Automatic bucket fill

Thesis in Automatic Control
at Linköpings Tekniska Högskola

By

Håkan Almqvist

LITH-ISY-EX—09/4253—SE

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Sammanfattning

This report contains the first step towards a complete, fully autonomous, robust bucket fill regulator for a wheel loader working with gravel materials.

The bucket fill procedure is the most critical part of the work cycle of a wheel loader. It is a task that has a long learning curve and also is weary, even for experienced drivers. The automation of it could therefore have a big impact on the cost effectiveness for wheel loaders and for the comfort of the drivers.

In this report a suggestion for the complete solution of an automatic bucket fill regulator is presented. A regulator prototype is also constructed with a Volvo L120F as the base. The scope for the prototype is limited to one type of gravel material and quite optimal conditions for the wheel loader, but the complete solution is kept in mind throughout the synthesis. The constructed regulator is prepared for expansion, but the implementation and field testing is limited to the scope.

Nyckelord
Autonomous wheel loader, automatic control, construction equipment

Abstract:

This report contains the first step towards a complete, fully autonomous, robust bucket fill regulator for a wheel loader working with gravel materials.
The bucket fill procedure is the most critical part of the work cycle of a wheel loader. It is a task that has a long learning curve and also is weary, even for experienced drivers. The automation of it could therefore have a big impact on the cost effectiveness for wheel loaders and for the comfort of the drivers.
In this report, a suggestion for the complete solution of an automatic bucket fill regulator is presented. A regulator prototype is also constructed with a Volvo L120F as the base. The scope for the prototype is limited to one type of gravel material and quite optimal conditions for the wheel loader, but the complete solution is kept in mind throughout the synthesis. The constructed regulator is prepared for expansion, but the implementation and field testing is limited to the scope.

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Definitions

The Torque Parallel linkage (TP-Linkage) has some important parts and angles which are defined in Figure 1 and Table 1. Capital letters are joints. The linkage parts are named after their joints, for example the GDF-link is the link that is attached at point G, D and F.

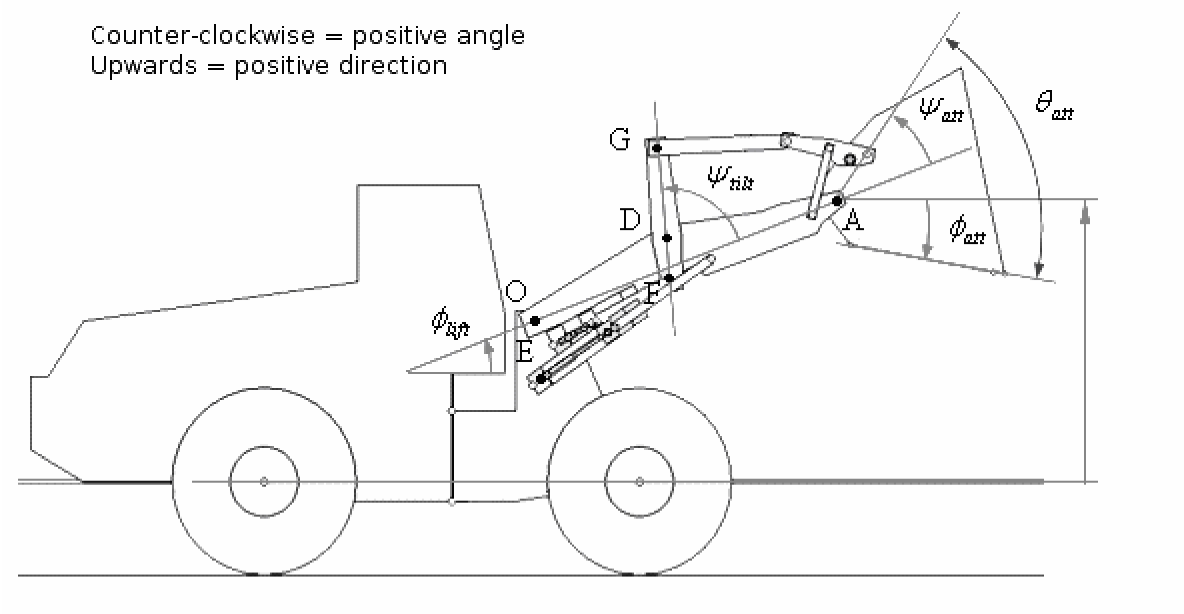

Figure 1, TP-Linkage definitions

Angle	Description
ϕ_{lift}	The angle between the horizontal axis of the machine and the boom.
ψ_{tilt}	The angle between the GDF-link and the boom.
ψ_{att}	The angle between the attachment and the boom.
θ_{att}	The angle between the attachment and the bucket bottom.
ϕ_{att}	The angle between the horizontal axis of the machine and the bucket bottom.

Table 1, Angle descriptions

The coordinate system used is three dimensional and is defined according to figure 2.

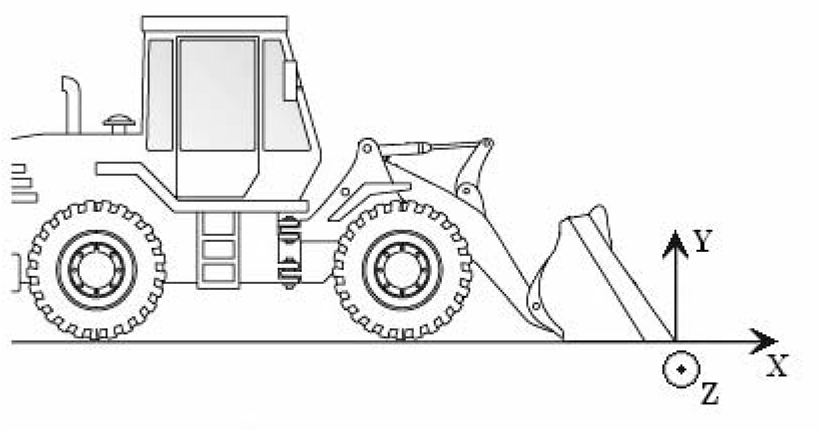

Figure 2, Coordinate system

Nomenclature

- **Boom:** The moveable lift arms holding the bucket
- **Bucket fill:** Filling of a bucket; the procedure where a wheel loader moves into a pile and fills the bucket with material.
- **CAN-bus:** Controller area network bus; A vehicle bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer.
- **Chic-chic strategy:** A strategy for filling the bucket where the bucket is translated through the gravel pile with an alternating switching between the lift and the tilt.
- **ECU:** Electronic control unit; an embedded system that controls one or more of the electrical systems in a vehicle.
- **Efficiency:** Efficiency is the term for how much material is handled per fuel unit.
- **HMI:** Human-Machine Interface, the interface between the operator and the machine, i.e. information displays, buttons etc.
- **Lift stall:** When the pile counter force on the lift cylinder is greater than the maximum hydraulic force and the lift speed reaches zero.
- **Pile counter force:** The force from the pile acting on the machine as a normal force against the force induced by the machine on the pile.
- **Productivity:** Productivity is the term for how much material is handled per time unit.
- **RPM:** Revolutions per minute.

- **Translation Force:** The total force induced by the machine translation.

- **Translation stall:** When the counterforce is greater than the translation force and the velocity reaches zero.

1. Introduction

Effective ways of moving gravel material is a task of great importance, today as well as through history. In many construction projects it is important to have solid foundations, which often require the moving of large amounts of soil, dirt, gravel and rocks. This is often a time and cost consuming process but nonetheless very important. In this project, the aim is at loading gravel material from piles on the ground onto trucks or into gravel pockets.

1.1. Motivation

Speed and efficiency is of utmost importance in the loading process. Short loading times with good performance can reduce the cost per ton of moved material drastically. When dealing with wheel loaders, the bucket fill procedure is critical for the effectiveness of the driver.

Experienced drivers fill the bucket completely and faster than inexperienced drivers and also have more endurance. But all drivers have their limitations and no matter whether it is wear or inexperience that is the cause, the productivity is not always on top.

Today's technology allows for electronic driver aid systems in most machines, and for wheel loaders the biggest problem is the bucket fill. An automated bucket fill regulator would therefore provide an improvement in productivity, efficiency and driver comfort.

1.2. Problem formulation

The first question is: How is a bucket fill performed by a human operator? The answer to this question leads to the next ones: Can this behaviour be transferred to an autonomous machine and can the autonomous solution reach a productivity and efficiency comparable to the human operator?

1.3. Scope

The goal for this project is to make a wheel loader be able to fill one bucket of gravel with a number of prerequisites listed in table 2. The scope has been considerably limited to give the project good chances for success.

Req. no.	Description	Level
1	The pile shall consist of pea gravel in the size range of 10-15 mm	Basic
2	The pile shall be homogenous and dry	Basic
3	The pile shall have a known and constant profile angle	Basic
4	The pile shall have a flat extension on the Z-axis that is twice as wide as the bucket in both directions	Basic
5	The pile shall be backed by a solid support higher than 2 meters	Basic
6	The ground shall be flat in the entire area of operation	Basic
7	The machine shall be positioned at a known distance from the pile	Basic
8	The machine shall stand facing straight towards the pile	Basic

Table 2, Prerequisites

1.4. Format of thesis

First a short background is presented in chapter 2. It is followed by a review of currently existing automatic bucket fill systems in chapter 3. Chapter 4 summarizes the previous work on this project. Chapter 5 continues with research performed on the matter and chapter 6 with the conclusions drawn and isolation of problems. Chapter 7 concerns the design of the system and chapter 8 contains a short description of the main parts of the synthesis. Chapter 9 goes through tests of the system and the results are summarized in chapter 10 which is followed by a brief discussion and suggestions on future work in chapter 11.

2. Background

This chapter contains some information about wheel loaders in general and more specifically about Volvo wheel loaders. The machine used in this project is also presented along with some of its important features. Finally there is a short description of the intended application for the machine.

2.1. Wheel loaders, an introduction

A wheel loader is a machine with wheels and a bucket mounted on two arms in the front. Its main purpose is to move loose material like sand, dirt and gravel, from one place to another without pushing it along the ground. To be able to pick up the material and to drop it off, the bucket must be able to move. Most wheel loaders use hydraulics to control the bucket.

Wheel loaders exist in a great variety of sizes and power, depending on what the purpose for them is. Most wheel loaders have the ability to change the bucket into other tools, for example forks or a snowplough. This makes wheel loaders versatile machines and they are a common sight on building sites and in industrial areas.

Volvo created it is first wheel loader in 1954. It was simply a tractor turned back-to-front with the load unit placed over the bigger wheels which resulted in higher breakout forces and the ability to carry bigger loads. Also the placing of the steering wheels at the back resulted in great manoeuvrability.

The wheel loader has evolved quite a bit since the 1950's even though the basic idea is the same. Most new wheel loaders have articulated steering, which means that the machine is turning by twisting it is body around it is centre. The advantages are better manoeuvrability in tight spaces and the ability to move the bucket sideways in an arc while the machine stands still. The disadvantage is that when a heavy load is raised high up in the air, the risk for falling over increases.

2.2. Volvo's current wheel loaders

Volvo is manufacturing wheel loaders in a great variety of sizes; from the tiny L20B to the massive L350F. The L20B weighs 4.5 tons, has a 55 hp engine and use buckets from 0.65-1.1 m³. The L350F on the other hand weighs 50-56 tons, has a 16 litre 540 hp engine and use buckets from 6.2 up to 12.7 m³. The most popular wheel loaders though are the middle sized ones, for example the L120F which is used in this project.

2.2.1. L120F

The L120F features a 7.1 litre 170 kW (245 hp) engine and weighs 19-21 tons depending on configuration. It uses buckets from 2.6 to 9.5 m³ with a variety of applications. The bucket size depends on the purpose and the machine is available with a hydraulic attachment bracket for fast swapping of tools. The standard, general purpose bucket is 3.3m³ in size.

