lead-Lag compensator a pole-zero is added to the open loop transfer function of the system. The lead compensator gives phase at high frequencies, shifting the poles to the left, leading to a higher stability and responsiveness of the system. The lag compensator introduces phase at low frequencies, resulting in lower steady state error (Ljung and Glad, 2006, p. 105).

The desired pole and zero location depends on the closed loop response as well as on the system being controlled. It should be kept in mind to keep the pole and zero close together, not further than a factor of ten from each other, to prevent poles from shifting to the right, which would cause instability or slow convergence. Ultimately they should be placed near the origin to affect the low frequency behaviour (Levine, 1996, p. 196).

When implemented the Lead-lag controller is expressed as an integral equation, because when differentiating signals the noise gets amplified. Integrators are the most numerically stable when implemented.

The Lead-Lag compensator may be designed in several ways depending on the constraints. Below is an approach where the compensator is designed in two separate steps (Babuska, 2011). The Lead compensator is designed as follows

1. Determine the desired crossover frequency ω_c.

2. Calculate how much extra phase the lead compensator must add at ω_c and then calculate β and τ_D.

3. Compute the overall controller gain K such that ω_c becomes the crossover frequency.

4. Check whether the bandwidth specifications are met, if not, recalculate a new ω_c.

and the Lag compensator part as follows

1. Determine the DC gain $1/\gamma$ of the lag compensator to meet the steady-state requirements.

2. Choose τ_I between $2/\omega_c$ and $10/\omega_c$.

3. Check whether all the control specifications are met, if not, revise.

The advantages with the Lead-Lag compensator is that it gives a low frequency phase and a high frequency roll-off. However, it is slightly more complicated to implement than a PID-controller.

2.2.3 Decentralized control system

An interactive multiple input/multiple output (MIMO) process can be controlled by either a centralized multivariable controller, or if it is possible, a decentralized multi-loop controller which consists of a set of single input/single output (SISO) controllers. The big difficulties with cross-coupled controllers are their complexity and that they are weak in control-system integrity (Xiong et al., 2006). Consider an multi-variable process plant with the transfer function

$$G(s) = \begin{bmatrix} g_{11} & \cdots & g_{n1} \\ \vdots & \ddots & \vdots \\ g_{1n} & \cdots & g_{nn} \end{bmatrix} \tag{7}$$

Decentralization of the system refers to disregarding cross couplings and treat one loop at the time as if the other inputs and outputs didn't exist. A controller that satisfies this condition is

$$G_c(s) = \begin{bmatrix} g_{c1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & g_{cn} \end{bmatrix} \tag{8}$$

This means that the sub-part of the controller G_{ci} is only based on the measured signal y_i and its reference r_i. Decentralized controllers are always square, so if the number of outputs exceed the number of inputs some need to be disregarded. The cross couplings from the off-diagonal elements that are disregarded in the control structure may affect both the stability and the performance of the closed loop system. If no interference between the cross couplings exist, then the system can be seen as different uncorrelated systems (Glad and Ljung, 2000, p. 221).

How to map which input to which output in order to get the least amount of cross coupling is an important part of making sure that the system has the ability to be decentralized. This is called the pairing problem and it also includes the problem of knowing which measurements to use when the number of outputs exceeds the number of control inputs.

The relative gain array (RGA) is an indicator for the stability of a decentralized controller. It is defined by Glad and Ljung (2000, p. 219) as

$$RGA(G) = G \otimes (G^{-1})^T \tag{9}$$

Two conditions that that determine whether the decentralized system is stable or not are as follows

- If a decentralized controller is stable in each single-input-single-output (SISO) loop, and if $RGA(G(i\omega)) = I$, then the closed loop system is also stable. I is the identify matrix with the same size as $G(i\omega)$ (Glad and Ljung, 2000, p. 222)

- If some diagonal element of $RGA(G(0))$ is negative, and a diagonal controller is used, then either the closed loop system is unstable, or it will become unstable if one of the SISO loops are broken. (Glad and Ljung, 2000, p. 222)

A pairing rule according to Glad and Ljung (2000, p. 222) can be derived from the first condition as

- Make the diagonal elements of $RGA(G(i\omega_c))$ as close to the point 1 in the complex plane where ω_c is the intended cross-over frequency of the closed loop system.

If the system is stable then the multi-loop feedback system can always be made stable provided the loop gains are de-tuned to be sufficiently small. De-tuning means adding a common factor to all loops such that the overall system is stable and gives acceptable load disturbance rejection responses. If the conditions above are not met, or if it's difficult to see which input that matches which output, an alternative is to try to make a dynamic decoupling of the system. This means that the controller compensates so that the system can be treated as a decentralized system (Johnsson and Moradi, 2005, p. 107). The decoupling method uses two weighted matrices to transform the transfer function matrix, G, into the matrix

$$G_{diag} = W_2 \begin{bmatrix} g_{11} & \cdots & g_{n1} \\ \vdots & \ddots & \vdots \\ g_{1n} & \cdots & g_{nn} \end{bmatrix} W_1 \tag{10}$$

which is as diagonal as possible. The weighted matrices W_1 and W_2 can be chosen dynamically or real valued. Dynamical matrices suits all frequencies whilst real valued matrices are chosen to compensate at selected frequencies. The matrices are typically related to to the system matrix G and requires a good knowledge of the plant model (Glad and Ljung, 2000, p. 226).

A drawback with using a decentralized controller is that only steady-state information is used in the design, which limits the controller performance (Xiong et al., 2006). The controller is not adaptive to changes in the model parameters, e.g. different loads or even different states of the system. This can be solved by introducing different multiple SISOs for different loads and for different states of the system with some kind of condition when the system changes which controller is used. However, the complexity of the system increases with multiple controllers which contradicts the purpose of making a decentralized controller.

Some advantages with a decentralized control system if implemented are, according to Xiong et al. (2006), that the structure is easier to understand and to implement, it requires fewer parameters to tune, and loop failure tolerance of the resulting control can be evaluated during the design phase.

2.2.4 Model predictive control

The MPC is a control approach that predicts the outcome of a specific model. The idea with MPC is to use the model as a reference point and, in real time, calculate multiple paths that can be taken by assigning different values for the controlled variables and look at the system model response. An algorithm is implemented that goes through the different paths and choses the control action that is closest to the desired outcome within a specified timespan. The approach allows for specifying rules and constraints which the controller takes into consideration when choosing the appropriate control action and can in some cases sacrifice the short term properties to optimize for the long term outcome. (Anderson et al., 2007)

MPC can be used with either a model design based on ordinary differential equation (ODE) or as a fuzzy model, for example neural networks. However, the use of the MPC approach shifts the problem of creating a controller to the modeling part. This due to simpler implementation of a controller, especially when dealing with multiple-input-multiple-output (MIMO) systems, but it needs a good model to correctly predict the different outcomes and take the appropriate path. Apart from MIMO it can also be implemented in single-input-multiple-output (SIMO) systems which will have lower computational time due to fewer possible paths. (Anderson et al., 2007)

The approach can be shown in a few very general and flexible steps that has to be customized to fit the model and controller that is to be created. (Glad and Ljung, 2000, p.383) & (Anderson et al., 2007)

1. Create a very accurate model of the system, either an ODE or fuzzy model. And set desired constraints and rules for the system.

2. Use the current conditions, at time t, as the initial conditions.

3. Compute or predict a set of candidate control actions based on the initial conditions within a finite timespan.

4. Based on these control actions, choose the outcome that is within the error margin and has the shortest path, i.e. optimize that control action with respect to some conditions.

5. Apply the control action to the physical plant.

6. Observe the system and wait for the next sample, at time $t + 1$, and iterate from step 2.

Using the MPC approach come with some advantages compared to other control approaches, such as regular PID controllers etc. It allows the programmer to specify constraints and rules, e.g physical constraints on the plant, that needs to be met. Due to the long term view of the controller it will also go through less undesirable states to get a large return as well as anticipate consequences of a specific control action.

The disadvantages are mostly due to the predictions being based on the model. A very inaccurate model can cause poor control decisions. The algorithm for the prediction can be very computationally demanding for a big MIMO system and poorly written algorithms might result in a path that includes an undesirable state before reaching the desired outcome. (Anderson et al., 2007)

2.2.5 Linear-quadratic-Gaussian controller

The LQG control problem is to find the optimal control u(t) which minimizes the deterministic cost, i.e

$$J_r = \int_0^\infty \left(x(t)^T Q x(t) + u(t)^T R u(t) \right) dt \tag{11}$$

where Q and R are design parameters, x is the system state and u the control signal. This is solved by using two different algebraic Riccati equations which depends on A, B, C, Q and R. (Skogestad and Postlethwaite, 2005, pp. 375 − 385)

Assuming a system

$$\begin{aligned} \dot{x} &= Ax + Bu + w \\ y &= Cx + v \end{aligned} \tag{12}$$

where w and v are zero mean white Gaussian noise, A, B and C are state space matrices and y is the output signal. If this system is linear and the cost is described by a quadratic function, see eq. (11), this is called a LQ-problem. to control this system the LQG controller is then designed in two steps, which is also called the separation theorem. First, the linear-quadratic regulator (LQR) is used to determine the optimal controller to this LQ-problem without noise. This gives the control signal

$$u(t) = -K_r x(t). \tag{13}$$

Second is to find the optimal estimate $\hat{x}$ of x such that the quadratic error, i.e.

$$E\left\{ [x - \hat{x}]^T [x - \hat{x}] \right\} \tag{14}$$

is minimized using the Kalman filter. This gives a control signal

$$u(t) = -K_r \hat{x}(t). \tag{15}$$

The LQG controller is relatively easy to design and to compute for both SISO and MIMO. Since the LQG controller uses the same methodology independently of the number of state variables and input and output signals, it fits well for this projects purpose. However, some problem with stability and robustness suggests this should be investigated further. (Athans, 1986, pp. 2 − 3)

The quality of the approximated feedback loop depends on the system model. To get an arbitrary good approximation, the system should be minimum-phase (all poles and zeros lies in the unit circle for a discrete-time system for example). If the system is non-minimum-phase, the correctness of the approximation will depend on the location of the specific non-minimum-poles.(Athans, 1986, p. 3)

In general, a more accurate sensor gives a more accurate estimation. However, the increase in control accuracy is not necessarily improved by much with a better sensor. The difference in sensors only affect the last term (out of four) in the evaluated cost function. Moreover, the difference in accuracy for the actuators is slightly more important since they affects the last two terms in the same function. (Athans, 1971, p. 547)

2.2.6 $\mathcal{H}_\infty$-control

The $\mathcal{H}_\infty$ norm of a stable scalar transfer function is simply its peak value as a function of frequency, i.e.

$$\|f(s)\|_\infty \equiv \max_\omega |f(j\omega)| \tag{16}$$

where it's peak value can be defined as

$$\max_\omega |f(j\omega)| = \lim_{p\to\infty} \left(\int_{-\infty}^{\infty} |f(j\omega)|^p \mathrm{d}\omega \right)^{1/p} \tag{17}$$

since raising $|f(j\omega)|$ to an infinite power will result in the peak value. This makes $\mathcal{H}_\infty$ a purely mathematical term. The control design method simply aims to press down the peaks of one or more selected transfer functions. The $\mathcal{H}$ is the Hardy space, a set of stable and proper transfer functions. Replacing infinity with 2 in the eqs. (16) and (17) equals $\mathcal{H}_2$ instead (i.e. the Hardy space with square norm). (Skogestad and Postlethwaite, 2005, p. 60)

Skogestad and Postlethwaite (2005, p. 385) argues that the method is motivated by the shortcomings of LQG, which are mainly its poor robustness properties. LQG is a special case of $\mathcal{H}_2$ optimal control.

Given a standard configuration of the system (see fig. 5),
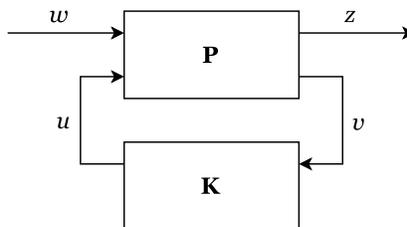
Figure 5. The standard configuration of multivariable systems

the system equations can be set up as

$$\begin{bmatrix} z \\ v \end{bmatrix} = \mathbf{P}(s) \begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix}$$

$$u = \mathbf{K}(s)v \tag{18}$$

where z is the error signals that are to be minimised and the measured variables v that are used to control the system. By expanding the matrix operations, it can be noted

$$z = f(\mathbf{P}, \mathbf{K})w = \left(P_{11} + P_{12}\mathbf{K} \left(I - P_{22}\mathbf{K} \right)^{-1} P_{21} \right) w. \tag{19}$$

Using $\mathcal{H}_\infty$ control, the goal would be to find a controller $\mathbf{K}$ such that $f(\mathbf{P}, \mathbf{K})$ is minimised according to eq. (17). The controller can be found using several different methods, including $\mathcal{H}_\infty$ optimal control, mixed-sensitivity $\mathcal{H}_\infty$ control, signal based $\mathcal{H}_\infty$ control, $\mathcal{H}_\infty$ loop shaping, etc. (Skogestad and Postlethwaite, 2005, pp. 390–400)

The techniques have the advantage over classical control techniques in the sense that they are applicable to problems involving multivariable systems with cross-coupling. However, since the controller will be optimal in the formulated sense a good model of the system to be controlled is needed. Additionally, the mathematics behind the control strategy might be difficult to understand. (Cubillos and de Souza, 2009, p. 4)

2.2.7 Exact Linearisation

Exact Linearisation Non-linearities within systems can be helped by introducing inner loops. A systematic way of introducing inner loops which removes these non-linear behaviours completely is called exact linearisation. There are generally two different control techniques associated with exact linearization, input/output linearization and input/state linearization. In order to describe these two approaches, consider the system

$$\begin{cases} \dot{x} = f(x) + ug(x) \\ \quad y = h(x) \end{cases}, \tag{20}$$

where the control signal, u, and the output signal, y, are scalars. Furthermore, the functions f,g and h are indefinitely differentiable.