The machine has an automatic gear box. It has four different gears and forward, neutral and reverse mode. The four gears are common for both forward and backward movement.
The engine is used both for translation and to run the hydraulic system. A converter distributes the engine power between the wheels and the hydraulics.

The L120F has many different features, and the ones which are relevant to this project is listed here:

- **APS:** Automatic power shift. The L120F is fitted with the APS gear system that automatically shifts between gear 2, 3 and 4. It has 4 different settings, L, M, H and AUT that provide different gear shift profiles for different conditions.

- **FAPS:** Fully automatic power shift. An extension to the APS system. The FAPS can also engage the first gear when necessary.
- **Tool Lock:** To ensure fast tool changes, the L120F has a hydraulic tool lock that locks or releases the current tool.
- **BSS:** Boom suspension system. The boom suspension system prevents the rocking of the machine when driving on bumpy roads with heavy loads in the bucket. The system has two settings. Gear dependant or speed dependant. The gear dependant setting activates the BSS when driving in gear 2 or higher. The speed dependant activates the system when the speed exceeds 5 km/h in forward direction or 2km/h while going backwards.
- **CDC:** Comfort drive control. The CDC provides electronic steering with a lever instead of the steering wheel. The aim is to increase the comfort for the driver by letting him manoeuvre the machine with much smaller movements.
- **Kick down:** Kick down applies the first gear if the machine is travelling slower than 8 km/h. This gear is then kept until the gear direction is changed or if the engine RPM reaches very high values.

2.3. Re-handling and gravel types

One typical and common application area for the wheel loader is the re-handling of materials. A good example of re-handling is an asphalt mill. Asphalt is made of different kinds of gravel and binding agents according to different recipes. Haulers or trucks transport the gravel to the site and put it in big piles. The wheel loader is then used to supply the mill with the different gravel types.

Re-handling is a very repetitive work and contains isolated work tasks often in a confined area. The materials are also well defined and homogenous and further emphasises the repetitive nature of the work.

There are many different gravel types, classified by their size. The particles found in mud and sand are the smallest ones with particle diameters from 0-4 mm and on the other end of the scale is boulder with particle diameters above 256 mm.

The gravel types which are used in an asphalt mill range from sand/granule mixture to coarse gravel. The particle sizes are from 0-4 mm in diameter for sand/granule up to 16-32 mm in diameter for coarse gravel. The materials characteristics are defined by the size of the particles and their adhesive ability. Also temperature and humidity can have effect on the characteristics.
One of the easiest materials to handle is the medium sized gravel because of it is inability to stick together and it is fluid-like characteristics. When material is removed from a pile, the material above roll down and keeps the angle of the pile quite intact. Small-sized materials on the other hand often glue together and could cause the angle of the pile to be very steep, in some cases even with a negative angle.

3. Technology review

Since the fill grade of material in the bucket has such big effect on productivity, it is of great interest for the manufacturers of wheel loaders to make the filling process as easy as possible. This has rendered in a number of studies and tests in the area and also some implementations in production. The existing production systems though are all semi-automatic. The bucket lift and tilt motion is autonomous but it is up to the driver to control the advancement of the machine

3.1. Competitor systems

Komatsu and Caterpillar, two of Volvo CE's main competitors, have developed semi automatic bucket fill functions to help drivers to keep up productivity. A small evaluation of these systems has been made. The interesting areas are the speed, bucket fill grade and smoothness of the systems.

3.1.1. CAT

CAT has an aggregate autodig system option available on their wheel loaders since 2002. The feature documentation claims that it "fully automates the loading process" and it is, according to CAT, well received among both experienced and novice operators.

The system will control the lift and tilt functions when loading the bucket. Some conditions however must be fulfilled for the system to work.
The driver must:

- Place the bucket within 60 cm from the ground.
- Tilt the bucket to a near-level position (+- 10 degrees).
- Not perform any gear change within 0.5 seconds before activating the function.
- Not make any directional changes and keep the neutralizer inactive.
- Center the lift and tilt levers.

The autodig system is designed for loose gravel-like material of different sizes, but not large rocks or other "big" materials. It has nine different factory installed bucket fill sequences which are designed for different material weights. It has a recording mode where the driver can record and store his own filling sequence and there is also a function for setting the autodig kickout height (How high the wheel loader lifts the bucket before deactivating autodig).

The autodig function is, when active, started the moment the bucket enters the material, from that instant all that the driver needs to do is to handle the gas pedal and the steering. There is also a possibility to deactivate this "autostart" function and let the driver decide when to activate the autodig.

The autodig is activated by the pressure on the bucket, even when used in driver activation mode. If there is no pressure on the bucket (i.e. there is no material in the bucket) the function will not start. When the pressure on the bucket reaches a certain level the autodig function lifts the bucket a little to apply pressure on the front wheel axle. Then it seems to wait until the bucket pressure reaches a new threshold value before it starts to tilt the bucket. The function mainly uses the tilt function in all nine different factory settings but it also does small movements with the lift. Those lift movements seems to vary depending on which setting is currently used.

When tested in a mixed material (gravel size ranging from sand to 10-15 cm rocks) the autodig fills the bucket almost completely but the material was, on every attempt, placed too

close to the front edge of the bucket and the function doesn't adjust the placement of the material in the bucket.
When tested in a more homogenous material (gravel size approx. 15-30mm) the autodig performed better. It filled the bucket even better than the mixed material tests. The material was also placed closer to the middle of the bucket. The filling grade and the placement of the gravel seems to be independent of which gravel-size setting is used, but this is based on too few tests to be reliable.

3.1.2. Komatsu

Komatsu has an electronic two-lever control option (EPC) and it contains among other features a semi automatic dig function. It was introduced in the DASH 5 series of wheel loaders in the year 2001.

The Komatsu system is simpler than the CAT system. It has an on/off button and a selector for ROCK and LOOSE materials. To activate it, the driver must lower the bucket to approximately 30 cm above the ground, press the kick down button to shift gear to the lowest possible, drive the bucket into the pile and move the lifter to RAISE and then back to HOLD. The system will manoeuvre the lift and the tilt during the bucket filling sequence until any of the following occurs:

- The bucket is fully tilted.
- The lifters are above their horizontal position.
- The gear shifter is put in another position than FORWARD.
- The switch for semiautomatic dig is turned to the OFF position.

All those cases inactivate the semiautomatic dig function.

The semiautomatic dig is manually activated by the driver but it does not start until there is enough material in the bucket just as the CAT system. Since the driver has to apply pressure manually on the front axle of the machine, the systems task is easier. It wait is until a pressure threshold and then starts to tilt the bucket. The observations that were made in the field test show that the semiautomatic dig mainly, if not only, uses the tilt function. The machine seems to use feedback from at least the pressure sensors to adjust the tilt since every attempt in the test shows a different tilt movement pattern. The difference between the ROCK and LOOSE modes is small, but the ROCK setting seems to work best independent of material.

Just as the CAT the Komatsu has the problem of placing the mixed material in the front end of the bucket and not adjusting it at all. It is almost impossible to fill the bucket completely without a proper placement of the material in the bucket. The performance in the homogenous material is better but in this material the bucket gets overloaded and a lot of gravel is spread out as a consequence; this could though be a matter of practice to get the acceleration to work better with the semiautomatic dig.

The biggest problem with the Komatsu system is that the function is tricky to start in a good way. When driving into the pile the driver has to, as mentioned, apply pressure by himself as a starting signal to the semiautomatic dig. The semiautomatic dig also sometimes seem to take a while to start which lead to the machine just standing still with the bucket in the pile for several seconds which affects productivity in a negative way.

4. Previous work

This thesis is a continuation on the work of three previous students. Two of the students constructed the hardware for the autonomous machine, and the third one constructed a software interface to the machine and the extra hardware *[2][3]*. This chapter contains a brief summary of their work.

Figure 3, The autonomous machine

4.1. The autonomous machine

The machine is, as mentioned earlier, a Volvo L120F wheel loader as shown in Figure 3. Volvos modern wheel loaders are already fitted with several sensors and they are also in many ways controlled by computers. Each wheel loader features at least three ECU units. There is an instrument ECU, an Engine ECU and a hydraulics ECU. In the larger models there is also a separate transmission ECU, the transmission is handled by the engine ECU in the smaller models. They communicate via a CAN bus interface. The previous thesis workers have implemented an interface to the machine which gives full controllability as well as sensor feedback to the connected equipment.

4.1.1. The interface

Most functions in Volvo wheel loaders are nowadays electrically controllable, and all internal communication in the machine travels on the CAN bus. To connect to the CAN bus a Pip8 (Packaged Industrial PC) from the Swiss company MPL AG, has been used. It is connected to the CAN bus, the machines electrical system and some special equipment.

The Pip8 is running a compiled Simulink model, shown in Figure 4, through the XPC-target™ interface.

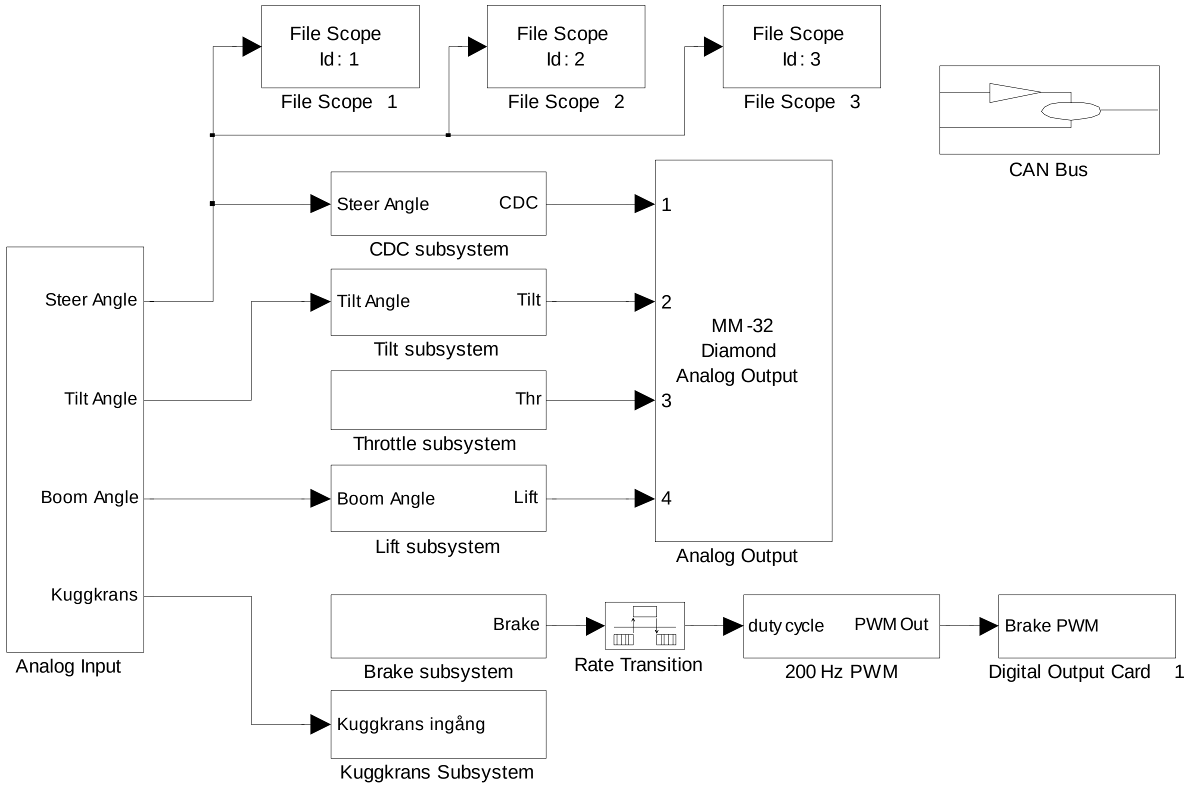

Figure 4, Original Simulink main structure

The Pip8 is connected to a windows laptop and they communicate via the TCP/IP protocol. The laptop is the supervisor of the Simulink model and is supposed to contain most of the intelligence. The supervisor program is custom made for this application in C++ by one of the previous thesis workers.