Input/output linearization is a control technique where the output y of the non-linear system is differentiated until a physical input u appears in the r^v derivative of y according to

$$\begin{bmatrix} \dot{y} \\ \ddot{y} \\ \vdots \\ y^{v-1} = \alpha(x) + \beta(x)u \end{bmatrix}, \tag{21}$$

where $\beta(x)$ and $\alpha(x)$ are linear functions of x. The sign v is the relative degree of the system which is the smallest integer which satisfies the equation

$$\underbrace{\left(g_1 \tfrac{\partial}{\partial x_1} + \ldots + g_n \tfrac{\partial}{\partial x_n} \right)}_{L_g} \underbrace{\left(f_1 \tfrac{\partial}{\partial x_1} + \ldots + f_n \tfrac{\partial}{\partial x_n} \right)^{v-1}}_{L_f} h(x) \not\equiv 0 \tag{22}$$

where L_f and L_g are the lie derivatives. The feedback, u, is then chosen as a transfer function dependent on a synthetic output

$$y^{v-1} = v \tag{23}$$

which gives

$$u = \frac{1}{\beta(x)}[-\alpha(x) + v]. \tag{24}$$

The closed loop system can then be written on the form

$$\frac{y(s)}{v(s)} = \frac{1}{s^{v-1}}.$$ (25)

This system which is the result from an input/output linearization may contain inner dynamics. This approach is therefore only suitable when the zero dynamics of the resulting system are well behaved. Otherwise, a input/state linearization solution should be explored instead (Glad and Ljung, 2000, p. 401) (Hedrick and Girard, 2005, p. 140). This technique aims to find a state feedback control

$$u = \alpha(x) + \beta(x)v$$ (26)

as well as change variables

$$z = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix} = \begin{bmatrix} \dot{y} \\ \ddot{y} \\ \vdots \\ y^{n-1} \end{bmatrix} = \begin{bmatrix} h(x) \\ L_f h(x) \\ \vdots \\ L_f^{n-1} h(x) \end{bmatrix}$$ (27)

that will transform eq. (20) to

$$\begin{cases} \dot{z} = Ax + Bv \\ y = h(T^{-1}(z)) \end{cases}$$ (28)

which is a linear system that can be controlled by appropriate control techniques.

Methods which utilizes feedback linearization has successfully been applied to a number of practical non-linear problems (Lemmen and Bröcker, 2000; Kwon et al., 2006). It can be used for both SISO and MIMO systems for stabilization and tracking control problems. On the negative side, feedback linearization cannot be used in all systems due to singularities, it also requires states to be measures which are not always possible. It also needs an accurate model because parameter uncertainty and not modelled dynamics will cause a non-robust controller (Hedrick and Girard, 2005, p. 136).

2.2.8 Sliding mode control

In sliding mode control (SMC), the main idea is to design a sliding surface, where a chosen parameter $\sigma = 0$, in the state space which divides the space into two disjoint subspaces ($\sigma < 0$ and $\sigma > 0$). Both subspaces then "direct" the system states towards that surface so they can "slide" on it towards desired control output, this is illustrated in fig. 6. Once the system state has joined the surface, it stays there. (Husson, 2009)
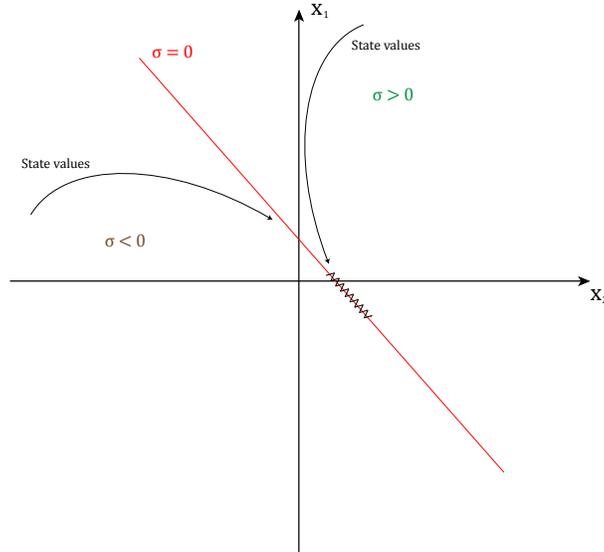
Figure 6. Illustration of the SMC.

The SMC has a variable structure, i.e. it's discontinuous. It was a result of studies to find a controller which was insensitive to variations of the system. This is also why the controller can be designed for both linear and non-linear systems. (Perruquetti and Barbot, 2002)

One condition for a sliding mode to exists (that the controlled system is stable) is that the sliding surface is attractive. This basically means that the system states always should move towards the sliding surface. Another condition for a sliding mode to exist is that system equations should meet the Lipschitz condition which guarantees that a unique solution exists for all states.

2.2.9   Model reference adaptive control

Model reference adaptive control (MRAC) is a control approach that adjust the control parameters to make the physical plant follow a specific output given by a reference model with the same input. This approach consists of three parts, see fig. 7, a reference model to give the desired response of the system, a controller of some sort with adjustable parameters and lastly an adjustment mechanism that is used to update the controller parameters to allow the physical plant to follow the reference model. (Jain and Nigam, 2013)
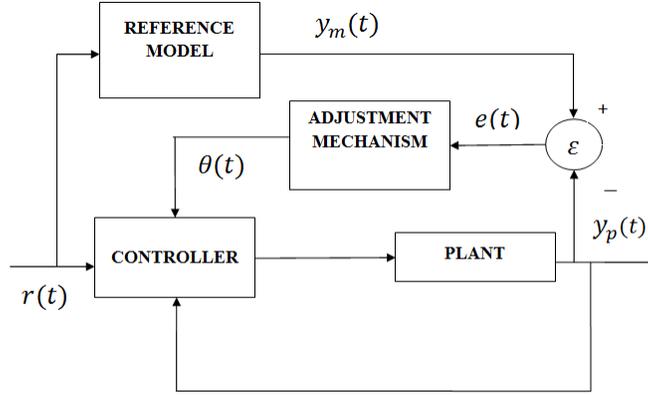
Figure 7. Inner and outer loop for the MRAC approach

There are many different methods of how to adjust the control parameters, one of them is the MIT rule that is built around the assumption that the adjustable parameters change more slowly than other variables within the system. (B.M. Vinagre and Chen, 2002) This MIT rule, by Jain and Nigam (2013), works by introducing a cost function

$$J(\theta) = \frac{e^2}{2} \tag{29}$$

where e is the error between the physical plant and the reference model output and θ is the parameter that is to be adjusted. The idea is to adjust θ in a way that allows the cost function to be minimize to zero. That means that the change of θ will follow the negative gradient of J and can be written as

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} \tag{30}$$

which combined with eq. (29) gives

$$\frac{d\theta}{dt} = -\gamma e \frac{\partial e}{\partial \theta} \tag{31}$$

where γ is the adaptive gain of the controller.

The partial equation $\frac{\partial e}{\partial \theta}$ is called the sensitivity derivative and indicates how the error e change with respect to θ. To implement this theory for a specific system, the error between the plant and the reference model is written as the difference between the two transfer functions.

$$E(s) = KG(s)U(s) - K_0 G(s)U_c(s) \tag{32}$$

where K is an unknown parameter, $G(s)$ is the transfer function for the system, $U(s)$ is the control signal, K_0 is a known parameter and $U_c(s)$ is the reference signal.

To introduce the controlled parameter θ into the equation a control law is defined as

$$u(t) = \theta u_c \tag{33}$$

15

which gives the following combined with equation eq. (32)

$$E(s) = KG(s)\theta U_c(s) - K_0 G(s) U_c(s). \tag{34}$$

Using the sensitivity derivative and then restate the equation in terms of model output gives the following equation

$$\frac{\partial E(s)}{\partial \theta} = KG(s)U_c(s) = \frac{K}{K_0} Y_m(s) \tag{35}$$

where $Y_m(s)$ is the model output.

From this, the MIT law can be concluded which gives an expression for updating the controlled parameter θ as

$$\frac{\partial \theta}{\partial t} = -\gamma e \frac{K}{K_0} y_m = -\gamma\prime e y_m \tag{36}$$

where $\gamma\prime$ is the adaptation gain.

Choosing the adaptation gain is a crucial part of the control approach and is the basis to get a good system response. Often this value is to be kept relatively low due to experience from some industrial plant has shown that large values might cause instability of the system.

2.3   Non-model-based control

In non-model based control (NMBC) no mathematical models are used for the control design. Instead, the parameters of the controller are mainly determined by using human experience and trial-and-error. NMBC design might be useful when the plant is too complex to model sufficiently, as no dynamic equations or linearizations are needed. As said however, a lot of knowledge and experience are needed to make a suitable controller. (Keshmiri et al., 2012, p. 16)

As NMBC doesn't depend on a model, it's flexible to changes in load or set-point values. The control parameters can be made self-tuning which in some cases makes the NMBC out-perform the MBC, especially in more complex dynamic systems.(Wang, 1997, p. 837)

Some of the different NMBC methods are described further below.

2.3.1   Fuzzy control

In fuzzy control there is a more significant emphasis on the use of heuristics. There is a focus on the use of rules to represent how to control the plant rather than ODE. This approach can offer some advantages in that the representation of knowledge in rules seems more lucid and natural to some people. For others, though, the use of differential equations is more clear and natural. Basically, there is simply a language difference between fuzzy and conventional control: ODEs are the language of conventional control, and rules are the language of fuzzy control. (Passino and Yurkovich, 1998, p. 11)
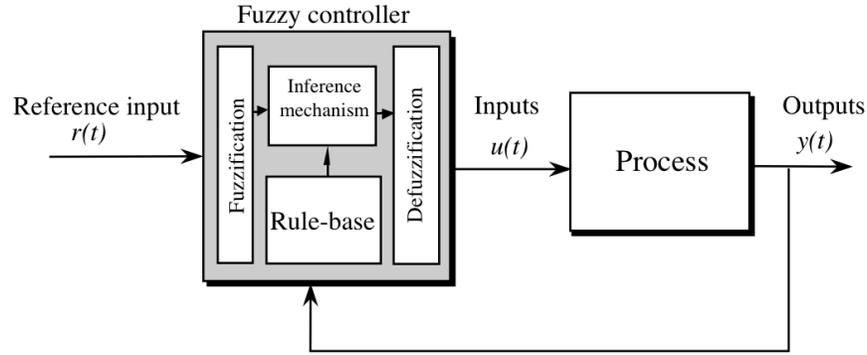
Figure 8. Fuzzy controller architecture

Passino and Yurkovich (1998, p. 11) argue that fuzzy control provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system. The controller has four main components:

1. The "rule-base" holds the knowledge, in the form of a set of rules, of how best to control the system.

2. The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be.

3. The fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base.

4. The defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the plant.

To design the fuzzy controller, the control engineer must gather information on how the artificial decision maker should act in the closed-loop system. Sometimes this information can come from a human decision maker who performs the control task, while at other times the control engineer can come to understand the plant dynamics and write down a set of rules about how to control the system without outside help. These "rules" basically say, "If the plant output and reference input are behaving in a certain manner, then the plant input should be some value." A whole set of such "If-Then" rules is loaded into the rule-base, and an inference strategy is chosen, then the system is ready to be tested to see if the closed-loop specifications are met. Generally speaking, if a very detailed rule-base is implemented, the chances of obtaining a better control performance is enhanced. (Passino and Yurkovich, 1998, pp. 12–13)

2.4 Hydraulic Control Strategies

In Bech et al. (2013), several control structures are studied for tracking of a hydraulic robot arm to find the optimal control strategy. Both linear and non-linear controllers are analyzed. Results show that pressure feedback and state space control increases the performance over classical linear structures, while passive feed-forward (PFF) control gives the best performance of the linear controllers. However, all the non-linear control designs shows superior performance to the linear ones. Findings show that all the non-linear control structures have relatively small root mean square (RMS) errors compared to the linear ones. These include SMC, adaptive inverse dynamics control (AIDC), AIDC combined with a PI-controller and MRAC.

Bonchis et al. (2002) also compares several different control structures on a similar hydraulic system, mainly with position accuracy and robustness in mind. Same as above, findings show that non-linear controllers outperform the linear designed controllers. Best result was given by acceleration feedback control (AFC) using an experimentally identified friction model, MRAC, and variable structure with sliding mode (VSC).

In the analyses, Bonchis et al. (2002) derives three characteristics for an ideal hydraulic controller. These are

- Online self-adjusting controller. Controller changes calculations and parameters on-the-go depending on some adjustments algorithm. Such as adaptive controllers or auto-tuning PID.

- Low number of parameters to adjust. This is to save computational power. For example, pole placement control (PPC) has no parameters to adjust and MRAC has only the adaptation gain.

- Existence of guidelines for parameter settings. Some guidance on how to select the control parameters. In for example MRAC, the initial trajectory parameters is crucial for good control performance.

However, results also show that self-tuning controllers are not suitable when plant parameters changes quickly.

Kalmari et al. (2014) uses a non-linear model predictive control (NMPC) to control a forestry hydraulic crane. Experiments show that NMPC is a feasible controller for that specific purpose. The NMPC needs a lot of computational power since it always estimates the future states and considers them together with the current state to calculate the optimal controller.

Overall, research suggests that the non-linear control is the way to go for complex systems like hydraulics which is the case in this project. Further investigations have to be made before any decision on exactly which approach to go with. However, this investigation implies that both NMPC and MRAC should be considered.

Chapter 3   Critical function prototype

This chapter describes the accomplished work of a critical function prototype. It includes the work on system models, hardware and electronics as well as the software related to this prototype.

3.1   Revision of system models

The previous project that had the same goal, created a Simulink model of the system including both the hydraulic subsystem and the mechanical subsystem. The hydraulic subsystem depends primarily of two basic equations. The first is used to calculate the flow of hydraulic oil the equation as

$$q = C_d A_0 \sqrt{\frac{2}{\rho} \Delta p} \tag{37}$$

where q is the flow, C_d is the discharge coefficient, ρ the density of oil, Δp is the difference in pressure through the orifice and A_0 is the orifice area. The orifice area has been retrieved from the manufacturer and is a function of the spool displacement. The other equation used is the constitutive equation which expresses the compressibility of the oil as

$$C_f \frac{dp}{dt} = q \tag{38}$$

where $\frac{dp}{dt}$ is the derivative of the pressure, q is the flow and C_f the flow resistance. The flow resistance depends on the volume of oil in the hydraulic system and also on the bulk modulus. The equations are implemented in Simulink as seen in fig. 9.
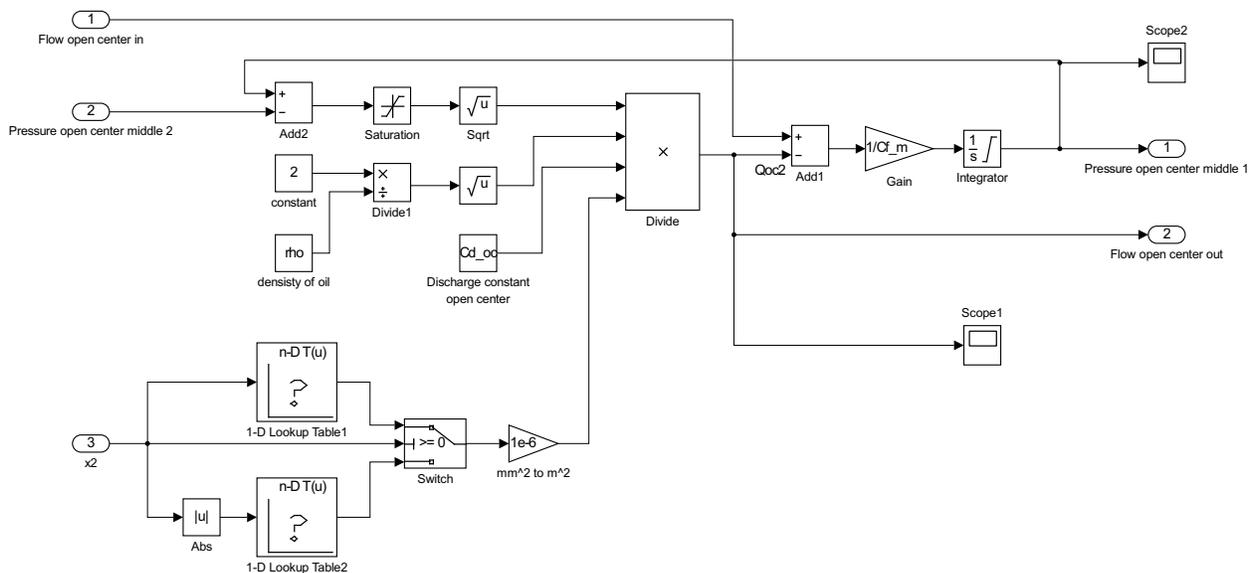
Figure 9. Implementation of the equations in SimuLink

The hydraulic valve consists of different subsystems to calculate the gallery pressure in relation to pump flow and the operator reference, as well as the pressure and flow to the different cylinder work ports in regard to the reference.

Due to lack of solenoid data from the hydraulic valve supplier, the spool dynamics have been black-box modeled. The results of the experimental approach were second-order transfer functions which describes the spool dynamics for the first and second boom, as well as for the extension boom. These transfer functions are defined as

$$G_{S1}(s) = G_{S2}(s) = \frac{-0.246s + 680}{s^2 + 43.0s + 565} \tag{39}$$

and

$$G_{S3}(s) = \frac{-4.12s + 849}{s^2 + 44.4s + 681} \tag{40}$$

The first boom spool and the second boom spool are considered similar mechanically. Therefore, only two functions are derived.

The gallery pressure delivered to the different cylinders is multiplied with their corresponding cylinder area and outputs the resulting force to the mechanical model. The velocity is then returned from the mechanical model and multiplied with the cylinder area which gives the return flow. The mechanical subsystem is generated as a dynamic model with the Simulink extension SimMechanics from a computer aided design (CAD) drawing of the crane.
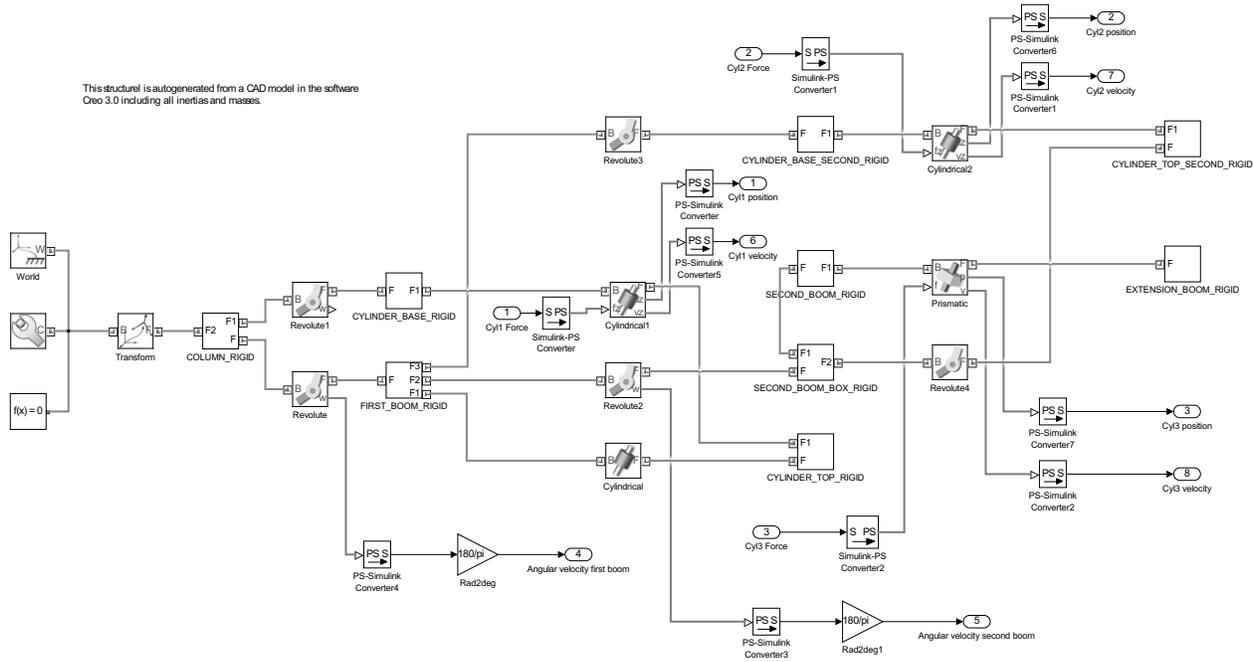
Figure 10. Image of the auto-generated SimMechanics blocks for the mechanical subsystem

As seen in fig. 10, this subsystem is rather complex which is expected of an auto-generated model. The inputs to the system are forces from the cylinders and the output are the corresponding velocities.

3.2 Corrections of system models

The model has not been verified or validated. According to the previous year's findings, the simulated gallery pressure did not correspond to the actual gallery pressure measured and the accuracy of the velocity was unacceptable (Nordenmark et al., 2014, p. 37). In order to achieve better performance, much effort was spent on adjusting the dynamic friction and adding counter-balancing valves to tune their simulation according to measurements, but it did not give reasonable results (Nordenmark et al., 2014, p. 37). In order to locate what in their model that was inadequately modeled, all of the equations were dissected in search for errors that could explain the difference between simulation and measurements.

One fault found is that the spool position to orifice area functions which were retrieved from the manufacturer were wrongly used. The different spools have different areas to reduce the interference. The Simulink model used the wrong area curve for extension boom which could explain some of the problems that occurred in the model. Another fault which is identified is that the slew function is connected as the last part of the open-center valve. According to drawings of the valve and ocular inspection of the crane, the slew is connected as the first function directly from the pump. The impact of this error should however be considered low as the slew function is disconnected for safety reasons, but it may still be a part of the dynamics that generates the gallery pressure.

3.3 Further development on available models

The spool dynamics from operator reference to spool displacement are considered to behave accordingly, but investigation whether the same transfer function can be used for both the first boom and the second boom is needed, as well as a definite quantitative verification.

To reduce the complexity of the Simulink model, an investigation to see if the open-center channel can be simplified ought to be done. At the moment, the pressures between the different open-center channels are calculated but not used, as the work ports all share the same gallery pressure and hence the dynamics may be redundant.

Additionally, in order to simplify the model structure somewhat, the model may need some restructuring. For example, the mechanical subsystem could be reformatted such that it is clearer which blocks belong to which mechanical parts.

To quickly validate the behavior of the existing model, i.e. to ensure that the calculations seem to be producing a qualitatively adequate output, a hydraulics model was designed in SimHydraulics. This Simscape package for Simulink provides hydraulic physical modeling and thus the means of quickly setting up various systems. By restructuring the mechanical model and connecting it to the new hydraulics model, the end result is displayed in fig. 11.
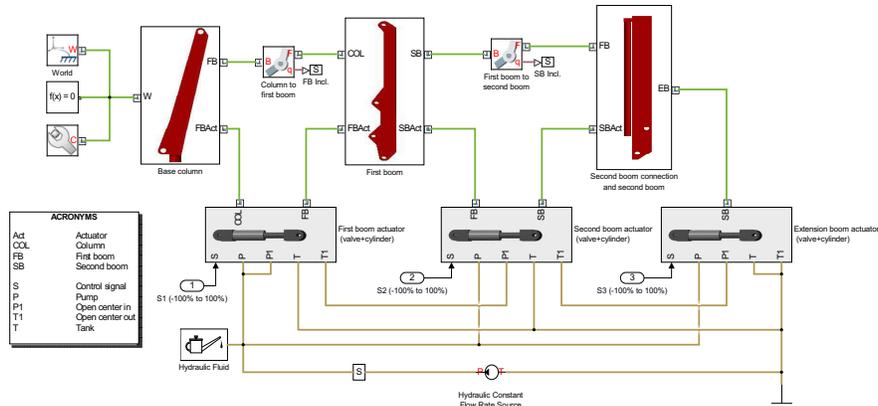
Figure 11. The main layout of the Simscape (SimHydraulics and SimHydraulics) model used for the quick qualitative validation.

The valve and cylinder subsystems are divided into the directional valves and cylinders, as seen in fig. 12. The valve model is constructed of models of variable orifice blocks, using the lookup tables provided by the manufacturer. The valve is then connected to a cylinder, which in turn converts the hydraulic pressure into a force which is input to the SimMechanics model. In return, the velocity is fed back to the cylinder in order to model the back-pressure.
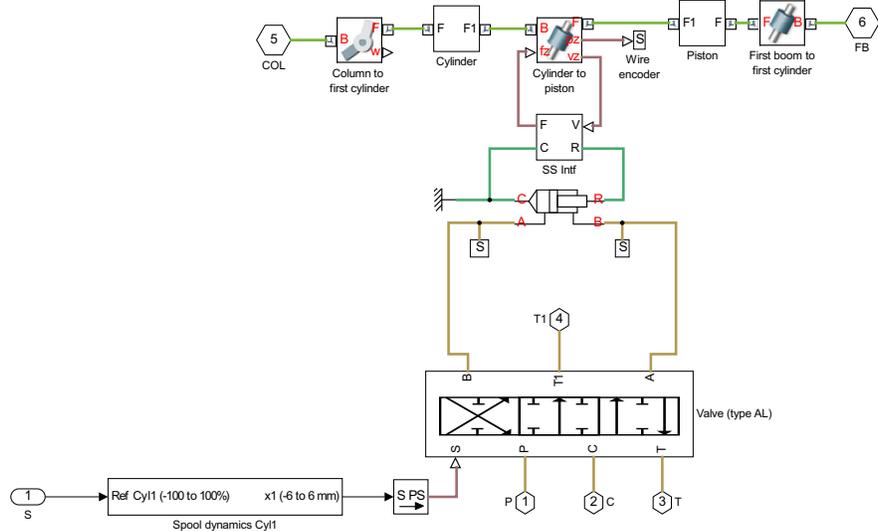
Figure 12. The layout of the hydraulic components and connection to mechanical system

Both of the models (qualitatively) display the same type of behavior, which suggests that the equations are correctly modeled. This returns a starting point for the model verification as it is no longer possible to point out any obvious modeling errors.