4.1.2. Special equipment

Where the machines own sensors or systems was not sufficient, the previous thesis workers added equipment to ensure full controllability of the machine.

4.1.2.1. Brakes:

The machine braking system is hydro mechanical, therefore an electric brake pump has been added to allow electric control of the brakes.

4.1.2.2. Inclinometer:

To get information about the machines angle of inclination, an inclinometer has been mounted. It is mounted in the centre of the machine and outputs the machines inclination in the horizontal plane.

4.1.2.3. Speed sensor:

The machines standard speed sensor has too low resolution for this application, and it also does not know which direction the machine travels in. Therefore a new speed sensor with better resolution and direction detection has been mounted on the drive shaft. It replaces the standard speed sensor. The only drawback with the new sensor is that it can not detect wheel spin.

4.1.3. The Simulink model

The Simulink model recieves commands from the laptop and execute them in the machine. It also monitors sensor feedback and continuously regulates the commands passed on to the machine. The regulators are PI-regulators with saturation compensation as seen in Figure 5.

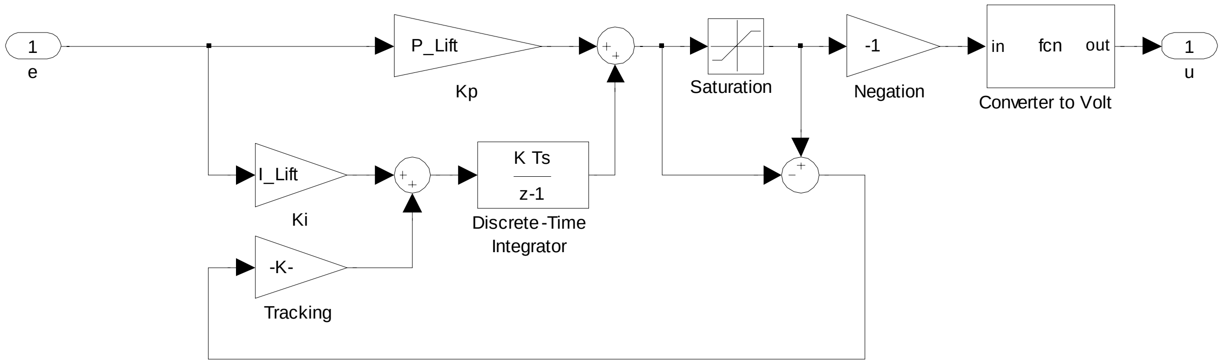

Figure 5, Example of PI-regulator with saturation compensation

The model in the format passed on by the previous thesis workers only handles simple commands, but it can handle several commands at one time so the machine can perform simultaneous tasks.

4.1.4. The C++ supervisor program

The top level machine control takes place in the C++ program. There are two different demonstration sequences created and it also features a manual mode where commands can be sent to the machine by the user, shown in Figure 6.

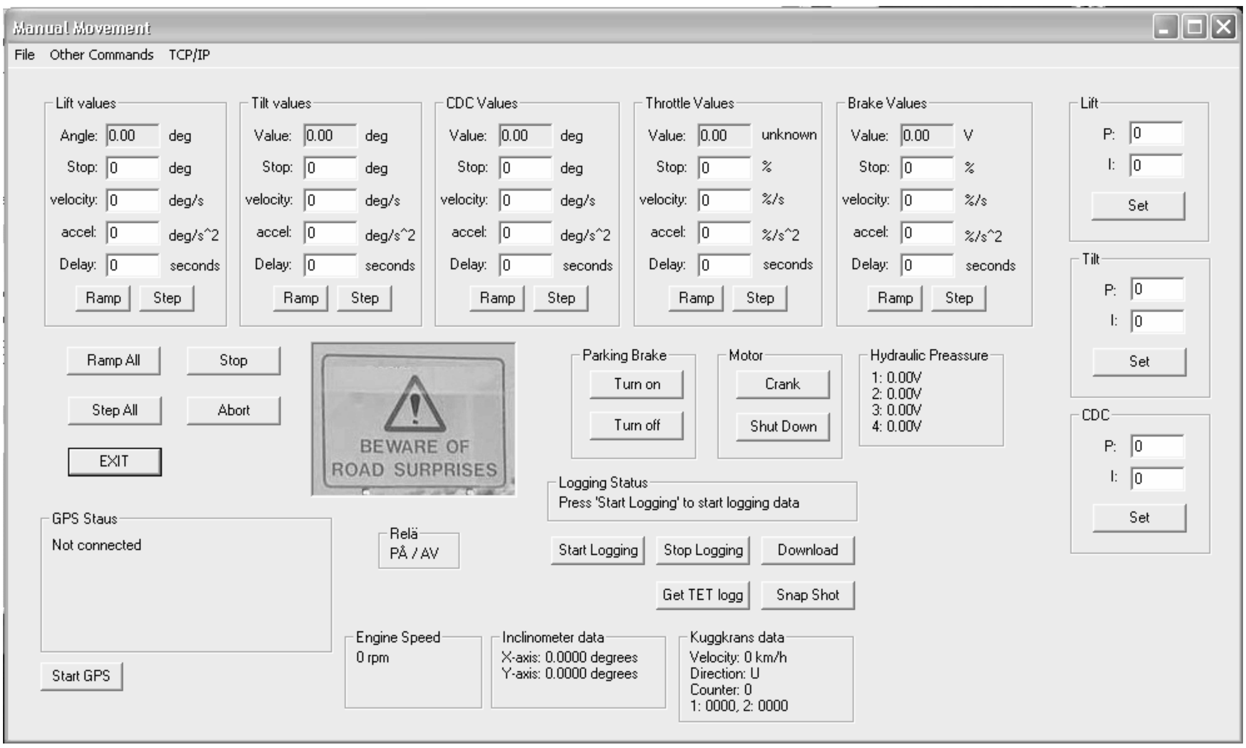

Figure 6, The manual window

The user can send different types of commands to the machine, from smooth controls of the hydraulics to turning on the horn.

4.1.5. Ramp function

To perform smooth movement of for example the boom, one of the previous thesis workers has developed a ramp function. The user defines a start and stop angle for the boom and a velocity and acceleration value. The program then translates the boom from the starting angle to the stop angle, using the acceleration value to initiate and stop the movement smoothly. The velocity value decides the maximum movement speed.

Ramp functions are available for the lift, tilt and steering control.

5. Research, interviews and measurements

The bucket fill procedure is a complex operation with a lot of input parameters and choices to be made. To understand all details and also see the big picture, interviews, literature research and measurements have been performed. The material has been evaluated and compiled into a theoretic description of the bucket fill procedure.

5.1. State definition

The bucket fill procedure is a complex procedure. To easier understand and describe the process it has in this project been divided into several parts, called states. Each state contains one or more distinctive tasks and has well defined entry conditions and exit conditions which will be presented soon. The entry conditions are the information needed by the state to perform it is task. The exit conditions are the information passed on by the state. The current machine status, derived from the machine sensors, is a common entry and exit condition for all state transitions.

Status type	Description
Translation speed	The current speed of the machine, measured on the drive shaft.
Translated distance	Distance travelled since the system was activated.
Translation direction	Forward, neutral or backward.
Boom angle	The current angle of the boom relative to the machine.
Tilt angle	The current angle of the GDF-link relative to the boom.
CDC angle	The current waist angle of the machine.
Lift cylinder pressures	The pressures on both ends of the lift cylinder.
Tilt cylinder pressures	The pressures on both ends of the tilt cylinder.
Brake pressure	The current brake pressure.
Inclinometer data	The angle of the machine in X- and Y-direction.

Table 3, Machine status parameters

The states are always carried out in the same order. The machine status conditions listed in table 3 are inherited as entry and exit conditions by the states when a state shift occurs. In some states special parameters are added to the machine status parameters. Those are listed in their respective state description.

5.1.1. State 1: Approach

State 1 is the beginning state of the procedure. This state begins with the machine standing in standby on the ground at a known distance from the pile. During this state the task is to translate the wheel loader from it is starting position to the pile, reaching and holding a set speed when entering the pile. The bucket is also placed in the correct position for entering the pile during this state. The translated distance, and thereby the remaining distance to the pile, is calculated continuously throughout the state and the state is finished when the bucket tip reaches the pile.

5.1.1.1. Extra entry conditions state 1

Pile Angle: The machine has to have some knowledge about the gravel pile to be able to perform a bucket fill.
Distance to pile: The machine also must know where the pile is located since no vision system is currently used.

5.1.2. State 2: Entry

State 2 is activated the moment the bucket tip enters the pile. The task during this state is to move the bucket into the pile while not moving it vertically. The counter force from the pile will increase during this state. This is seen in the feedback from the lift cylinder pressure sensor. The state is finished when a certain pressure threshold is reached.

5.1.3. State 3: Apply pressure

The purpose of state 3 is to apply pressure on the front axis of the machine to avoid wheel slip. During this state, the bucket is lifted but not tilted until a sufficient pressure is reached. The state is finished when the pressure threshold is reached.

5.1.4. State 4: Fill the bucket

State 4 is the most complex state during the bucket fill procedure. During this state the bucket is lifted and tilted through the gravel pile with the aim to fill the bucket with gravel. The state is finished when the bucket tip exit the original gravel pile profile. This occurance is calculated with the aid of the translated distance, the pile angle and the boom and bucket angles.

5.1.4.1. Extra entry condition in state 4

Distance Travelled since state 2: This parameter is needed to be able to calculate the pile profile.

5.1.5. State 5: Position the material

The purpose of the final state is to position the material in the bucket to avoid unnecessary spilling of material. The state is finished when the bucket tilt cylinder reaches its end position.

5.2. Literature Research

Several documents regarding autonomous construction equipment in general and wheel loaders in particular have been studied. One of the most extensive ones is presented here.

5.2.1. A study on automatic control of wheel loaders in rock or soil loading

In “A study on automatic control of wheel loaders in rock or soil loading” (Long Wu 2003) a method for autonomous loading is proposed. The method is backed by a thorough theory and simulations, but has never been tested in reality. Wu’s theory on bucket fill proposes a smooth movement of the bucket through the pile. He divides the bucket fill into three steps, attacking, crowding and scooping. The attack phase consists of placing the bucket in the correct position and approaching the pile. The crowding phase begins when the bucket enters the pile and ends when the bucket leaves the ground. Finally, the scooping is the phase where the bucket is moved through the pile following a smooth trajectory and ending with the bucket exiting the pile. Wu also considers rock loading, but since this is out of the scope of this project, these parts are not considered here.

There are several parts in his approach which are too simplified or left out to perform a high quality bucket fill. These are the three main issues with Wu’s approach:

1. During the crowding phase, it is of great importance to actively apply pressure on the front axis of the machine. If this is left out, the risk for wheel slip is too large to be neglected. Wheel slip must never occur during normal conditions due to the massive increase in running costs.
2. Lu is suggesting a smooth trajectory through the pile as the most appropriate way to perform the scooping phase. This might be true in a perfect pile, but the experience and studies of wheel loader operators suggest that when the bucket fill is performed in a real pile, another approach is required. The materials in piles stick together more or less, depending on material size, material pollution, humidity and temperature. The consequence of this is that if the operator don’t want to move unnecessary amounts of gravel through the pile, he needs to break loose the material by using the lift and tilt levers stepwise. This method will be described more thoroughly in chapter 6.