3.4 Model verification planning

One of the main purposes of this project is to create a realistic model of the Hiab XS 022. This was attempted by the Hiab project group at KTH last year which resulted in a fairly complex model which they had not been able to verify with the crane currently stationed at KTH.

In order to verify the complete model, the different parameters used in the Simulink must be verified. The impact on the dynamics of the counter-balancing valves as well as the dynamic friction in the cylinders are considered especially uncertain. The stakeholders have bought the counter-balancing valves from a third-party and therefore retrieving the actual documentation is considered difficult.

In order to satisfy the needs of the stakeholders, found in Appendix B, the model has to be verified and modified. This required, primarily, a set of well defined system requirements as well as their corresponding test cases.

The system requirements where derived from the stakeholder requirements provided by Hiab, see Appendix C. Although research was made on the subject of formal specification languages, the requirements where ultimately written in natural language. This was due to the fact that it was deemed unnecessarily complex and time consuming to rewrite the system requirements to formal language. Also, as there is just a small group working with the requirement and test cases, the chance of ambiguity or lack of understanding is small.

The test cases that will be used to verify the model, were at first written as descriptive text. From these, more complex and detailed test cases were developed. These were created with inspiration from acceptance test-driven development and can be seen in Appendix D. In order to run these test cases on the crane and model, the structure of an automatized testing program has been created in Matlab. This piece of code uses measured/simulated values, initial state and expected outcome as inputs and after the analysis outputs the outcome of the test, i.e. whether the test was successful or not. An example of this code can be seen in listing 1.

Listing 1. Example of code used for automated analysis of test outcome

```matlab
% Automated test 1
% Requirement no. 2a: The simulated steady state angular velocity of the
% first boom shall be within 10 % margin of the real system during 90 %
% of the time.
%
% Input:  First boom velocity, initial state, Measurement, expected outcome.
% Output: True or false


function [Outcome] = Requirementstest(FirstboomVelocitySim,...
  InitialState,Measurement,ExpectedOutCome)

% Remove the samples outside the steadystate area
FirstBoomVelocity_SteadyState = findSteadyState(FirstboomVelocitySim);

% Make the measurements vector equal to simulated vector
Measurements = Measurements((length(Measurements)-...
  length(FirstBoomVelocity)):end);

TimeCounter = 0;

for i = 1:length(FirstBoomVelocity_SteadyState)

    if abs(1-FirstBoomVelocity_SteadyState(i)/Measurements(i)) >= 0.1
      % Increase the counter if the requirement is broken
      TimeCounter = TimeCounter + 1;
    end
end

if TimeCounter/length(Measurements) >= 0.1
    Outcome = 'false'; % Requirement test has failed
else
    Outcome = 'true'; % Requirement test is accepted
end
```

3.5 Preparation of the Hiab XS 022 loader crane

To get reliable measurements and ensure safe handling of the crane, professionally mounted hardware and electronics is required. Last years student mounted and wired the crane and the preparations of the crane this year are mainly improvements of their work. The majority of the work will be done with the wiring since it was not installed in a satisfactory way.

The improvements are done to reduce the risk of getting errors related to hardware during future verification of models and testing of controllers. It should also simplify the work and by that reduce the time spent on the earlier mentioned activities. In the following section the preparation of the different components in the system will be described more in detail.

3.5.1 Hardware, electronics and hydraulics

Table 1. List of hardware installed at KTH

Name	Amount	Type
Crane	1	HIAB XS022
Hydraulic valve	1	Parker P70
Remote controller	1	HIAB XS-drive
Controller	1	IFM CR7032
Power supply	1	IFM DN4013
WiFi CAN Bridge (WCB) logger	1	Electrum 253397-C
Display	1	IFM CR0451
Pressure sensor	3	HIAB 395-7888
Pressure sensor	1	IFM PT3551
Wire encoders	2	HIAB FSG
Laser distance sensor	1	IFM O1D100
Inclinometers	2	IFM JN2100
Spool position sensors	8	

The hydraulic valve of type Parker P70 is an open center directional valve pre-mounted on the Hiab XS022 crane. It also has a pre-mounted spool position sensors, one for each input and output.

The remote controller connects with the IFM-controller via XS-drive through CAN-bus, providing the user control over the valve spool position remotely.

The WCB logger is connected to the CAN-bus and broadcasts the data from the bus to any device connected to it via WiFi.

The display can be configured to monitor sensor data and some control signals, as well as used for switching between operation modes and tests.

Three pressure sensors of type Hiab 395-7888 are mounted on both the upper and lower sides of the first boom and the second boom respectively. There is another pressure sensor of type IFM PT3551 being installed in the pump gallery to measure the overall system pressure.

Two wire encoders of type Hiab FSG are mounted on the first and second boom, that measure cylinder extraction/retraction distance on the first and second boom.

The laser sensor of type IFM O1D100 is an analog distance measurement sensor mounted on the extension boom and the output of it is cylinder position for the extension boom.

Two inclinometers of type IFM JN2100 are mounted close to the rotational centers of second boom and extension, to minimize disturbances from vibrations of the crane, and they provide the first and second boom measured angles respectively.

According to Nordenmark et al. (2014, p. 68), the inclinometers mounted on the crane did not deliver acceptable results in terms of accuracy and delay. Two wire encoders were attached as an addition to the inclinometers. When this project started, one wire encoder had been disconnected due to bad performance and the remaining encoder was loosely attached. A new wire encoder was available since last year and was installed. To prevent vibration affecting the measurement precision, the two encoders were reattached in a more robust manner.

The second issue is that the electronics, primarily the WCB, display, XS-drive, IFM-controller and power supply were all exposed, the cables disorganized and not attached to anything laying on a table, as seen in fig. 13.

Figure 13. Hardware status before

Both of these two problems make the crane hard to manage, and can probably result in the confusion and cable connection error as well as damaged hardware if dropped on the floor.

To solve the wiring problem a cabinet was prepared for the arrangement of the hardware and cables. Instead of plugging cables in and out, the group use switches for power and various functions. The display, WCB and switches are mounted on a panel which is mounted within the cabinet together with the hardware, as seen in fig. 14. Panel mounted connections is as well added to the cabinet so that it is possible to detach the crane and external electronics with ease. This is as well required to be able to easily and quickly switch between different controller hardware. KTH is setting up the crane to run on dSpace in preparation for another course and so communicating about the connection interface was required so that no interference between the two different systems would exist. And so that it would be easy to switch between them two.

Figure 14. Hardware status now

There are several advantages to do all this work.

1. It is easy to read the display and operate the crane with tidy hardware and cables in a cabinet.

2. It is robust with tight attachment of each encoder which is good for accurate measurement and can minimize faults.

3. It's efficient to minimize hardware faults due to disconnected cables or damaged electronics.

4. It is then possible to choose the same connectors on the cabinet as the ones that are going to be used by KTH in the dSpace system, which makes it easy to switch between the systems.

3.5.2 Software and sensor reading

The software and sensor was divided into two parts; reading the sensor values and the capability to send information to the microcontroller, 32-bit ifm CR7032 safety controller , in forms of test cases and control programs. The reading of the sensors is intended to be used as the basis of confirming the hydraulic models as well as determining the behavior of the crane with and without control implementation. In terms of sending information, a complementary build of Hiab's software program for the crane is to be done by adding a controller part and specific test cases.

For reading sensor values, a continuation on last year's software program was applied. The programs inherited included reading and saving the sensor values as well as some graphical options for interpreting the data in real time as well as directly after conducting a test. The continuation on this build consists of added error handling to make the program more robust, lowering the probability of losing valuable data if something unexpected happens. A remake of the GUI interface was designed to make the process more user-friendly to allow for a reduced learning curve for using the program. Lastly the graphical design was changed to simplify the interpretation of the gathered data. See fig. 15 for GUI and graphical interface.
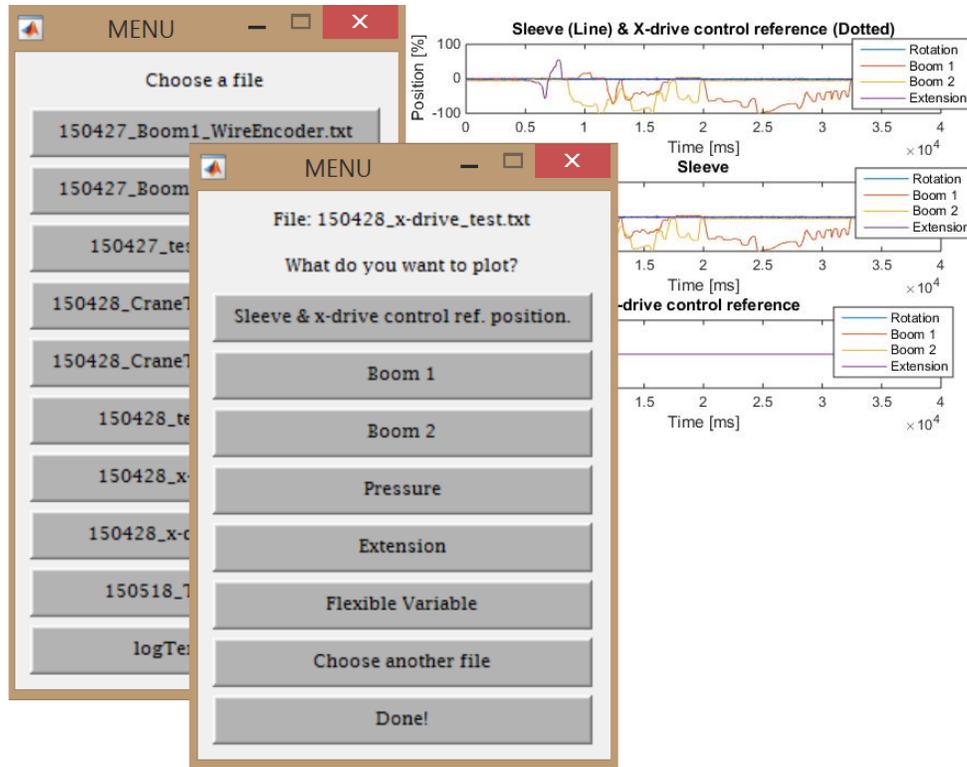
Figure 15. GUI and graphical interface for reading sensors

To be able to send information and program the crane, the software program CoDeSys (3S-Smart Software Solutions GmbH, 2013) needs to be up and running along with the understanding on how to utilize this tool later in the project. This consisted of setting up at least one of the projects' computers by adding all the necessary parts for starting up new projects within CoDeSys and also be able to run the last year's programs. Besides from starting up projects documentation stating all the necessary parts of sending information, e.g. flashing programs on the safety controller, is to be done for use in later stages of the project.

Chapter 4   Future work

In the fall the project will continue work with the investigation of how to validate and verify a model over the system. A suitable control structure for a linear velocity controller will be examined in different criterias such as robustness, stability and the ability to implement in real-time. If resources are available, the development and implementation of a tip-point controller will be made.

4.1   Model verification

In order to verify the system requirements formulated for the model, as well as ultimately validate the stakeholder requirements on this matter, it will be necessary to conduct an extensive series of test cases. The model needs to accurately simulate the dynamics of the crane, not only because Hiab wants a working model, but it is also essential for the development of a robust control system.

The test cases, which are specified in Appendix D, will be conducted on the Hiab XS 022 crane currently stationed at KTH. This will be done using the sensors installed on the crane. These consist of four pressure sensors, two wire encoders, a laser encoder as well as two inclinometers. If needed, more sensors will be installed in order to get a more accurate view on the real system. These are all connected to a IFM CR7032 safety controller unit that reads the sensor values and relay them to the user, as of now, through a CAN WIFI bridge. A more reliable hardware for relaying the data is to be implemented where the sensor values is read directly from the safety controller.

In order to efficiently validate the model, there is a plan to automatically run the test cases on the model and the real system by running a Matlab script testing the dynamics of the model with the parameter values specified in the description. The relevant values will be saved and compared with the values measured on the real system. These will be acquired by running a corresponding CoDeSys script on the crane. Considering the matrix structure in which the test cases are formulated, as seen in Appendix D, an automatic code, as shown in the draft in listing 2 would be a good example of how the test cases should be run on the model. The corresponding CoDeSys code has not yet been developed but will essentially have the same structure as this.