3. A high quality bucket fill procedure should leave the material well-centred in the bucket when finished. The reason for this is that if the material lies close to the edge of the bucket it is more likely that material will fall out during hauling or unloading. The amount of gravel falling out of the bucket could amount to several hundred kilos in a medium sized wheel loader which will decrease productivity considerably. Most experienced drivers carry out this centring manoeuvre while exiting the pile by letting the bucket slam into the tilt-stop in the end of the tilting manoeuvre.

5.3. Interviews

Interviews have been performed with three experienced Volvo employees, which all are excellent at operating a wheel loader. To get comparable results, a questionnaire has been used. The interviews were split into two parts, one part where questions about efficiency was asked and a second part which was aimed at how to perform a bucket fill.

5.3.1. Efficiency

There are several important factors that determine the efficiency of the bucket fill. The statements and conclusions drawn in this part is derived directly from the interviews.

5.3.1.1. Fill grade

According to EU-standards, a wheel loader shouldn't carry more material in the bucket than 50% of the tipping load. Volvos recommendation is 47% of the tipping load. All participants in the interviews agree that this recommendation is a good aim for a perfect fill grade. Since the weight is the measurement of a good bucket fill, different buckets should be chosen for different materials. The bucket should be filled to approximately 105% of it is internal volume, but this is also dependent on the material. Some materials are more fluid than others and it can therefore be hard to fill the bucket to 105% and also a lot of spilling will be the result. Sticky materials can on the other hand allow even better fill grade without the risk of unnecessary spilling.

The reason for using different buckets for different materials is that the bucket size greatly affects the machine's ability to press the bucket through the material. Also different materials diverse in weight and therefore require different bucket sizes to reach the optimal load. A small bucket is easier to press through the pile than a bigger one, so an optimal bucket results in faster loading times and decreased fuel consumption.

5.3.1.2. Speed

Speed is directly connected to productivity. Even if the bucket fill is perfect in all other aspects, from fill grade to fuel consumption, it can never be a productive process if every fill takes several minutes. The speed issue is not as easy as just being as fast as possible though. It is possible to fill the bucket very fast, but a too fast behaviour will affect the fuel consumption and the wear of the machine. The goal shall therefore be to find the optimal loading speed where the fuel consumption and machine-wear is weighted against production speed to find the most cost effective solution.

The fill time is measured from the moment the bucket enters the pile until the driver puts in the reverse gear to move away from the pile. For a bucket fill in pea-sized gravel, the participants in the interviews estimate from 5 seconds to 8 seconds. This time is based on a well performed and endurable bucket fill with a L120F standard bucket ($3.3m^2$). With full focus on speed for short times it is possible to reach 3-4 seconds.

The time is affected by the material type to some extent but the times mentioned above are legitimate for most gravel types. Small sized or sticky materials as well as larger buckets often require more time.

5.3.1.3. Fuel consumption

No accurate fuel consumption measurements have been made for different loading styles, but experience tells that the fuel consumption is affected by several factors. Some of these have already been mentioned, like the speed, the material weight and the fill grade of the bucket. The most effective way of running the engine, according to one of the participants, is to keep it at 1300-1400 RPM, where the hydraulics reaches their maximum power, all the time. He adds though that this is not possible because the power is not enough for both the hydraulics and the translation through the entire bucket fill.

5.3.1.4. Wear

There are several crucial parts of the machine that are extra sensitive to incorrect treatment.

Wheels: The tyres on a wheel loader have an expected lifetime of approximately 6000 hours. This assumes that the machine is properly operated. If the driver is reckless or inexperienced, wheel spin could easily occur. This can shorten the lifetime of the tyres to 2000 hours and if the ground is rough it could even destroy brand new tyres. Wheel spin is totally forbidden because the high price on tyres for wheel loaders would increase the maintenance cost massively. All three participants agree on this.

Filling more than recommended: The machine is adapted for carrying a certain weight, and even if it is possible to lift more material than recommended it is not good. Overfill will increase the wear on the axles and joints of the lifting linkage and it could also increase the tyre wear according to one of the participants.

RPM: The engine lifetime could be affected negatively if the machine holds a too high RPM for long periods of time or if there often are big and fast variations in the RPM. The engine reaches it is maximum performance at approximately 1750 RPM so everything above that is a waste of fuel.

5.3.1.5. Quality:

It is important to perform every bucket fill with respect to the next one. If the bucket is pointing upwards relative to the ground in the beginning of each fill, the pile will soon get a wedge-shaped base. This affects the performance in two ways: First some material is lost to the base and secondly the fuel consumption could increase because of the uphill slope formed by the wedge.

It is even more important not to point the bucket downwards. This could introduce contamination from the underlying ground into the material and make the entire pile useless.

5.3.2. Performing a bucket fill

The second part of the interviews is concerning the bucket fill procedure. The aim was to extract an, as accurate as possible, description of the bucket fill procedure. To get comparable results from the persons interviewed, the state model of the bucket fill has been used.

5.3.2.1. State 1, Approach

All three participants agree on the following:

- The bucket shall be put on the ground approximately 1.5 to 2 meters before the pile. The reason for putting it down so early is to gather material that might have fallen off or was missed in the previous bucket fill.
- The speed when entering the pile shall be in the range of 2 to 4 km/h.

- The bucket shall be parallel to the ground when lowered. It shall then be kept parallel and slightly pressed down so it scrapes up missed material. The down pressure shall be barely measurable on the lift cylinder.

Two of the participants claim that the kickdown shall be applied during this state, before the pile is reached. The other one says that the kickdown shall be applied during state 2. The RPM is supposed to be kept at approximately 1100-1200 according to two and 1300-1400 according to one.

5.3.2.2. State 2, Entry

All three participants agree on the following:

- The bucket shall be kept in the same position during the entire state.
- The speed shall be held at around 3 km/h.

One of the interviewed persons claims that the RPM should be increased to 1500 as soon as the counter force from the pile is sensed. The others are more restricted on the RPM, one wants to keep the same RPM as in state 1, around 1200, and the other want a slight increase up to around 1300-1400. They all agree on the exit conditions of this state. As soon as a considerable counter force is felt it is time to switch state. Also the engine sound will change when the counter force is increased. It is also possible to see on the material when it is time according to one participant. The distance translated when this occurs is diverse in the interviews. One participant is claiming at most 20 cm into the pile, another one claims approximately 30 cm, and the third one claims approximately 50 cm.

5.3.2.3. State 3, Apply pressure

All three participants agree on the following:

- The bucket shall be lifted smoothly.
- The speed shall be held at around 3 km/h.

Two of them claim that it shall be lifted to approximately 0.5 meters, and one say only 0.1 meter. The lift cylinder pressure shall increase above 50% of lift stall pressure, one claim up to 100% of lift stall. None of the drivers could give any exact values of the lift manoeuvre angle.

5.3.2.4. State 4, Fill the bucket

Two suggestions on different strategies during state 4 were presented in the interview. The drivers gave their opinion on both of them. The methods are the J-curve model, where the aim is a smooth movement through the pile, and the stepwise model, where the aim is a stepwise movement through the pile. There were also a third strategy, called re-take, where the bucket was tilted downwards a bit in the middle of the 4th state. The aim is to allow a deeper penetration than the other strategies. This model was rejected by all drivers because of the downwards movement. The risk for wheel slip is too big to consider this strategy. One of the drivers claims that he only uses the J-curve strategy, one claim that he uses both and one that he only uses the stepwise model.

<u>J-curve strategy:</u>

The two drivers that use the J-curve strategy agree on the following:

- There shall be a continuous output on the lift and tilt levers.
- The lift and tilt levers shall be used sequentially to follow a smooth path.
- The engine shall be kept at around 1500-1600 rpm.
- The machine shall come to a halt when the state ends.

One driver claims that the lift pressure shall be kept well below stall pressure. The exit condition is, according to the same driver, when the wheels are in line with the original pile profile. The other driver claims that the state ends when the lift arms are horizontal.

Stepwise strategy: Two drivers use the stepwise strategy. They agree that the throttle shall be used to determine the penetration depth. Otherwise they have a slightly different approach. One driver claims that the tilt shall not be moved more than 10° per step and this manoeuvre shall be rhythmically repeated until the bucket is almost fully tilted. The other driver claims 10°-15°. This driver also claims that only two steps shall be performed and that the J-curve strategy shall be used after these steps. Both drivers claim that an engine rpm between 1600 and 1800 is sufficient.

The speed during state 4 shall be kept at approximately 2-3 km/h independent of strategy according to all drivers. The speed is allowed to drop when the state is finished.

5.3.2.5. State 5, Position the material

All three drivers have a quite similar view on state 5. They agree on the following:

- The tilt shall be slammed into the mechanical stop position and the lever shall be released when this occurs.
- The machine shall come to a halt.
- The engine rpm shall return to almost idle.

The bucket fill procedure is over when the bucket has reached the end tilt position and the machine is ready to reverse away from the pile.

5.4. Measurements

To strengthen or dismiss the statements in the interviews measurements has been performed on bucket fill procedures performed by several skilled drivers, both drivers from the interviews and others.

5.4.1. Mathematics

The measurements are extensive and provide a lot of different data about the machine. Some of these are more interesting for the bucket fill than others. The ones that require certain attention are these:

- Boom angle
- Tilt angle
- Lift cylinder pressure
- Tilt cylinder pressure
- Machine velocity
- Translation distance
- Engine RPM

This selection of data should provide enough information to cover all manoeuvres of interest performed by a driver during the bucket fill. It is also possible to calculate the bucket tip movements during the bucket fill procedure from the above data selection.

Measurements from two different sources have been studied. The first measurement is carried out in the autonomous machine, which is fitted with a logging function for all sensor feedback signals. Here an experienced driver has been used who performed bucket fill procedures in a gravel material.

The second is measurements stored in the program Infield. These measurements aren't specifically carried out for the bucket fill project, but they contain all relevant data. The studied Infield data concerns bucket fill procedures performed by an experienced driver driving a Volvo L70E wheel loader.

5.4.2. Driver 1

This driver is an experienced driver working at Volvo. Measurements have been performed on the autonomous machine while he has been driving it, filling the bucket with gravel.

Several data sets have been acquired and the graphs below have been selected as representing a typical bucket fill sequence.

5.4.2.1. Lift Angle

The sensor measures the boom angle relative to the machines horizontal axle. The boom angle is changed stepwise during the bucket fill as seen in Figure 7. In this case the driver uses three steps, but it can vary slightly depending on the material. This driver holds a constant pressure on the lift lever. The flat sections take place when the tilt is applied, as the tilt is prioritized by the machine.