Listing 2. Example code structure to use for running test cases

```matlab
function result = run_test_case(input_matrix, init_states)
% Uses the input_matrix matrices containing
% the input values for the different functions as columns
% as well as the init_states matrix with the same structure
% outputs the simulated values for all boom velocities as
% well as the pressures

result=[];
for in_in = 1:size(input_matrix, 2);
    for in_st = size(input_matrix, 2);
        input_values = input_mat(:, in_in);
        init_values = input_mat(:, in_in);
        result=[result; sim('model', [input_values, init_values];
    end
end
```

4.2 Linear velocity controller

In the autumn, an investigation will be made considering which control strategy is viable. Considerations to the non-linear dynamical behavior that hydraulic systems usually demonstrate, and to stakeholder requirements were a certain assurance that the chosen controller is stable. A hydraulic crane will work with different loads and if the stability for the chosen control structure cannot be guaranteed, then the result can be hazardous.

Because of the complexity with using non-linear control methods as mentioned in section 2.4 , first an investigation will be made if using a linear, robust control structure is sufficient. If dynamic decoupling, or even decentralization of the system is possible the complexity decreases which makes the investigation of the stability criteria easier. However, according to Glad and Ljung (2000, p. 454), when the non-linear behavior is a big part of the system dynamics, linear control methods are not sufficient to get acceptable results. One solution can be to use exact linearization described in section 2.2.7 which uses an inner loop that deals with the non-linear behavior. The system can then be treated like linear systems were the PID or the lead-lag control methods can be used as described in section 2.2.1 and section 2.2.2. Another suitable option is using an optimal control such as $\mathcal{H}_\infty$ control or LQG control.

Non-linear control methods are according to Bonchis et al. (2002) best suited when working with a hydro mechanical system, such as NMPC and MRAC. However, further investigation to which strategies that can actually be implemented in real-time on a microcontroller is needed, as certain methods need large computational power (Kalmari et al., 2014). Non-model based control has advantages as they are not depending on an accurate model. However, difficulties emerge during verification that the controller doesn't render any hazardous behavior for different loads and all states of the crane. Even with extensive testing of the actual hardware, a guarantee can never be given that the controller will not be unstable. The same investigation as with a non-linear controller, that the control signal can be calculated under real-time constraints is needed as well.

In the fall the project will start investigating if the linear control structures are sufficient by doing analysis of how big impact the dynamical non-linear behavior of the actual system is. If this analysis can be done without deriving the equations that are encapsulated in the physical modeling of the auto-generated SimMechanics model needs to be investigated. If the linear approach fails, further state of the art of the non-linear methods described in section 2.4 will be made as well as investigation of which can be implemented in real-time.

4.3 Tip point controller

If the linear velocity controller is achieved and the requirements described in Appendix B are verified on the crane, the next phase of the project is to design a tip point controller. The idea with this controller is to let the user steer the tip point of the crane by inputting speed in a Cartesian coordinate system. The tip point controller should, unlike the linear velocity controller, that actuates the cylinders one by one from each lever input, compute the cylinder movement from this input.

The project in 2013 Tysk et al. (2013) designed a tip point controller onto a Hiab crane of a different model. This crane uses a closed center valve and because of that there were no interference between the various functions. To get a controller like this working, full control of every single cylinder is needed, which is why the linear velocity controller has to be implemented first.

System requirements for the tip point controller has been stated and are presented in Appendix C. The goal with the tip point controller is to make it fulfill all these requirements.

Bibliography

Cargotec, "Hiab XS 022 Brochure," 2015, accessed April, 2015. [Online]. Available: http://www.hiab.com/en/global/products1/loader-cranes-100/hiab-10/products/-51/selected-brand-hiab/

J. Wang, "A Non-Model-Based Controller Used in Process Control," *Decision and Control*, 1997.

M. Johnsson and M. Moradi, *PID Control - New identification and Design Methods*. Springer, 2005.

L. Ljung and T. Glad, *Reglerteknik : grundläggande teori*. Studentlitteratur AB, 2006.

W. S. Levine, *The Control Handbook*. CRC Press LCC, 1996.

R. Babuska, "Lead-lag position control of a hydraulic actuator," 2011, accessed April, 2015. [Online]. Available: http://www.dcsc.tudelft.nl/~wb2207/transp/examples/hydraulic/hydraulic_lead_lag.html

Q. Xiong, W.-J. Cai, M.-J. He, and M. He, "Decentralized control system design for multivariable processes – a novel method based on effective relative gain array," *Eng. Chem .Res*, vol. 45, p. 2769, 2006.

T. Glad and L. Ljung, *Multivariable and Nonlinear Methods*. CRC Press, 2000.

B. Anderson, A. Bennick, and M. Salciccioli, "Model Predictive Control," 2007, accessed May, 2015. [Online]. Available: https://controls.engin.umich.edu/wiki/index.php/MPC

S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control: Analysis and Design*. John Wiley & Sons, 2005.

M. Athans, "A Tutorial on the LQG/LTR Method," in *Proc. American Control Conference, Seattle, WA, June 1986*. Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, 1986.

——, "The role and use of the stochastic linear-quadratic-Gaussian problem in control system design," *IEEE Transactions on Automatic Control*, vol. 16, 1971.

X. C. M. Cubillos and L. C. G. de Souza, "Using of H-Infinity Control Method in Attitude Control System of Rigid-Flexible Satellite," *Mathematical Problems in Engineering*, 2009.

J. K. Hedrick and A. Girard, "Control of nonlinear dynamic systems," University of California, Tech. Rep., 2005.

M. Lemmen and M. Bröcker, "Different nonlinear controllers for hydraulic synchronizing cylinders," University of Duisburg, Department of Measurement and Control, Tech. Rep., 2000.

J.-H. Kwon, T. hyeong Kim, J.-S. Jang, and I. yeong Lee, "Feedback linearization control of a hydraulic servo system," *SICE-ICASE International Joint Conference 2006*, pp. 455–460, 2006.

R. Husson, Ed., *Control Methods for Electronic Machines*. ISTE Ltd, 2009.

W. Perruquetti and J. P. Barbot, *Sliding Mode Control in Engineering*. CRC Press, 2002.

P. Jain and D. M. Nigam, *Design of a Model Reference Adaptive Controller Using Modified MIT Rule for a Second Order System*. Research India Publications, 2013.

I. P. B.M. Vinagre, I. Petras and Y. Chen, *Using Fraction Order Adjustment Rules and Fractional Order Reference Models in Model-Reference Adaptive Control*. Kluwer Academic Publishers, 2002.

M. Keshmiri, A. F. Jahromi, A. Mohebbi, M. H. Amoozgar, and W.-F. Xie, "Modelling and Control of Ball and Beam System Using Model Based and Non-Model Based Control Approaches," *International Journal on Smart Sensing and Intelligent Systems*, vol. 5, 2012.

K. M. Passino and S. Yurkovich, *Fuzzy Control*. Addison-Wesley Longman, Inc., 1998.

M. M. Bech, T. O. Andersen, H. C. Pedersen, and L. Schmidt, "Experimental Evaluation of Control Strategies for Hydraulic Servo Robot," *Mechatronics and Automation*, 2013.

A. Bonchis, P. I. Corke, and D. C. Rye, "Experimental Evaluation of position Control Methods for Hydraulic Systems," *Control Systens Technology*, vol. 10, 2002.

J. Kalmari, J. Backman, and A. Visala, "Nonlinear model predictive control of hydraulic forestry crane with automatic sway damping," *Computers and Electronics in Agriculture*, vol. 109, 2014.

V. Nordenmark, M. Markström, J. Svantesson, C. Wessel, J. Lindgren, A. Forsgren, and O. Wallnäs, "Hiab team project report 2014," Institution of engineering design, KTH, Tech. Rep., 2014.

3S-Smart Software Solutions GmbH, "CoDeSys - The IEC 61131-3 Programming System," 2013, version 2.3.9.42.

P. Tysk, A. Szilassy, A. forss, F. Isaksson, F. Åberg, G. Storck, J. Simonsson, J.-E. Ericsson, and M. Raun, "The crane project," Institution of engineering design, KTH, Tech. Rep., 2013.

Appendices

Appendix A   Project plan

A.1   Background

The project is conducted as a collaboration between the the Royal Institute of Technology (KTH) and the Swedish hydraulic company Hiab. It features a team of M.Sc mechatronic students tasked to improve the operation of open valve hydraulic cranes manufactured by the company.

There are two approaches to supplying hydraulic oil to the actuators. Option one is using closed center valves and variable displacement pumps which can adapt the flow to the current workload. Option two is using open center valves with fixed displacement pumps which deliver a constant flow.

The open center valves are cheaper and more reliable. However, due to the constant oil flow from the pump, the various functions may interfere with each other. The goal of this project is to investigate the ability to counteract these interferences.

A project conducted by a team of M.Sc students in mechatronics regarding open valves was conducted the year of 2014. The project produced non-verified models of the hydraulics and mechanics of one of Hiab cranes. These models will serve as a starting point when approaching the task concerning this project.

A.2   Project goals

The goal of the project carried out in 2014 was to derive a model of the whole crane, with an open center valve and use that to create a velocity controller. Since the final goals were not reached, the goals are inherited into this project. In order to reach those goals the model from earlier project has to be verified so that it reflects the real crane. Specifically parameters and constants that are estimated has to be checked.

Moreover, the overall goal is to use the model to create a tip point velocity controller and then apply it on the real crane so that the tip point can move in a straight line with a constant velocity. This is to be accomplished by controlling the open center valve so that the oil flow is shared equally by all functions proportional to the user input.

From the team's aspect, the goal is to carry out a project from start to finish and to gain knowledge and experience while doing so. In the spring period, focus is on planning of the project. The goals are to define verifiable requirements, deliver a state of the art report and implement an interface for the communication with the crane i.e. reading sensors and sending reference signals. Later in the fall, the goals are to verify the old model, make a velocity controller and produce a project report.

From learning perspective and for own interest, another goal is to learn hydraulics and different methods for hydraulic control.

A.3   Organization

The organization is divided into seven main areas of responsibility. Under these, each person has their own personal responsibility. This personal responsibility includes having an overview of what needs to be done within this area and not the execution of that particular task. The person serves as an internal contact person for that area and is the one to talk to when the team has any questions regarding that field.

Figure A.1 displays the organisational structure and includes the organisation name as its top level. Underneath the top level, the main areas of responsibility are listed (gray-gradient boxes). Finally (white boxes), the individual responsibilities are displayed.
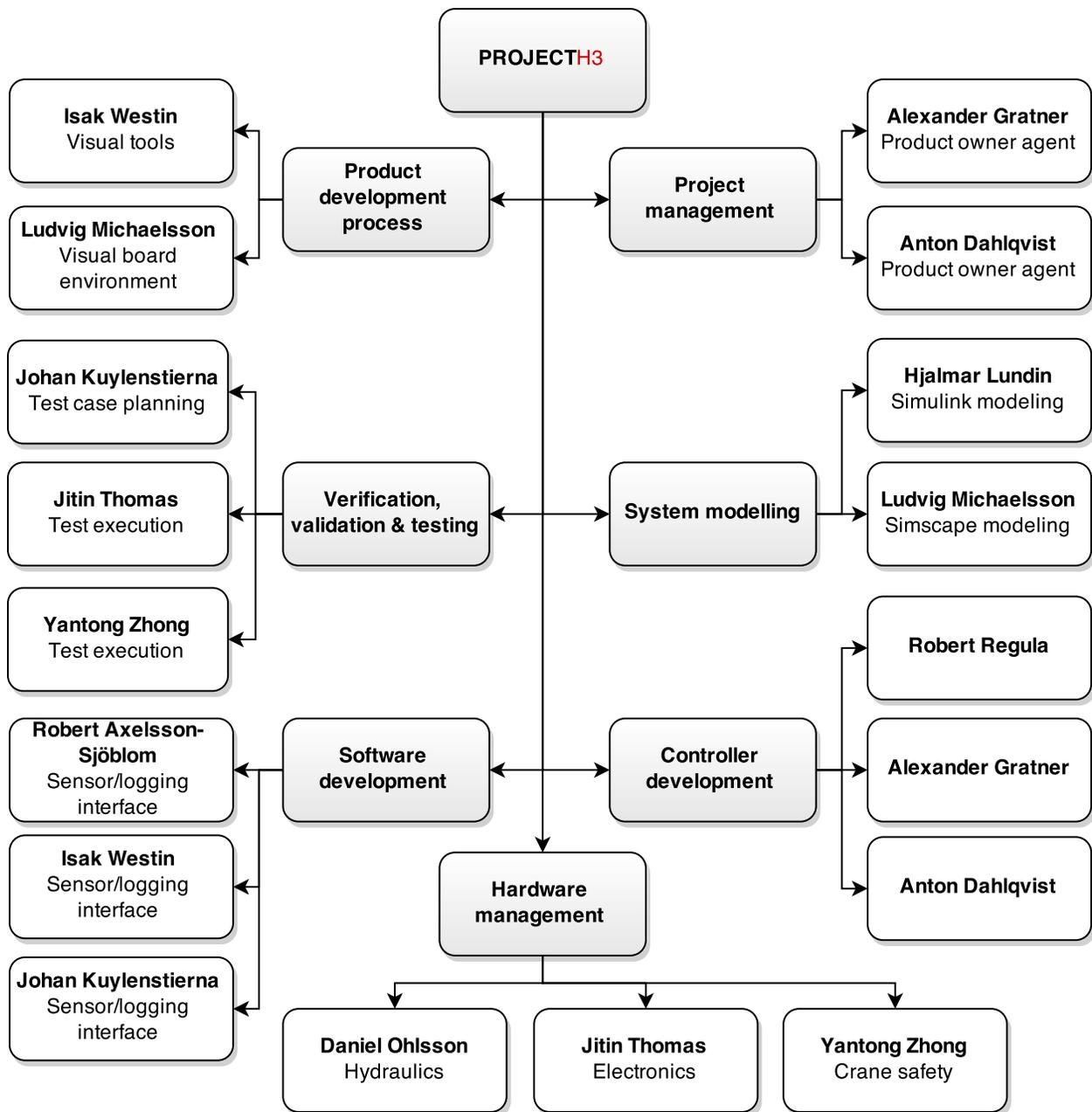
Figure A.1. Illustration of the project organization structure

A.4 Project development process model

As a development process, the team uses a combination of the V-model together with the Scrum methodology to get a visualised and structured process to follow with short and regular meetings. Sprint planning, Sprint review and Sprint retrospective are held every two weeks, whereas Scrum meetings are held on every

working day. Every meeting is held at 8.15 AM. Stakeholders are invited to the Sprint review meetings. As a complement to the internal Sprint review meetings, design review meetings are held with the teaching group.

Also, to get the continuous verification part from the V-model the Scrum set-up is slightly modified such that before a task is finished, it has to be verified by the person responsible for that specific area, as described in Organization section of this report.

A work breakdown structure (WBS) is derived to get an overview of the projects workload and to use as a reference in the sprint planning to decide tasks for the coming sprint. The WBS is presented in fig. A.2 following below.
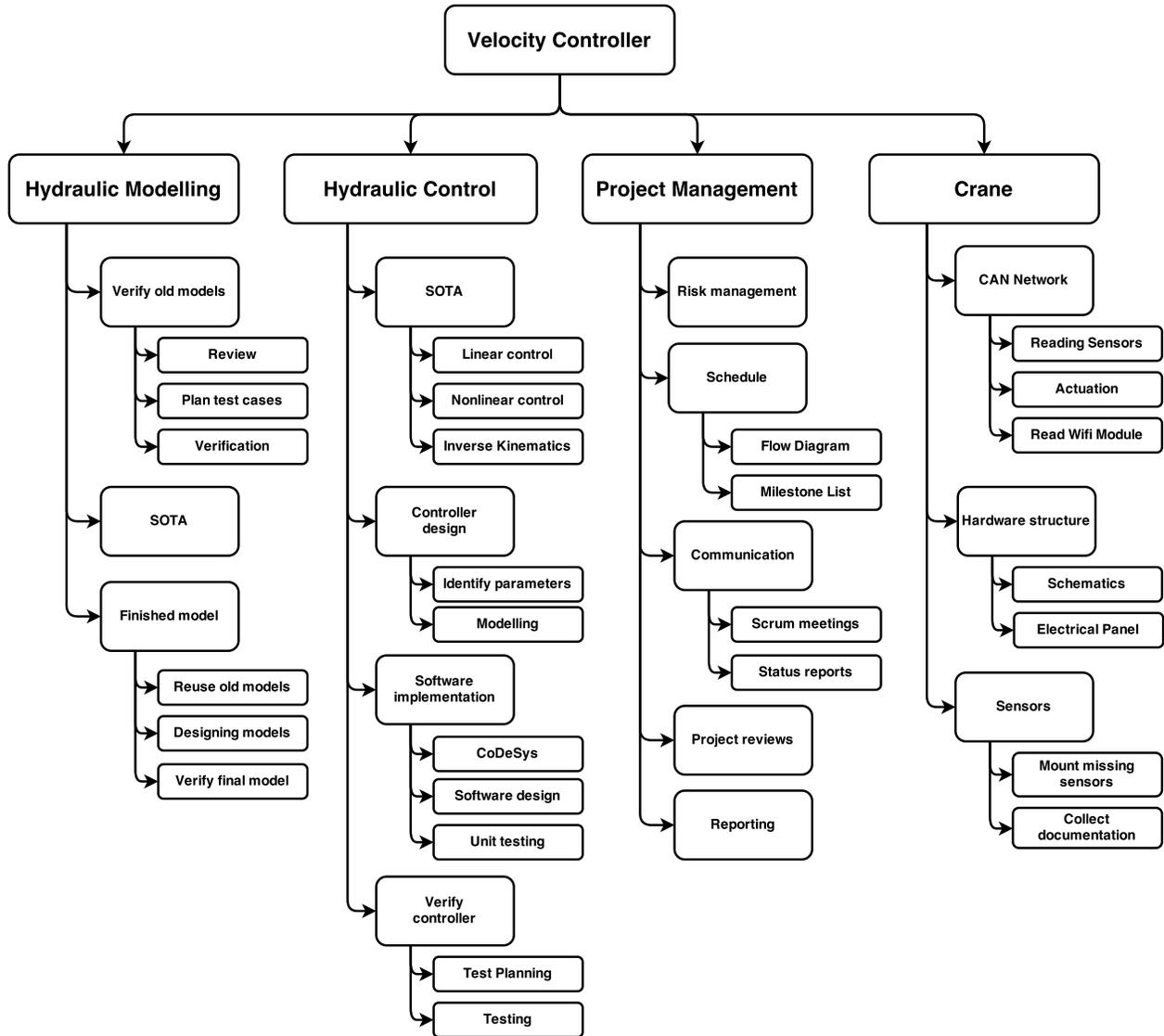
Figure A.2. Work breakdown structure for implementation of a velocity controller

The top level object is the main goal of the overall project (i.e. creating a linear relationship velocity controller between output and input, at all times). Underneath this level, the main categories for achieving this are displayed. For instance, hydraulic control refers to the control theory needed for designing and implementing a controller, including learning in the form of a SOTA. The third level describes a smaller task group needed

to accomplish the second level. The work breakdown structure serves as a basis for the Scrum planning meetings and will continuously be broken down further during these.

Rough milestones and time scheduling of the tasks needed to succeed with the project are displayed in the Gantt chart appended to the end of this document.

A.5   Risk analysis

A risk identification process has been conducted using the Delphi Technique. The probability, P, and the consequence, C, concerning every risk are defined on a scale between 1 to 5 according to table A.1 below. The same table then indicates the significance of the risk which is later referred to as a risk category, RC.

Table A.1. Risk evaluation matrix

Significance		Consequence				
		1 **Insignificant** **Impact**	**2** **Minor** **Impact**	**3** **Moderate** **impact**	**4** **Major** **impact**	**5** **Catastrophic** **impact**
Probability	1 Rare	Low	Low	Moderate	High	High
	2 Unlikely	Low	Low	Moderate	High	Very high
	3 Moderate /Possible	Low	Moderate	High	Very high	Very high
	4 Likely	Moderate	High	High	Very high	Extreme
	5 Certain	Moderate	High	Very high	Extreme	Extreme

The risk factor, R, concerning each event is defined as probability times the consequence. The events related to the highest risk factors are listed in table A.2 below whereas the rightmost column indicates the suggested action in order to prevent or reduce the probability concerning each event.

	P	C	R	RC	Suggested action
Hard to verify models	4	4	16	Very high	Define measurable requirements
Documentation error	5	3	15	Very high	Use a repository with a well defined documentation policy.
Group members fail to deliver expected work	5	3	15	Very high	Continuous meetings and demands
Wrong/misleading requirements	3	4	12	High	Maintain a good dialogue with Hiab concerning the requirements.
Injury when handling the crane	2	5	10	High	Define a safety document that should be followed when operating the crane.
Hardware malfunction	4	3	12	High	Follow operating guidelines.
Ineffective time management	3	4	12	High	Use Scrum to involve team members.
Overestimating our capability	4	3	12	High	Bare in mind that overestimation is a problem and approach problems with a more pessimistic view.
Bad stakeholder communication	2	4	8	High	Make sure to have continuous contact with the stakeholder.
Group disagreement concerning deliverables	3	3	9	High	Have a constant discussion and involve KTH and Hiab stakeholders.
Conflict between Hiab and teaching team interests	4	3	12	High	Have a continuous dialogue between the two parts to ensure that both interests can be realized.
Previous provided models not working	4	3	12	High	Verify the models as soon as possible.

A.6   Document rules

To facilitate the work of finding and saving documents some rules are given in this section. The rules includes how the documents can be shared, how and where it should be saved and an official convention on how to name different document types. Along with the document rules in this project plan two separate templates on how to name different files are given in the project folder.

A.6.1   Saving and sharing documents

Documents can be shared using two different programs, **Subversion** or **Slack**, depending on the type of document, to who it is shared and own preferences.

Subversion is the official way of sharing documents internally. If a document is to be processed by more than one person, Subversion shall be used along with the official file naming convention. Within the Subversion folder tree, personal folders have been assigned where no formal naming convention is mandatory and is intended as an easy way of channeling documents between computers. All official documents shall be saved within the "Project H3" folder in the appropriate sub folder. Subversion is also used as the final saving place for documents i.e. all the document relevant for the project can be found there. If a change is made on an existing document, a comment on what has been changed shall be added in the Subversion comment window.

Slack, the official way of communicating internally, can be used as a way of sharing a document if it is to be reviewed by maximum one other group member. By using Slack, the person sharing the document takes responsibility that the reviewed document is updated and makes sure that it ends up in Subversion in an appropriate location.

A.6.2 File naming - Documents

The file naming for **documents** shall be done according to the
"O_DocumentConvention_V01_RAS_H3KTH_150415" file that can be found in the Subversion depository.
The convention is as follows.

Naming instructions

[DOCUMENT TYPE(as below)]_[DOCUMENT NAME(No underscore, new word = capital letter)]_V[VERSION
NUMBER(two digits)]_[CREATOR OF DOCUMENT(as below)]_ [ORGANIZATION(H3KTH)]_[DATE WHEN
CREATED(Year/month/day)]

Example: PR_DesignReviewApril_V01_RAS_H3KTH_150415

**Document type (will continue adding in the
"O_FolderAndFileConvention_V01_RAS_H3KTH_150415" file when more document types is
created)**

- MP – Meeting Protocol
- PR – Presentation
- T – template
- O – Organization
- PIC – Pictures
- ... expanded upon as necessary.

Version

The version (in the file name) is to be changed **only** if a major change have been done i.e. when a document
have been severely altered or corrected. If a new version is made, the responsibility is on the creator of the
new version to make sure that no one else is working with the previous document at the same time. The
version handling for small changes is done using Subversion internal version handler.

Creator

AG – Alexander Gratner
AD – Anton Dahlqvist
DO – Daniel Ohlsson
HL – Hjalmar Lundin
IW – Isak Westin
JT – Jitin Thomas
JK – Johan Kuylenstierna
LM – Ludvig Michaelsson
RAS – Robert Axelsson- Sjöblom
RR – Robert Regula
YZ – Yantong Zhang

A.6.3 File naming - Software code & models

Naming for **software code** and **models** (ex Simulink models) shall be done according to "O_CodeAndModelConvention_V01_RAS_H3KTH_150423" that can be found in the Subversion depository. The conventions is as follows.

[DOCUMENT TYPE(as below)]_[DOCUMENT NAME(No underscore, new word = capital letter)]_V [VERSION NUMBER(two digits)]

Example: SC_PlotLoggedData_V01

Document type (will continue adding in the "O_CodeAndModelConvention_V01_RAS_H3KTH_150423" file when more document types is created)

- HM – Hydraulic Model
- SC – Sensor Code
- ... expanded upon as necessary.

Version

See section A.6.2

Creator

See section A.6.2

Additional information

Because the software code and model naming convention is more convenient to use with a shorter name some parts, compared to the document conventions, is removed. These shall be added within the software code and model instead. In the software code the information shall be written in the beginning of the code. The information is the name of the creator, date of creation and the organization name (H3KTH). In the Simulink models the information shall be added in the top left corner of the model. The information is the name of the creator, date of creation and the organization name (H3KTH).

A.6.4 Backup

Backing up all the documents in the Subversion depository shall be done at every scrum sprint start-up meeting and the responsibility falls on the current document manager. The backup files shall be saved on a hard drive not connected to the Subversion depository.

ID	Task Name	Start	Finish	Duration
1	Scrum review meetings	2015-03-30	2015-03-30	1d
2	Project start admninistration	2015-03-31	2015-04-21	16d
3	Project planning	2015-04-06	2015-04-20	11d
4	Design review #1	2015-04-27	2015-04-27	0d
5	Project plan submission of draft to HIAB	2015-04-30	2015-04-30	0d
6	Project plan feedback from HIAB	2015-04-30	2015-05-05	4d
7	Project plan revision	2015-05-06	2015-05-22	13d
8	Sensor testing and reading	2015-04-13	2015-05-04	16d
9	Electrical box mounting	2015-04-20	2015-05-18	21d
10	Design review #2	2015-05-07	2015-05-07	0d
11	Codesys Training	2015-05-08	2015-05-08	1d
12	Hydraulics basics training	2015-05-11	2015-05-11	1d
13	Old model review	2015-04-06	2015-05-22	35d
14	Old model test case planning	2015-04-06	2015-05-22	35d
15	Interface design	2015-05-05	2015-05-22	14d
16	State of the art research	2015-04-06	2015-05-22	35d
17	Final presentation of project plan	2015-05-25	2015-05-25	0d
18	Old tweaked model verification	2015-05-01	2015-09-18	101d
19	New model design and testing	2015-05-01	2015-10-15	120d
20	Controller design parameter identification	2015-09-01	2015-09-25	19d
21	Controller design	2015-09-28	2015-11-03	27d
22	Controller test planning	2015-09-30	2015-10-13	10d
23	Software implementation of controller	2015-09-28	2015-10-13	12d
24	Software implementation unit testing	2015-10-15	2015-10-22	6d
25	Controller testing	2015-10-15	2015-11-04	15d
26	Controller verification	2015-11-06	2015-11-23	12d
27	Project report writing	2015-09-15	2015-12-10	63d
28	Project recap and lessons learned	2015-12-16	2015-12-16	1d
29	Project finish	2015-12-18	2015-12-18	0d

Figure A.3. Milestone plan in the form of a Gantt chart

Appendix B   Stakeholder requirements

This project aims to reduce load interference without changing hardware components such as the hydraulic valve or pump; instead it will be done by adding a controller platform to the crane system and implementing a control structure between the user and the hydraulic valve. At the beginning of this project, stakeholder requirements were created in collaboration with HIAB as:

1. Create a linear relationship between users' input and crane function velocity.

2. Ensure that different crane functions move at the same velocity for the same input.

3. Make a tip point controller to enhance manoeuvrability for the user.

These specifications have been analysed and the following requirements were extracted.