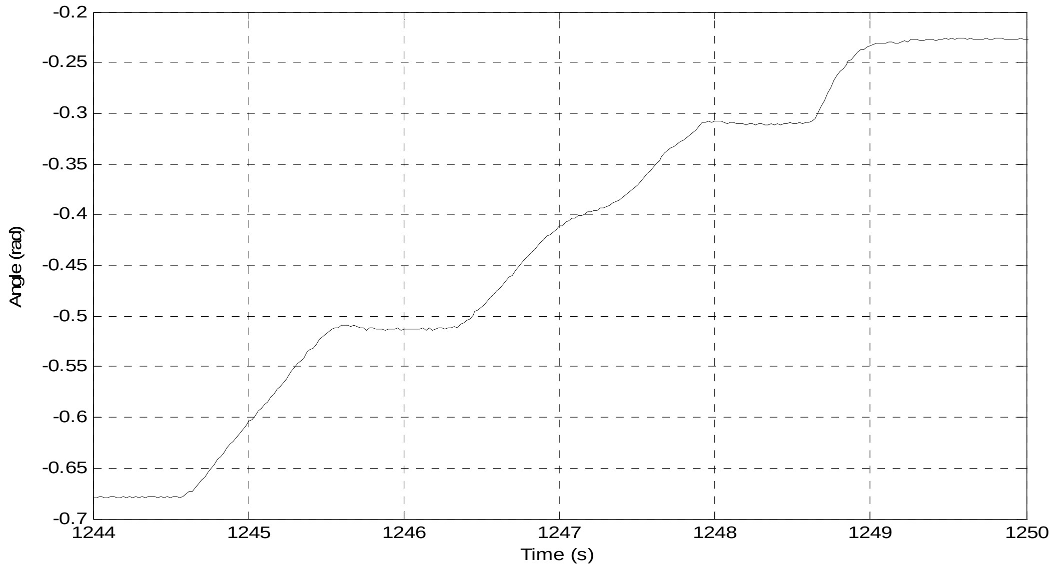

Figure 7, Lift angle driver 1

5.4.2.2. Tilt angle

The tilt angle sensor measures the GDF angle relative to the boom. The sections where the tilt angle is changing downwards actually correspond to the bucket keeping the same angle in the global coordinate system, shown in Figure 8. This occurs due to the TP-linkage which compensates for the boom movement. The tilt movement effect on the boom angle is clearly seen when the two graphs are compared. When the tilt is applied, the boom movement stops.

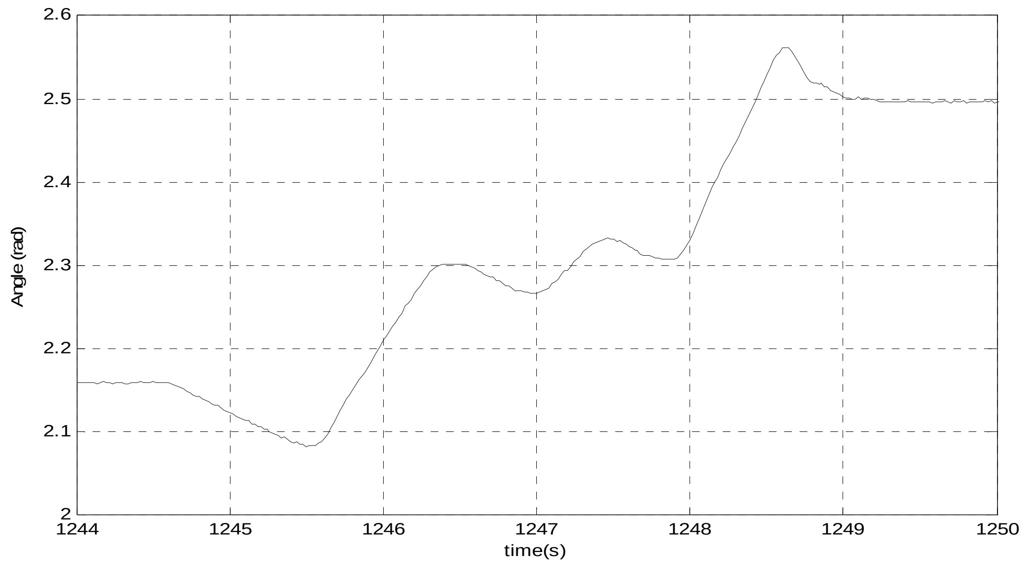

Figure 8, Tilt angle driver 1

5.4.2.3. Cylinder pressure

Both the lift and tilt cylinders are fitted with sensors. They both have two sensors, one at each end. The one of interest is the lift cylinders positive sensor, i.e. the one that sums up the counter force applied to the bucket. The stall pressure is at 240 bar, and as seen in this measurement in Figure 9 the machine almost reaches it at several points during the bucket fill.

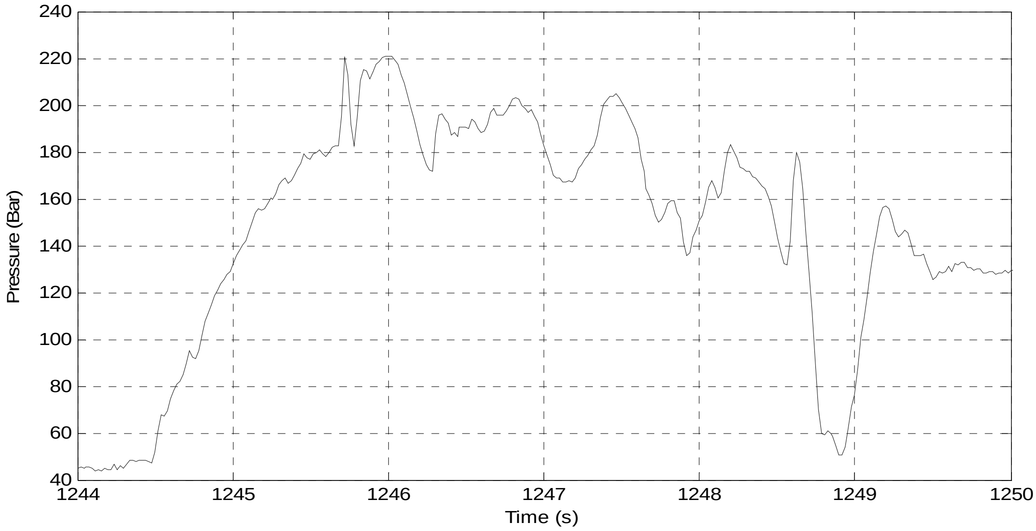

Figure 9, Lift cylinder pressure driver 1

5.4.2.4. Velocity

The machine velocity is measured on the drive shaft. As long as no wheel slip occurs it gives an accurate value. The driver was eager and kept a high speed when entering the pile, seen in Figure 10. The speed drops quite fast and is later kept around 3 km/h during the entire bucket fill.

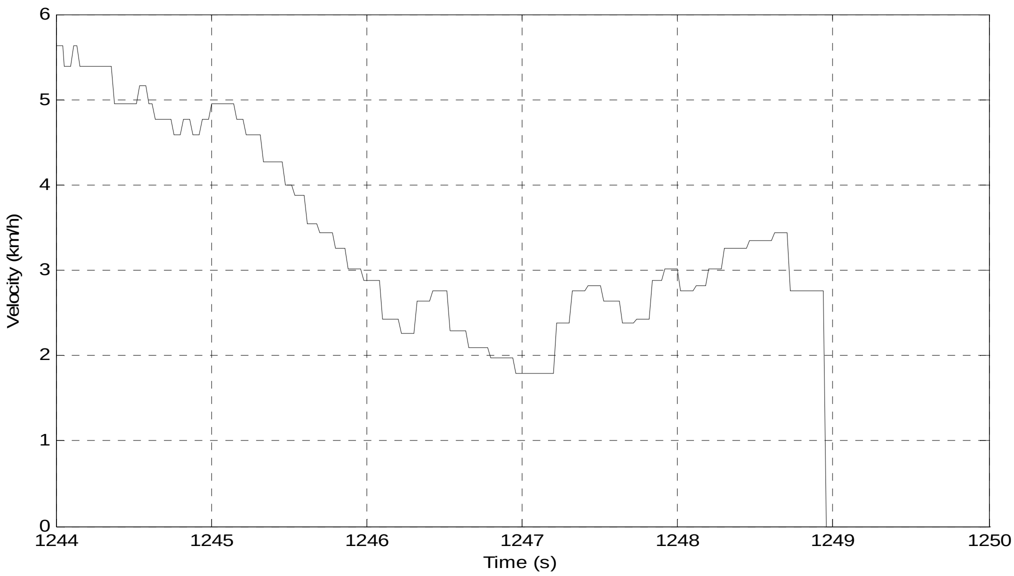

Figure 10, Velocity driver 1

5.4.2.5. Bucket tip movement

The graph in Figure 11 is calculated from the lift angle, tilt angle and translation measurements. It displays the bucket tip movement throughout the entire bucket fill.

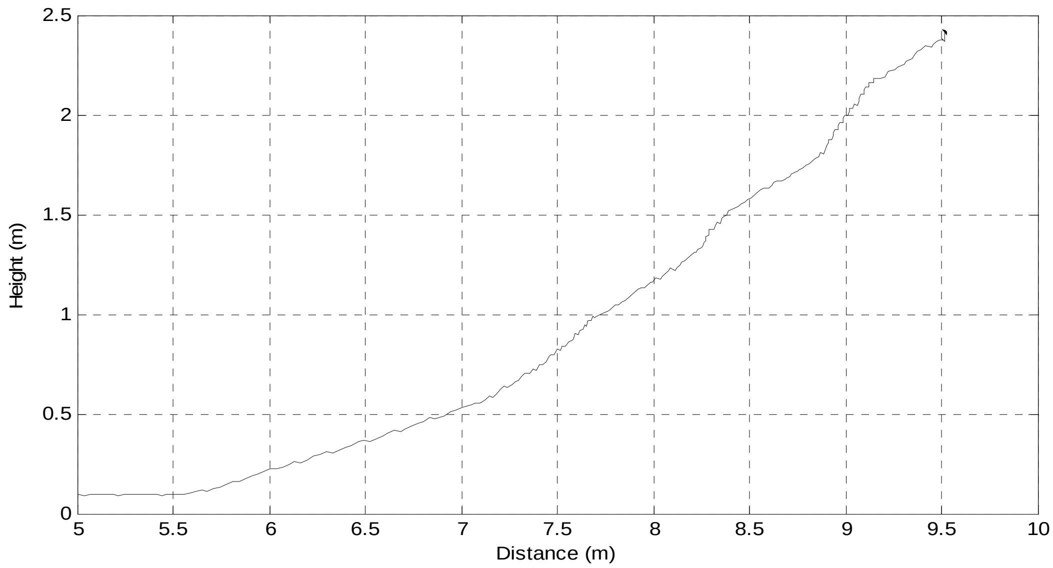

Figure 11, Bucket tip movement driver 1

5.4.3. Driver 2

These measurements are performed on a different machine with a different sensor setup. The machine is a L70E. The L70E is smaller than the autonomous machine but the measurements are still relevant because the machine construction is similar and the driving technique is the same. The main difference is the lift and tilt sensors. Instead of measuring the direct angle of the boom and the GDF-link, the prolongation of the respective cylinder is measured.

5.4.3.1. Lift Angle

This measurement, seen in Figure 12, shows the lift angle during a bucket fill sequence. The prolongation of the lift cylinder has been recalculated into the lift angle. This driver shows a very distinct stepwise behaviour. State 3, apply pressure, is clearly seen as the step between 1 and 2 seconds.