B.1   Design and verify a model of the crane

1. A model describing the dynamics of the system with enough precision so that a controller can be developed and control the crane.
   Rationale: The model should contain a detailed description of both the hydraulic system and the mechanical system, using a XS 022 crane from HIAB as a reference. The model may disregard dynamics that are not necessary for developing a controller.

2. The model should have three input signals in order to control the spool corresponding to each function and should accurately simulate the dynamics of the first boom, second boom and the extension boom as well as the pressures in the hydraulic system.
   Rationale: As the slew is disconnected for safety reasons, the functions only consists of moving the first boom, the second boom and the extension boom in a positive or negative direction.

3. The model shall be verified with the crane XS 022 and the hydraulic valve Parker P70 currently located in at KTH

B.2   Develop a control system that manages interference in the system

1. Regardless of disturbances the crane shall follow first boom reference signal provided by the operator.
   Rationale: Disturbance signals are for example varying loads or actuations of different cylinders simultaneously. The reference signal is the wanted cylinder velocity of the first boom

2. Regardless of disturbances the crane shall follow second boom reference signal provided by the operator.
   Rationale: Disturbance signals are for example varying loads or actuations of different cylinders simultaneously. The reference signal is the wanted cylinder velocity of the second boom.

3. Regardless of disturbances the crane shall follow extension boom reference signal provided by the operator.
   Rationale: Disturbance signals are for example varying loads or actuations of different cylinders simultaneously. The reference signal cylinder velocity.

4. The control system should use as few sensors as possible.
   Rationale: The purpose of switching to open center valve is to reduce the cost to the costumer so additional sensors mean more cost for the costumer customer.

5. The control system should be able to perform when using the sensors currently installed in the crane.
   Rationale: Sensors installed are spool position sensors, pressure sensors, two wire encoders, a laser distance sensor and two inclinometers.

B.3 Develop a tip point controller for the crane

1. The controller shall be able to move the tip of the crane at a constant velocity in a horizontal motion by the combined usage of the two booms and extension.

2. The controller shall be able to move the tip of the crane at a constant velocity in a vertically vertical motion by the combined usage of the two booms and extension.

Appendix C System requirements

By analyzing the stakeholder requirements given by Hiab, it was possible to derive a great deal of detailed and measurable system requirements. These will be used to verify that the output of this project is suitable. It is important to mention that these requirements are preliminary, and the values used are just estimates. More accurate values will be determined during the course of the project.

C.1 System requirements for crane model

1. The simulated steady state angular velocity of the first boom shall be within a 10% margin of the real system during 90% of the time.
   Rationale: The model only needs to follow the real system most of the time as high frequency spikes may occur.

2. The simulated steady state angular velocity of the second boom shall be within a 10% margin of the real system during 90% of the time.
   Rationale: The model only needs to follow the real system most of the time as high frequency spikes may occur.

3. The simulated steady state velocity of the extension boom shall be within a 10% margin of the real system during 90% of the time.
   Rationale: The model only needs to follow the real system most of the time as high frequency spikes may occur.

4. The rise time of the model with regard to the angular velocity of first boom shall be within a 10% margin of the real system.

5. The rise time of the model with regard to the angular velocity of second boom be within a 10%margin of the real system.

6. The rise time of the model with regard to the velocity of extension boom shall be within a 10% margin of the real system.

7. The gallery pressure during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.

8. The rod side pressure for the first boom during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.
   Rationale: This applies to a system without an external load.

9. The piston side pressure for the first boom during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.
   Rationale: This applies to a system without an external load.

10. The piston side pressure for the second boom during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.
    Rationale: This applies to a system without an external load.

C.2 System requirements for HW/SW

1. The controlled system for interference shall run on Controller (IFM CR7032).

2. The controller process shall perform in real time.

3. The controller code shall be written in a programming language with CODESYS support.

4. The controller code shall not interfere with the built in safety functionality.

5. The output delay when changing input shall not exceed 250 ms.

C.3 System requirements for crane safety

1. If the remote control emergency button is pressed, all movement shall cease within 1 second

2. All control aspects of the crane shall be turned off from the time that the emergency button is pressed until it is reset.

3. Once the emergency button is reset, the system shall be run in open loop from the interface and ignore all control actions.
Rationale: if the system becomes unstable, it can be hazardous if it is reset.

4. Each person who intends to run the crane shall read through, sign and follow the safety document Safety Routine for running the crane.

C.4 System requirements for interference control

1. The control system shall be stable for all reference input values on either port.

2. The steady state output angular velocity of the first boom shall be within a 10% margin of the scaled reference value during 90% of the time when operating independently of all other functions.
Rationale: The scaled reference value is used in order to not exceed the maximum capacity of the crane.

3. The steady state output angular velocity of the second boom shall be within a 10% margin of the scaled reference value during 90% of the time when operating independently of all other functions.
Rationale: The scaled reference value is used in order to not exceed the maximum capacity of the crane.

4. The steady state output velocity of the extension boom shall be within a 10%margin of the scaled reference value during 90% of the time when operating independently of all other functions.
Rationale: The scaled reference value is used in order to not exceed the maximum capacity of the crane.

5. The steady state output angular velocity of the first boom shall be within a 15% margin of the scaled reference value during 90% of the time when operating alongside other crane functions.
Rationale: The scaled reference value is used in order to not exceed the maximum capacity of the crane.

6. The steady state output angular velocity of the second boom shall be within a 15% margin of the scaled reference value during 90% of the time when operating alongside other functions.
Rationale: The scaled reference value is used in order to not exceed the maximum capacity of the crane.

7. The steady state output velocity of the extension boom shall be within a 15% margin of the scaled reference value during 90% of the time when operating alongside other functions.
Rationale: The scaled reference value is used in order to not exceed the maximum capacity of the crane.

8. The rise time of the angular velocity for a step response from rest to scaled maximum velocity shall be less than 1 second when operating the first boom independently of all other functions.
Rationale: independently means that all other boom functions are at rest.

9. The rise time of the angular velocity for a step response from rest to maximum velocity shall be less than 1 second when operating the second boom independently of all other functions.
Rationale: independently means that all other boom functions are at rest.

10. The rise time of the velocity for a step response from rest to maximum velocity shall be less than 1 second when operating the extension boom independently of all other functions.
Rationale: independently means that all other boom functions are at rest.

11. The overshoot for a step response shall for step inputs be less than 15% for all input values for the first boom.

12. The overshoot for a step response shall for step inputs be less than 15% for all input values for the second boom.

13. The overshoot for a step response shall for step inputs be less than 15% for all input values for the extension boom.

14. The control system shall be able to withstand a load varying from 0 to 250 kg.

C.5 System requirements for tip point control

1. The tip shall be able to move for a certain distance in the horizontal plane without deviating more than 10 cm from said plane.

2. The tip shall be able to move for a certain distance in the vertical plane without deviating more than 10 cm from said plane.

3. The speed of the tip shall not deviate more than 10% from the scaled reference value

Appendix D   Test cases

Test case application notes Each case in the input matrix should be performed once for each case in the initial state matrix, i.e. a test case which contains 4 input cases and 2 initial state cases needs 8 different test instances. The velocities stated refer to the velocity relative to the previous fixed point, i.e. the angular velocity of the second boom is relative to the angular velocity of the first boom. All velocities are also relative to the scaled values, i.e. the velocity calculated in order to avoid interference.

Table D.1. Nomenclature

ω	Angular velocity
V	Linear velocity
$f1$	First boom
$f2$	Second boom
$f3$	Extension boom
θ	Angle
X	Distance
m	Modelled system
r	Real system
t	Rise time
p	Pressure
g	Gallery
u	upper
l	lower

1. Requirement: The simulated steady state angular velocity of the first boom shall be within a 10% margin of the real system during 90% of the time.

Table D.2. Test case 1 input values

Input (angular velocity)	Case 1	Case 2	Case 3	Case 4
Function 1	$\omega_{f1,max}$	$\omega_{f1,max}/2$	$-\omega_{f1,max}/2$	$-\omega_{f1,max}$
Function 2	0	0	0	0
Function 3	0	0	0	0

Table D.3. Test case 1 initial state

State (position)	Case a	Case b	Case c	Case d
Function 1	N/A	N/A	N/A	N/A
Function 2	$\theta_{f2,max}$	$\theta_{f2,min}$	$\theta_{f2,max}$	$\theta_{f2,min}$
Function 3	$X_{f3,max}$	$X_{f3,min}$	$X_{f3,min}$	$X_{f3,max}$

Table D.4. Test case 1 Expected outcome

State/input	Case 1	Case 2
Case a	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$
Case b	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$
Case c	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$
Case d	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$

Table D.5. Test case 1 Expected outcome

State/input	Case 3	Case 4
Case a	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$
Case b	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$
Case c	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$
Case d	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$	$\omega_{f1,m} = \omega_{f1,r} \pm 10\%$

2. Requirement: The simulated steady state angular velocity of the second boom shall be within a 10% margin of the real system during 90% of the time

Table D.6. Test case 2 input values

Input (angular velocity)	Case 1	Case 2	Case 3	Case 4
Function 1	0	0	0	0
Function 2	$\omega_{f2,max}$	$\omega_{f2,max}/2$	$-\omega_{f2,max}/2$	$-\omega_{f2,max}$
Function 3	0	0	0	0

Table D.7. Test case 2 initial state

Input (angular velocity)	Case 1	Case 2	Case 3	Case 4
Function 1	$\theta_{f1,max}$	$\theta_{f1,min}$	$\theta_{f1,max}$	$\theta_{f1,min}$
Function 2	N/A	N/A	N/A	N/A
Function 3	$X_{f3,max}$	$X_{f3,min}$	$X_{f3,min}$	$X_{f3,max}$

Table D.8. Test case 2 expected outcome

State/input	Case 1	Case 2
Case a	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$
Case b	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$
Case c	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$
Case d	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$

Table D.9. Test case 2 expected outcome

State/input	Case 3	Case 4
Case a	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$
Case b	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$
Case c	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$
Case d	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$	$\omega_{f2,m} = \omega_{f2,r} \pm 10\%$

3. Requirement: The simulated steady state velocity of the third boom shall be within a 10% margin of the real system during 90% of the time.

Table D.10. Test case 3 input values

Input (angular velocity)	Case 1	Case 2	Case 3	Case 4
Function 1	0	0	0	0
Function 2	0	0	0	0
Function 3	$V_{f3,max}$	$V_{f3,max}/2$	$-V_{f3,max}/2$	$-V_{f3,max}$

Table D.11. Test case 3 initial state

State (position)	Case a	Case b	Case c	Case d
Function 1	$\theta_{f1,max}$	$\theta_{f1,min}$	$\theta_{f1,max}$	$\theta_{f1,min}$
Function 2	$\theta_{f2,max}$	$\theta_{f2,min}$	$\theta_{f2,min}$	$\theta_{f2,max}$
Function 3	N/A	N/A	N/A	N/A

Table D.12. Test case 3 expected outcome

State/input	Case 1	Case 2
Case a	$V_{f3,m} = V_{f3,r} \pm 10\%$	$V_{f3,m} = V_{f3,r} \pm 10\%$
Case b	$V_{f3,m} = V_{f3,r} \pm 10\%$	$V_{f3,m} = V_{f3,r} \pm 10\%$
Case c	$V_{f3}, m = V_{f3,r} \pm 10\%$	$V_{f3,m} = V_{f3,r} \pm 10\%$
Case d	$V_{f3,m} = V_{f3,r} \pm 10\%$	$V_{f3,m} = V_{f3,r} \pm 10\%$

Table D.13. Test case 3 expected outcome

State/input	Case 3	Case 4
Case a	$V_{f3,m} = -V_{f3,r} \pm 10\%$	$V_{f3,m} = -V_{f3,r} \pm 10\%$
Case b	$V_{f3,m} = V_{f3,r} \pm 10\%$	$V_{f3,m} = V_{f3,r} \pm 10\%$
Case c	$V_{f3}, m = V_{f3}, r, \pm 10\%$	$V_{f3}, m = V_{f3,r} \pm 10\%$
Case d	$V_{f3,m} = V_{f3,r} \pm 10\%$	$V_{f3,m} = V_{f3,r} \pm 10\%$

4. Requirement: The rise time of the model with regard to the velocity of first boom shall be within a 10% margin of the real system for a step input.

Table D.14. Test case 4 input values

Input (angular velocity)	Case 1	Case 2
Function 1	$-\omega_{f1,max}$ to $\omega_{f1,max}$	$\omega_{f1,max}$ to $-\omega_{f1,max}$
Function 2	0	0
Function 3	0	0

Table D.15. Test case 4 input values

Input (angular velocity)	Case 3	Case 4
Function 1	0 to $-\omega_{f1,max}/2$	0 to $\omega_{f1,max}/2$
Function 2	0	0
Function 3	0	0

Table D.16. Test case 4 input values

Input (angular velocity)	Case 5	Case 6
Function 1	$-\omega_{f1,max}$ to $\omega_{f1,max}$	$\omega_{f1,max}$ to $-\omega_{f1,max}$
Function 2	$\omega_{f2,max}$	$\omega_{f2,max}$
Function 3	$-V_{f3,max}$	$V_{f3,max}$

Table D.17. Test case 4 input values

Input (angular velocity)	Case 7	Case 8
Function 1	0 to $-\omega_{f1,max}/2$	0 to $\omega_{f1,max}/2$
Function 2	$-\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.18. Test case 4 initial state

State (position)	Case a
Function 1	N/A
Function 2	N/A
Function 3	N/A

Table D.19. Test case 4 expected outcome

State/input	Case 1	Case 2
Case a	$t_{f1,m} = t_{f1}, r \pm 10\%$	$t_{f1,m} = t_{f1}, r \pm 10\%$

Table D.20. test case 4 expected outcome

State/input	Case 3	Case 4
Case a	$t_{f1,m} = t_{f1}, r \pm 10\%$	$t_{f1,m} = t_{f1}, r \pm 10\%$

Table D.21. test case 4 expected outcome

State/input	Case 5	Case 6
Case a	$t_{f1,m} = t_{f1}, r \pm 10\%$	$t_{f1,m} = t_{f1}, r \pm 10\%$

Table D.22. Test case 4 expected outcome

State/input	Case 7	Case 8
Case a	$t_{f1,m} = t_{f1}, r \pm 10\%$	$t_{f1,m} = t_{f1}, r \pm 10\%$

5. Requirement: The rise time of the model with regard to the velocity of second boom shall be within a 10% margin of the real system for a step input.

Table D.23. Test case 5 input values

Input (angular velocity)	Case 1	Case 2
Function 1	0	0
Function 2	$-\omega_{f2,max}$ to $\omega_{f2,max}$	$\omega_{f2,max}$ to $-\omega_{f2,max}$
Function 3	0	0

Table D.24. Test case 5 input values

Input (angular velocity)	Case 3	Case 4
Function 1	0	0
Function 2	0 to $-\omega_{f2,max}/2$	0 to $\omega_{f2,max}/2$
Function 3	0	0

Table D.25. Test case 5 input values

Input (angular velocity)	Case 5	Case 6
Function 1	$\omega_{f1,max}$	$\omega_{f1,max}$
Function 2	$-\omega_{f2,max}$ to $\omega_{f2,max}$	$\omega_{f2,max}$ to $-\omega_{f2,max}$
Function 3	$-V_{f3,max}$	$V_{f3,max}$

Table D.26. Test case 5 input values

Input (angular velocity)	Case 7	Case 8
Function 1	$-\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	0 to $-\omega_{f2,max}/2$	0 to $\omega_{f2,max}/2$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.27. Test case 5 initial state

State (position)	Case a
Function 1	N/A
Function 2	N/A
Function 3	N/A

Table D.28. Test case 5 Expected outcome

State/input	Case 1	Case 2
Case a	$t_{f2,m} = t_{f2,r} \pm 10\%$	$t_{f2,m} = t_{f1}, r \pm 10\%$

Table D.29. Test case 5 Expected outcome

State/input	Case 3	Case 4
Case a	$t_{f2,m} = t_{f1,r} \pm 10\%$	$t_{f2,m} = t_{f1,r} \pm 10\%$

Table D.30. Test case 5 Expected outcome

State/input	Case 5	Case 6
Case a	$t_{f2,m} = t_{f1,r} \pm 10\%$	$t_{f2,m} = t_{f1,r} \pm 10\%$

Table D.31. Test case 5 Expected outcome

State/input	Case 7	Case 8
Case a	$t_{f2,m} = t_{f1,r} \pm 10\%$	$t_{f2,m} = t_{f1,r} \pm 10\%$

6. Requirement: The rise time of the model with regard to the velocity of extension boom shall be within a 10% margin of the real system for a step input.

Table D.32. Test case 6 input values

Input (angular velocity)	Case 1	Case 2
Function 1	0	0
Function 2	0	0
Function 3	$-V_{f3,max}$ to $V_{f3,max}$	$V_{f3,max}$ to $-V_{f3,max}$

Table D.33. Test case 6 input values

Input (angular velocity)	Case 3	Case 4
Function 1	0	0
Function 2	0	0
Function 3	0 to $-V_{f3,max}/2$	0 to $V_{f3,max}/2$

Table D.34. Test case 6 input values

Input (angular velocity)	Case 5	Case 6
Function 1	$\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	$-\omega_{f2,max}$	$\omega_{f2,max}$
Function 3	$-V_{f3,max}$ to $V_{f3,max}$	$V_{f3,max}$ to $-V_{f3,max}$

Table D.35. Test case 6 input values

Input (angular velocity)	Case 7	Case 8
Function 1	$-\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	$\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	0 to $-V_{f3,max}/2$	0 to $V_{f3,max}/2$

Table D.36. Test case 6 initial state

State (position)	Case a
Function 1	N/A
Function 2	N/A
Function 3	N/A

Table D.37. Test case 6 expected outcome

State/input	Case 1	Case 2
Case a	$t_{f3,m} = t_{f3,r} \pm 10\%$	$t_{f3,m} = t_{f3,r} \pm 10\%$

Table D.38. Test case 6 expected outcome

State/input	Case 3	Case 4
Case a	$t_{f3,m} = t_{f3,r} \pm 10\%$	$t_{f3,m} = t_{f3,r} \pm 10\%$

Table D.39. Test case 6 expected outcome

State/input	Case 5	Case 6
Case a	$t_{f3,m} = t_{f3,r} \pm 10\%$	$t_{f3,m} = t_{f3,r} \pm 10\%$

Table D.40. Test case 6 expected outcome

State/input	Case 7	Case 8
Case a	$t_{f3,m} = t_{f3,r} \pm 10\%$	$t_{f3,m} = t_{f3,r} \pm 10\%$

7. The gallery pressure during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.

Table D.41. Test case 7 input values

State/input	Case 1	Case 2
Function 1	$\omega_{f1,max}$	0
Function 2	0	$\omega_{f2,max}$
Function 3	0	0

Table D.42. Test case 7 input values

State/input	Case 3	Case 4
Function 1	0	0
Function 2	0	$-\omega_{f2,max}$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.43. Test case 7 input values

State/input	Case 5	Case 6
Function 1	$-\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	0	$-\omega_{f2,max}$
Function 3	$-V_{f3,max}$	0

Table D.44. Test case 7 input values

State/input	Case 7	Case 8
Function 1	$\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	$\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	$V_{f3,max}$	$V_{f3,max}/2$

Table D.45. Test case 7 input values

State/input	Case 9	Case 10
Function 1	$-\omega_{f1,max}$	$\omega_{f1,max}/2$
Function 2	$\omega_{f2,max}/2$	$-\omega_{f2,max}$
Function 3	$-V_{f3,max}$	$-V_{f3,max}$

Table D.46. Test case 7 initial state

State (position)	Case a
Function 1	N/A
Function 2	N/A
Function 3	N/A

Table D.47. Test case 7 expected outcome

State/input	Case 1	Case 2
Case a	$p_{g,m} = p_{g,r} \pm 10\%$	$p_{g,m} = p_{g,r} \pm 10\%$

Table D.48. Test case 7 expected outcome

State/input	Case 3	Case 4
Case a	$p_{g,m} = p_{g,r} \pm 10\%$	$p_{g,m} = p_{g,r} \pm 10\%$

Table D.49. Test case 7 expected outcome

State/input	Case 5	Case 6
Case a	$p_{g,m} = p_{g,r} \pm 10\%$	$p_{g,m} = p_{g,r} \pm 10\%$

Table D.50. Test case 7 expected outcome

State/input Case 7	Case 8	
Case a	$p_{g,m} = p_{g,r} \pm 10\%$	$p_{g,m} = p_{g,r} \pm 10\%$

Table D.51. Test case 7 expected outcome

State/input	Case 9	Case 10
Case a	$p_{g,m} = p_{g,r} \pm 10\%$	$p_{g,m} = p_{g,r} \pm 10\%$

8. The upper side pressure for the first boom during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.

Table D.52. Test case 8 input values

Input (angular velocity)	Case 1	Case 2
Function 1	$\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	0	0
Function 3	0	0

Table D.53. Test case 8 input values

Input (angular velocity)	Case 3	Case 4
Function 1	$\omega_{f1,max}$	$\omega_{f1,max}/2$
Function 2	$\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.54. Test case 8 input values

Input (angular velocity)	Case 5	Case 6
Function 1	$-\omega_{f1,max}$	$-\omega_{f1,max}/2$
Function 2	$\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.55. Test case 8 initial state

State (position)	Case a
Function 1	N/A
Function 2	N/A
Function 3	N/A

Table D.56. Test case 8 expected outcome

State/input	Case 1	Case 2
Case a	$p_{1u,m} = p_{1u,m} \pm 10\%$	$p_{1u,m} = p_{1u,m} \pm 10\%$

Table D.57. Test case 8 expected outcome

State/input	Case 3	Case 4
Case a	$p_{1u,m} = p_{1u,m} \pm 10\%$	$p_{1u,m} = p_{1u,m} \pm 10\%$

Table D.58. Test case 8 expected outcome

State/input Case 5	Case 6	
Case a	$p_{1u,m} = p_{1u,m} \pm 10\%$	$p_{1u,m} = p_{1u,m} \pm 10\%$

9. The lower side pressure for the first boom during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.

Table D.59. Test case 9 input values

Input (angular velocity)	Case 1	Case 2
Function 1	$\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	0	0
Function 3	0	0

Table D.60. Test case 9 input values

Input (angular velocity)	Case 3	Case 4
Function 1	$\omega_{f1,max}$	$\omega_{f1,max}/2$
Function 2	$\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.61. Test case 9 input values

Input (angular velocity)	Case 5	Case 6
Function 1	$-\omega_{f1,max}$	$-\omega_{f1,max}/2$
Function 2	$\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.62. Test case 9 initial state

State (position)	Case a
Function 1	N/A
Function 2	N/A
Function 3	N/A

Table D.63. Test case 9 expected outcome

State/input	Case 1	Case 2
Case a	$p_{1l,m} = p_{1l,r} \pm 10\%$	$p_{1l,m} = p_{1l,r} \pm 10\%$

Table D.64. Test case 9 expected outcome

State/input	Case 3	Case 4
Case a	$p_{1l,m} = p_{1l,r} \pm 10\%$	$p_{1l,m} = p_{1l,r} \pm 10\%$

Table D.65. Test case 9 expected outcome

State/input	Case 5	Case 6
Case a	$p_{1l,m} = p_{1l,r} \pm 10\%$	$p_{1l,m} = p_{1l,r} \pm 10\%$

10. The lower side pressure for the second boom during steady state shall be within a 10% margin of the real system in all cases during 90% of the time.

Table D.66. Test case 10 input values

Input (angular velocity)	Case 1	Case 2
Function 1	0	0
Function 2	$\omega_{f2,max}$	$-\omega_{f2,max}$
Function 3	0	0

Table D.67. Test case 10 input values

Input (angular velocity)	Case 3	Case 4
Function 1	$V_{f1,max}$	$-\omega_{f1,max}$
Function 2	$\omega_{f2,max}$	$\omega_{f2,max}/2$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.68. Test case 10 input values

Input (angular velocity)	Case 5	Case 6
Function 1	$\omega_{f1,max}$	$-\omega_{f1,max}$
Function 2	$-\omega_{f2,max}$	$-\omega_{f2,max}/2$
Function 3	$V_{f3,max}$	$-V_{f3,max}$

Table D.69. Test case 10 initial state

State (position)	Case a
Function 1	N/A
Function 2	N/A
Function 3	N/A

Table D.70. Test case 10 expected outcome

State/input	Case 1	Case 2
Case a	$p_{2l,m} = p_{2l,r} \pm 10\%$	$p_{2l,m} = p_{2l,r} \pm 10\%$

Table D.71. Test case 10 expected outcome

State/input	Case 3	Case 4
Case a	$p_{2l,m} = p_{2l,r} \pm 10\%$	$p_{2l,m} = p_{2l,r} \pm 10\%$

Table D.72. Test case 10 expected outcome

State/input	Case 5	Case 6
Case a	$p_{2l,m} = p_{2l,r} \pm 10\%$	$p_{2l,m} = p_{2l,r} \pm 10\%$