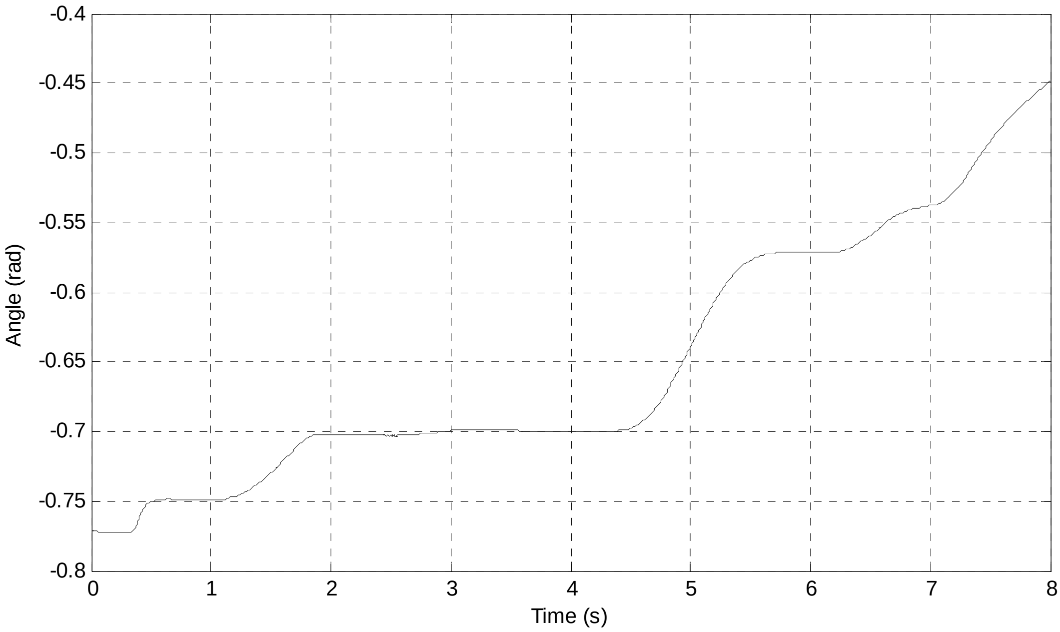

Figure 12, Lift angle driver 2

5.4.3.2. Tilt Angle

The tilt angle is also measured during a bucket fill procedure and shown in Figure 13. The prolongation of the tilt cylinder is recalculated into GDF-link angle relative to the boom. The same behaviour as the previous driver measurements when the lift is applied is seen, the tilt angle decreases as a result of the TP-linkage. The stepwise behaviour is also seen in the tilt measurements. The sharp edge on the end is when the bucket reaches the mechanical stop.

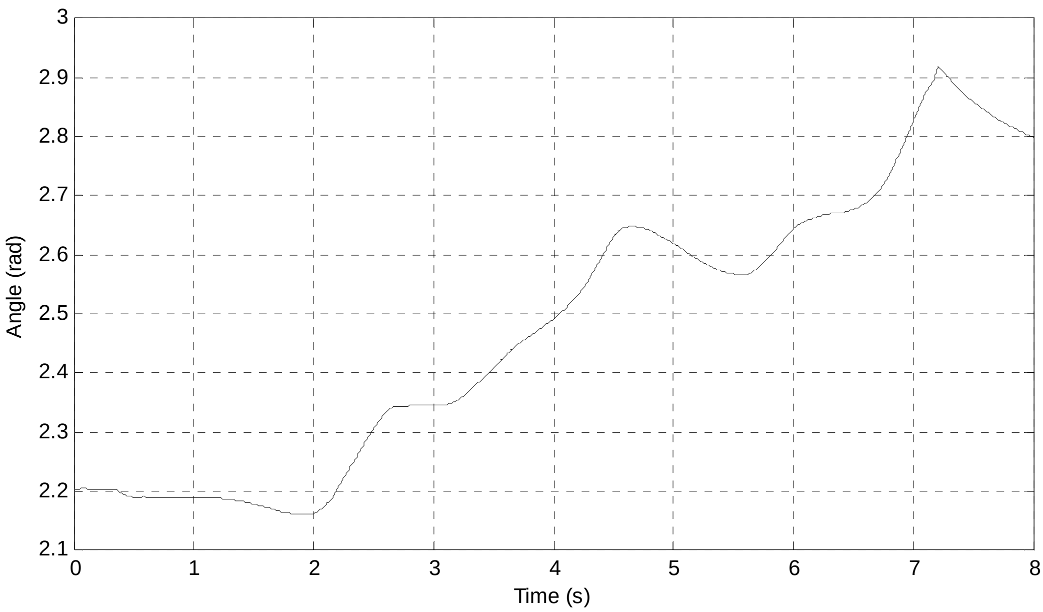

Figure 13, Tilt angle driver 2

5.4.3.3. Velocity

Driver 2 keeps a much lower speed compared to driver 1. He also has bigger variations in speed during the bucket fill procedure as seen in Figure 14.

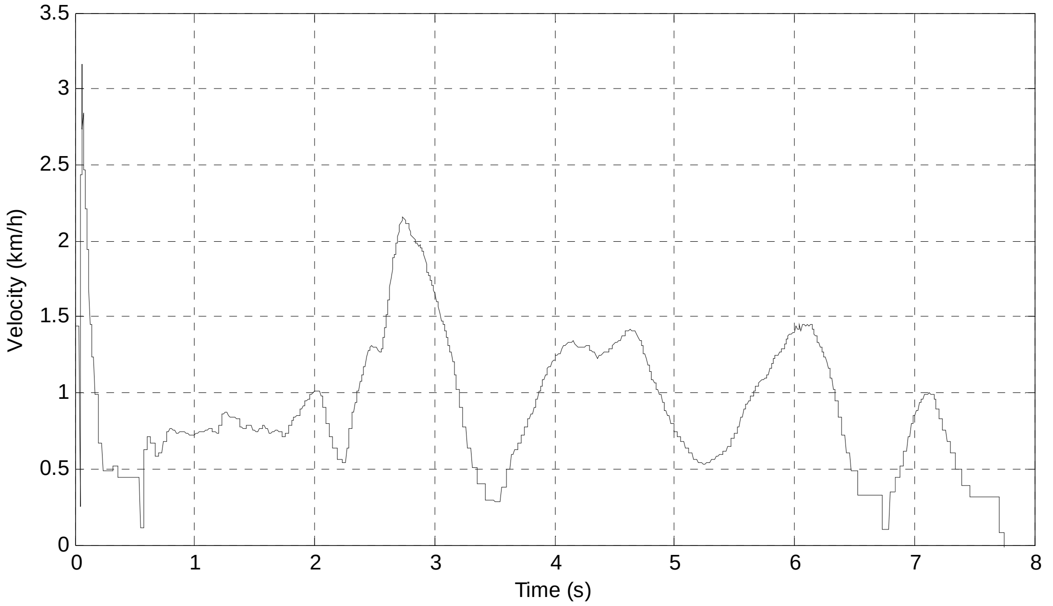

Figure 14, Velocity driver 2

5.4.3.4. Bucket tip movement

The bucket tip movement during the bucket fill has been calculated from the lift, tilt and velocity measurements and is shown in Figure 15. Note: The height axis zero crossing is at the height of the boom/machine joint.

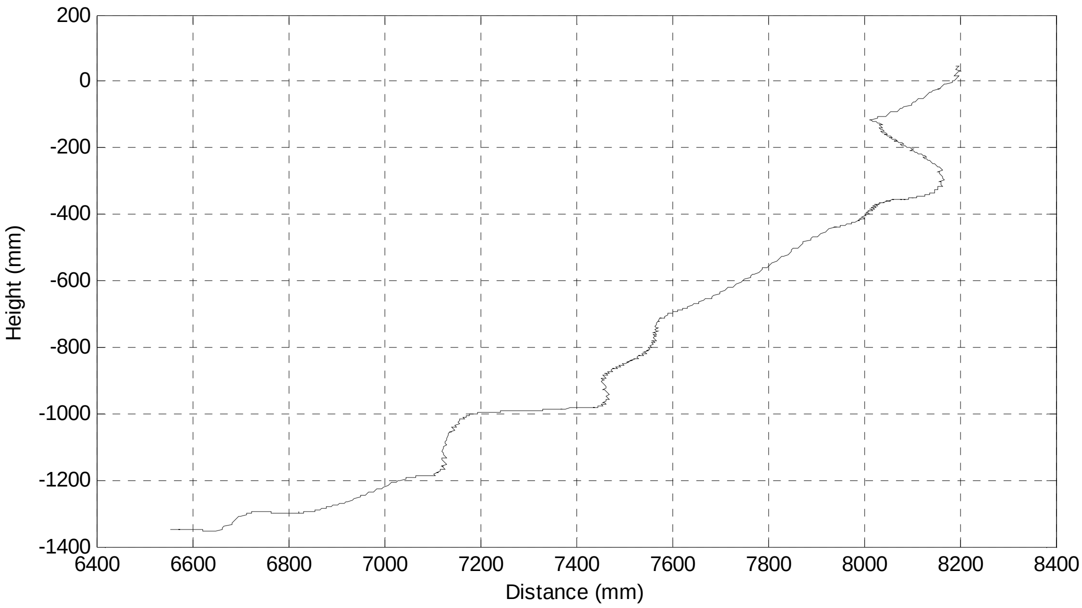

Figure 15, Bucket tip movement driver 2

6. Bucket fill compilation

The theory, interviews and measurements in the previous chapter is analysed in this chapter. It starts with a description of the discovered problems connected to the bucket filling procedure. Then follows a theoretic description on a solution to the problems and finally a list of requirements on the bucket fill procedure is presented.

6.1. It is almost impossible to fill the bucket

The title of this section might sound a little bit bold and provoking, not to mention its illogical appearance. Wheel loader operators do in fact fill the bucket; otherwise the machine would be completely useless. But after careful review of the research and many discussions it is in fact logical to claim: It is almost impossible to fill the bucket. The following sections will explain it further.

Most operations and tasks performed with machines, whether they are related to gravel handling or not, are straightforward and easy to understand. Even though many tasks differ in learning time and difficulty, the logical solution is in principal always the best one. For example operating a crane or driving a hauler, there are no oddities. The bucket fill procedure with a wheel loader on the other hand is a quite different story. The most straightforward solution to the problem will inevitably lead to big problems. The bucket fill is not as simple as it might seem to a person without experience of wheel loaders. The obvious inexperienced solution looks something like this:

- Drive into the pile with the bucket on the ground
- Drive until the bucket is full of gravel
- Tilt the bucket and then lift it out of the pile

This approach to the problem will fail almost every time, and the few times it manages to get through the entire procedure the result will not be good. The obvious solution is obviously not a good solution. The reasons for this will be shown in the following sections.

But what about experienced drivers? They manage to fill the bucket every time, without any bigger problems. The key lies in knowing how to trick the material into the bucket. Through the research, six not so obvious but very important problems during the bucket fill procedure have been isolated:

6.1.1. Problem 1: Wheel slip, State 3

The inexperienced driver would probably try to penetrate the bucket as deep as possible into the pile before tilting. If the machine is driven straight into the pile with this aim, wheel slip will inevitably occur. This happens because the counter force from the pile on the machine when the bucket is penetrated into the pile rapidly increases above the frictional force on the tires. Since the machine has a very powerful engine it will try to keep translating anyway and the wheels will spin.

Wheel slip is, as mentioned earlier, never under any circumstances allowed to occur. If it occurs, the bucket fill procedure has failed.

The solution to this problem is to increase the friction between the wheels and the ground. This is accomplished by lifting the boom while translating into the pile, referred to as state 3. This manoeuvre must take place before the counter force of the pile causes the wheels to slip. The lift manoeuvre can’t be performed too early though since the bucket won’t penetrate the pile deep enough in that case.

6.1.2. Problem 2: Lift pressure vs. tilt

When the lift cylinder pressure reaches a certain limit, the hydraulics does not have the power to lift the boom any longer and lift stall occurs. It occurs when the bucket is deeply penetrated into the pile, typically late in state 3 and early in state 4.

The solution to this problem is to tilt the bucket at the correct time. When the bucket is tilted upwards (the tilt sensor is inverted on the machine and therefore the graph displays a decrease in the tilt angle value when it is tilted upwards), the lift cylinder pressure decreases, as seen in Figure 16. It will occasionally drop below the lift force limit, allowing the boom to be lifted once again. The bucket must be tilted enough to allow the boom to move again. If it is tilted too much, the penetration depth will not be sufficient and the fill grade will be poor.

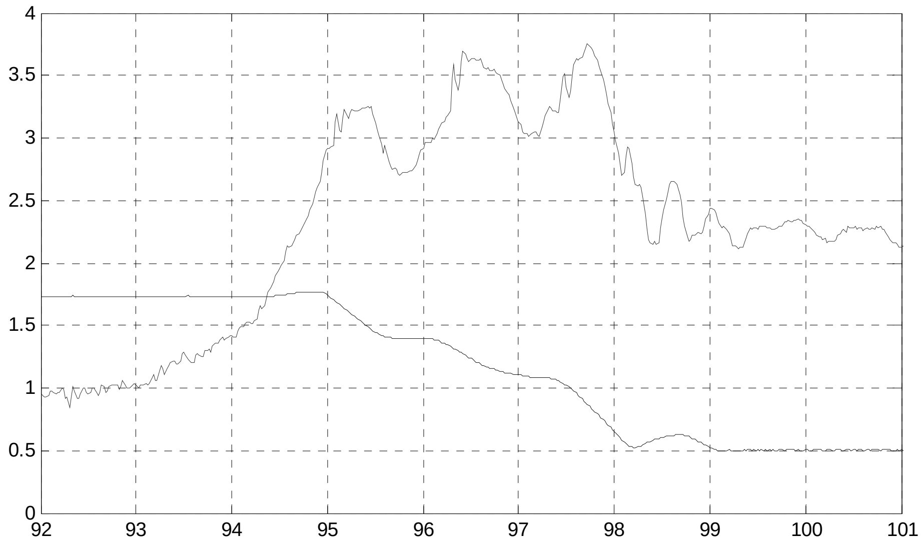

Figure 16, Lift pressure (noisy) and tilt angle (smooth)
Note: The values on the y-axis in figure 16 are normalized.

6.1.3. Problem 3: Break loose material

This aspect must be considered when working in all kinds of materials, but it is especially important in sticky materials. When the bucket is moved through the pile, it pushes the material in front of it iself. Some of the material will fall into the bucket and some will fall on the sides. To make enough material fall inside, the material has to be forced into the bucket. Otherwise the material will be pushed upwards or to the sides and out of reach of the machine.

This is accomplished by making several breaking manoeuvres with the tilt during the bucket fill. The lift is used to press the material upwards, invoking a strain force. When the tilt is applied, the material strained by the lift is broken loose from the unstrained material and falls into the bucket. This manoeuvre can be performed several times during a single bucket fill.

6.1.4. Problem 4: Stall handling

Lift stall has already been mentioned in Section 6.1.2, but another situation where lift stall plays an important role is when it occurs in combination with translation stall. When forcing the bucket into the pile with both the lift cylinder force and the translation force it is easy to reach a lift cylinder pressure high above the limit of the lift cylinder force. The natural reaction to the translation stall would be to increase the forward thrust and thereby forcing the bucket through the pile. This is not the solution though.

The boom angle is negative during the entire bucket fill procedure, and the bucket actually performs a circular movement when it is lifted upwards. So the bucket movement is pointed forward and upward. When more translation force is added in the forward direction, the lift cylinder pressure increases even further and thereby jams the bucket even more. The solution is consequently to *decrease* the translation force. When the translation force is decreased, so is the lift cylinder pressure, and the boom can be operated when the pressure falls below the threshold.

6.1.5. Problem 5: Final push, state 5

When filling the bucket, most of the material is placed in the front of the bucket. This is completely natural because it is the front of the bucket that actually penetrates the pile. The optimal placement of the material in the bucket is not in the front of the bucket. The material is supposed to be placed in the centre of the bucket to reduce the amount of spilling during translation and to allow for maximum fill grade. The problem is especially to pack the material against the back wall of the bucket.

The solution to this problem is a trick performed at the absolute end of the bucket fill. At approximately the same time as the bucket leaves the pile, a quick, almost aggressive, upwards tilt manoeuvre is performed. This manoeuvre throws the material into the bucket, forcing it to pack against the back wall and centres it at the same time. The effect is maximised if the bucket slams into the mechanical end position of the tilt just before the excess material falls off the bucket. In this way the bucket fill grade will be completely maximised and the material perfectly centred.

6.1.6. Problem 6: The lift and tilt collision

The lift and tilt cylinders are two separate hydraulic systems. But there is only one hydraulic pump, so the hydraulic flow is controlled by two valves, one for the lift cylinders and one for the tilt cylinder. The hydraulic pressure is needed when the lift or tilt is moved upwards. The problem occurs when the driver wants to move both the lift and tilt upwards at the same time. It is possible to do this at slow speeds and with little force, but when more force is needed, for example during a bucket fill, the machine only operates one cylinder at a time. Otherwise the lift and tilt would affect each other and always strive to reach the same pressure in both cylinders, making the machine virtually uncontrollable. The machine is constructed so that the tilt cylinder is always prioritized. This is clearly seen in Figure 17. As soon as the tilt is applied, the lift stops moving. Note: The upward slope in the beginning of the tilt signal is due to the lift manoeuvre and the geometry of the TP-linkage.

The solution to this problem is to use the lift and tilt stepwise, otherwise the movement would consist of a tilting manoeuvre until the tilt reaches it is end position and then the lift would be applied. The alternative is to move the lift and tilt extremely slow, but this strategy has a great negative impact on productivity and is not an option.

Figure 17, The lift (increasing trend) and tilt (decreasing trend) collision

Note: The values on the axles in Figure 17 do not represent any specific quantity.

6.2. *Requirements*

The problems and the human driver strategies when filling the bucket has been used to form a list of requirements as a guideline for the project. Some of the requirements have already been described and the others will be described in this section.

6.2.1. Performance

These are the performance requirements on the automatic bucket fill procedure.

Req. no.	Description	Level
1	The machine shall reach more than 70% productivity compared to an experienced driver.	Basic
2	The machine shall reach more than 70% efficiency compared to an experienced driver.	Basic
3	Wheel spin shall not occur.	Basic
4	Translation stall shall not occur.	Basic
5	Lift stall shall not occur.	Basic
6	The machine shall autonomously fill one bucket with gravel at a time.	Basic

Table 4, Performance requirements

6.2.2. Implementation

These are the requirements on the implementation of the automatic bucket fill procedure

Req. no.	Description	Level
7	The bucket shall attack the pile horizontally and at ground level.	Basic
8	The machine shall apply pressure on the front axis to counteract wheel slip.	Basic
9	The machine shall move the bucket through the pile following the J-curve.	Basic
10	The machine shall move the bucket through the pile with the chic-chic strategy.	Extra
11	The machine shall handle common stall situations.	Extra
12	The machine shall perform a final push with the bucket to position the material.	Extra

Table 5, Implementation requirements

6.3. *The solution*

The conclusion is that the straightforward approach to the bucket fill will not work. It is crucial for the success of the bucket fill procedure that the solutions to the six problems are included in the system. The development of the bucket fill procedure has been split into four stages, the J-curve, chic-chic, stall handling, and aggression. They can be seen as different levels of driver skill implemented in the machine.

6.3.1. J-curve

This stage is the basic level. When implemented, the J-curve shall be able to fill the bucket and fulfil the requirements under the defined conditions. The stage consists of the four first states.

J-curve is the name of the basic movement pattern of the bucket tip through the pile during state 4. It was initially formed as the letter J but has later in the project received a more edgy look. Today it is formed as a polygon. The principal for the J-curve is derived from the measurements acquired from experienced drivers. It is illustrated in Figure 18 which contains the measured bucket tip movement from Driver 1's driving and the principal J-curve.

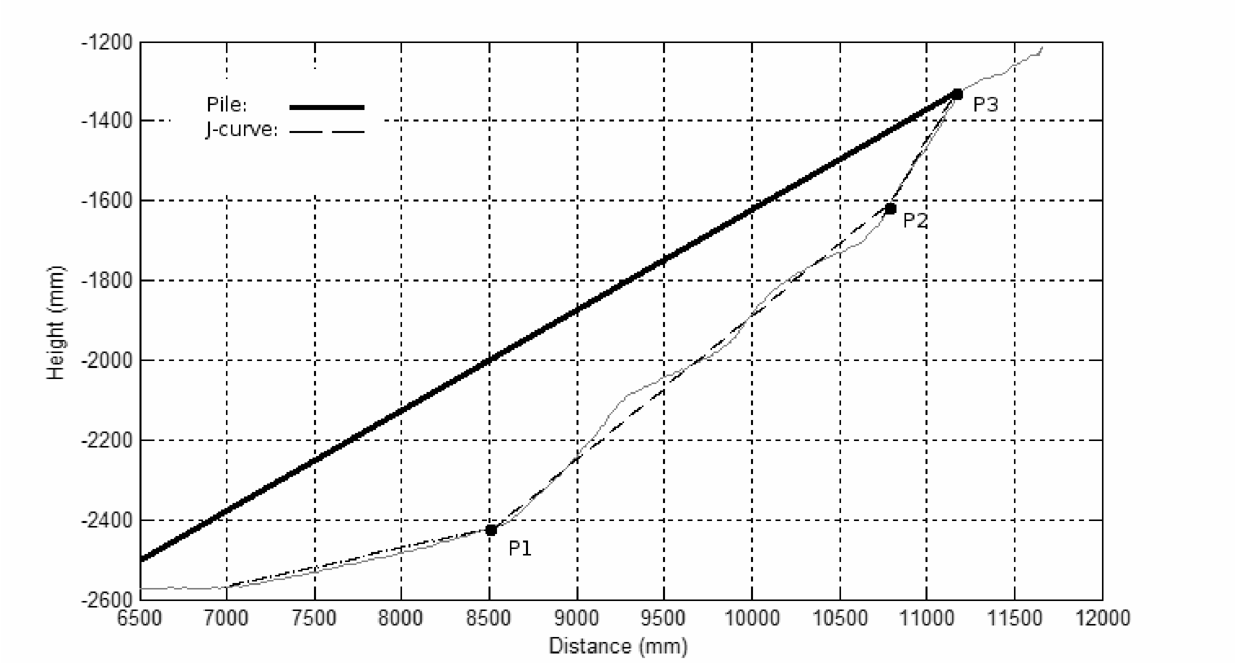

Figure 18, J-curve with state markings

As seen in figure 18 the J-curve is defined by three points:

- P1, the start point
- P2, the depth point
- P3, the exit point

These three points is all that is needed to set the movement pattern for the bucket tip during state 4. A requirement that helps positioning point 2 is that the material enclosed by the curve shall be approximately 215% of the buckets internal volume. The measurements have proven this to be enough to reach a fill grade of 105%.

Problem 1 is solved by state 3, apply pressure, where the bucket is lifted enough to provide sufficient pressure on the front axis. The pressure shall be high enough to ensure that wheel slip never occurs. The J-curve it itself does not solve any of the problems with the bucket fill but it forms a good base for the next levels of implementation.
The J-curve stage does not handle:

- Problem 2: Lift pressure versus tilt
- Problem 3: Break loose material
- Problem 4: Stall handling
- Problem 5: Final push
- Problem 6: The lift and tilt collision

6.3.2. Chic-chic

This stage is referred to as the amateur stage. It introduces the solution to problem 3 and 6. The J-curve stage form the basis of this stage but a new behaviour during state 4 is introduced. Instead of following the J-curve exactly, the bucket tip should oscillate around the J-curve.

This pattern will make the machine imitate the stepwise lift and tilt manoeuvres which was clearly seen in the measurements and mentioned in the interviews. When the pattern is followed by the bucket tip, the bucket will break loose the material as described in the solution to problem 3. As a side effect the lift and tilt will be applied separately most of the time, thereby solving problem 6 at the same time.

Another important motivation for the chic-chic behaviour is the differential angle between two vectors. The first vector is the velocity vector of the bucket tip. The second vector is the bucket bottom vector. The differential angle between these two vectors shows the effect of the tilt manoeuvres on the bucket's attack angle on the pile, seen in Figure 19, and can be an important ingredient in finding the regulation strategy for the chic-chic stage.

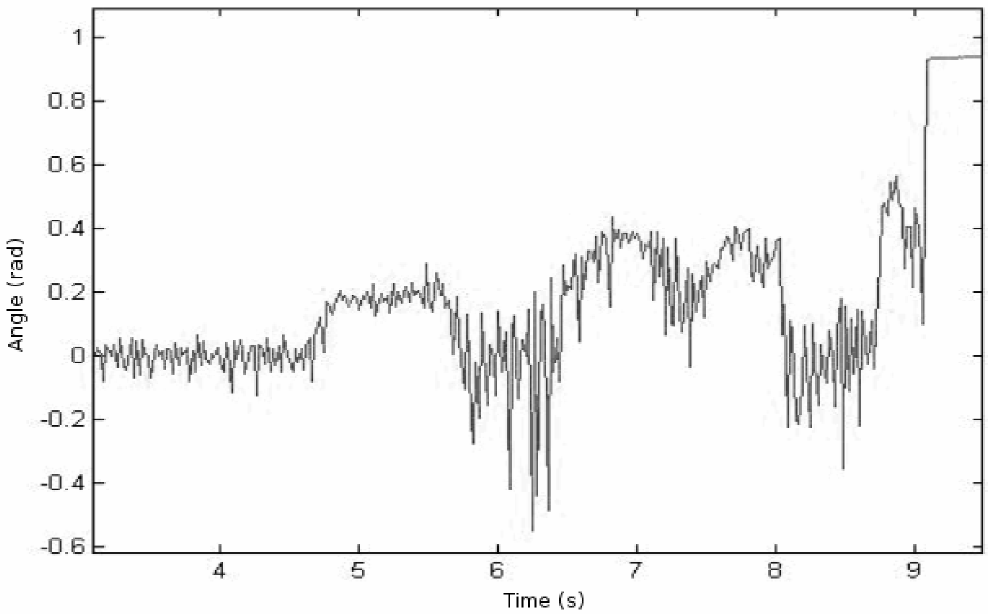

Figure 19, Differential angle

The Chic-chic stage does not handle:

- Problem 2: Lift pressure versus tilt
- Problem 4, Stall handling
- Problem 5, Final push

6.3.3. Stall handling

This is the advanced stage. When this stage is implemented, the machine will perform similarly to a quite experienced driver. The goal is to handle exceptional stall situations and thereby greatly increase the robustness of the procedure and solve problem 2 and 4. Many different stall situations can occur, but the ones that are an imminent threat during the bucket fill procedure are translation stall and lift stall.

Translation stall can occur if the bucket is penetrated too deep into the pile or if the bucket hit is a rock or other solid particles or structures.

Lift stall mainly occurs in combination with translation stall when the bucket is penetrated too deep into the pile.

A skilled driver can handle these situations differently from time to time depending on many variables. This stage is not within the scope of this project and no solution to this problem has been developed.

The Stall handling stage does not handle:

- Problem 5, final push

6.3.4. Aggression (the final solution)

This is the expert stage. When all stages have been implemented, the automatic bucket fill will perform equally or better than an experienced driver. The final stage solves problem 5 by adding the aggression in the end part of the bucket fill. An experienced driver finalizes the bucket fill by throwing the material into the centre of the bucket. This is performed through an aggressive manoeuvre with the tilt, and sometimes also a short translation thrust. With this manoeuvre, the driver minimizes the dropped material from the bucket, which is especially important if the machine is supposed to translate long distances with material in the bucket.

An extremely simple version of this behaviour has been developed but not implemented. It consists of a maximum speed tilt manoeuvre until the bucket reaches the mechanical stop position. This manoeuvre is performed when the bucket leaves the pile.

7. Bucket fill design

This chapter describes the design of the automatic bucket fill system in detail. First are some general design elements presented and then a detailed description of the functions in the separate states follows.

7.1. *State external input*

The actions during some of the states depend on parameters from systems that are not included in the automatic bucket fill system. Those parameters are external inputs to the automatic bucket fill system and are treated as constant parameters within the system.
State 1 is dependent on one parameter from external systems. It has to know the distance to the pile. During state 3, several actions have dependencies: The lift angle is a function of the pile profile angle, and the required pressure to exit the state is also dependent on the material weight and “stickiness”. If the material is light it might be hard to acquire sufficient pressure and then it would be wise to instead use the translation distance as an exit condition.

7.2. *Regulator interface*

The Simulink model is using generic PI-regulators for the lift, tilt and steering control. They receive the reference values from the C++ application and the feedback signals from the Simulink model. The bucket fill system however requires different regulator systems for different states. But instead of constructing separate regulators for each state and disconnect the generic regulators, control signals for the regulators has been introduced. The generic PI-regulators have been fitted with a control interface consisting of 6 signals. The signals give the bucket fill system full control of all important settings in the PI-regulators. 3 of them are booleans and 3 of them are numerical values.

Regulator interface signal	Type	Description
Reference value	Double	The reference values from the bucket fill system.
Activate Control signals	Boolean	A switch which disconnects the generic reference value and activates the control signals of the regulators.
P-part	Double	Adjustable P-value when Activate control signals is active.
I-part	Double	Adjustable I-value when Activate control signals is active.
Reset I-part	Boolean	Switch that resets the I-part to zero on rising edge.
Disconnect I-part	Boolean	Switch that disconnects the I-part from the regulator but keeps it counting.

Table 6, Regulator interface signals

7.3. *Digital control*

A number of functions on the machine are controlled by boolean or integer values. All these functions are gathered in a control block called digital control. This block sets the digitally controlled functions to different values depending on the current state of the machine.

Digital control	Type	Function
APS	Integer	Automatic Power Shift, Volvos name on the automatic gear box function, changes gear automatically when active. It has 3 different settings: low, medium and high, which adjusts when the gears are changed.
Rotation Light	Boolean	Activates the orange rotation light on the roof of the machine when true.
Hazard Flasher	Boolean	Activates the hazard flasher system when true
Tool Lock	Boolean	Unlocks the tool lock when true and locks it when false.
BSS	Integer	Activates the boom suspension system in two different modes.
Gear Lever	Integer	Decides which gear to put in. Ranging from 1 to 4
Gear Direction	Integer	Decides if the gear box shall be put in Forward, Neutral or Reverse.

Work Light	Integer	Activates the work light in different configurations.
Horn	Boolean	Activates the horn when true.
CDC Activation	Boolean	Activates the CDC system when true.
Kick Down	Boolean	Activates the Kick down when true.
FAPS	Integer	Decides which setting the FAPS shall be put in.
Crank	Boolean	Cranks the engine when true.
Parking Brake	Boolean	Activates the parking brake when true.
Shut Down	Boolean	Shuts down the engine when true.

Table 7, Digital control functions

7.4. State machine

The bucket fill process is controlled on the top level by a state machine. It triggers the system when the start command arrives and it controls the state transitions. It outputs the current state continuously and switches states in the correct order when a state shift command is received.

7.4.1. State finished flags

Each state holds ready flags for each regulator. The value on these flags decides whether the regulator is finished with it is tasks during the state or not. These signals are passed on to the state shift demand function.

7.4.2. State shift demand

A function called state shift demand holds the intelligence for the state shift commands. It monitors all regulators during each state. There are four available state finished flags, one for the lift regulator, one for the tilt regulator, one for the steering regulator and one for the speed regulator. When the relevant state finished flags are set for the current state, the state shift function sends a state shift demand to the state machine.

7.5. Hold state

While not operational the bucket fill procedure is held in a default state, called the hold state. This state sees to it that the bucket fill system is disconnected from the rest of the autonomous machine system and wait is for the bucket fill trigger. When the bucket fill trigger is detected, the state machine leaves the hold state and initializes the bucket fill procedure. When finished or when stopped, it returns to this state.

7.6. State 1

When the bucket fill trigger is set, the transition between the hold state and state1 is performed. The task during state 1 is to position the bucket on the ground and to translate towards the pile. The state ends when the machine enters the pile.

When the state is initialized, the bucket's current position is stored. Then a ramp function is performed to move it to a preset position, which corresponds to the ground on a fairly even surface. The bucket is then kept on the ground with a small pressure downwards to ensure contact with the ground throughout the state. If the bucket was only kept in place by holding angle values, then a small rock underneath a wheel could lift the bucket from the ground. If this occurs repeatedly, then a slope could build up in front of the pile which could in time make the ground too uneven to perform well on.

7.6.1. Lift control

The lift control subsystem in state 1 consists of two parts which are controlled by a small state machine.

First there is a ramp function. This function translates the lifting arms from their current position to the sensor value -57 degrees which corresponds to "bucket on ground". The ramp ensures that the movement is performed in a smooth way.

When the ramp function is complete, the state machine switches to the "hold on ground" subsystem. This system consists of a quite slow PI-regulator which regulates the lift arm angle with the positive lift cylinder pressure as input. It seeks to keep the pressure on 35 bar, which corresponds to a light pressure on the ground. The positive lift cylinder pressure sensor is returning 44 bar if the bucket is floating above ground.
The slow behaviour of the regulator is chosen so that the lift arms don't make fast movements up and down, as this could cause the bucket to smash into the ground. The ground around a gravel pile is often filled with small rocks and bumps which should be ignored. There is also some noise in the sensor feedback. A slow regulator won't have time to regulate on fast variations in the pressure caused by these small obstacles.

7.6.2. Tilt control

The tilt angle for keeping the bucket horizontal to the ground is a constant value. The tilt control subsystem therefore only performs a ramp function from the current tilt angle to the correct angle for "horizontal bucket when on ground". The same tilt sensor angle at other heights doesn't put the bucket in a global horizontal position because of the geometry in the TP-linkage.

The bucket is kept at the same angle after the ramp is finished by using a PI-regulator with the input sensor value as the reference value.

7.6.3. Throttle control

The RPM during state 1 must be sufficient to keep the machine translating at the desired speed and feeding the hydraulic pump with enough power to move the bucket into position during the desired time frame.

Translation:
The translation during state 1 is kept at a constant value of 4 km/h. A PI-regulator controlling the RPM with the current speed as input is used. The gear box is kept in second gear forward throughout the state.

Hydraulic pressure:
The moving of the empty bucket into position does not require a high flow from the hydraulic pump. It is enough to let the engine run in idling state to get a quite fast movement. Especially as the lift arm movement (if any) always is downwards in state 1. A higher RPM could be considered if a faster translation into position of the bucket is required, but this will also affect the speed of the machine.

7.6.4. State finished

State 1 is finished when the pile is reached. A distance counter measures the travelled distance during the state and when the input distance is reached, the state shift is performed.

7.7. State 2

State 2 translates the bucket straight into the pile until the threshold pressure on the lift cylinder is reached. This pressure is the result of the pile's counter force.

7.7.1. Lift control

The lift regulator used during state 1 to keep the bucket pressed against the ground is disconnected in this state since the pressure on the lift cylinder will increase when the pile is entered. The bucket is kept on it is current level simply by passing through the sensor value as the reference value to the P-regulator. The I-part is disconnected to ensure an even lift force.

7.7.2. Tilt control

The tilt control is the same as the latter part of state 1, keep the bucket at the current angle.

7.7.3. Throttle control

The speed and hydraulic force must be enough to keep the machine translating into the pile while the counter force from the pile builds up.

Translation:
The PI-regulator from state 1 is copied into this state and so is the reference velocity setting of 4 km/h. The system applies the kick down function on entrance to this state. This results in a slightly higher RPM value to keep the current speed. Because of the kick down, there is no need to inherit the integrator part of the previous translation regulator. The next state transition is more sensitive though because of the counter force. The I-part of this speed regulator is available as a signal for the next state and is continuously updated. When this state goes inactive it is stored at it is current value.

A distance counter is activated during this state for later use in state 4. It keeps track of how far into the pile the machine has travelled.

Hydraulic pressure:
The gear change carried out by the kick down also provides the bonus feature of increasing the hydraulic force just as the pile counter force starts to rise. This is a wanted side effect to provide the best possible condition for state 3.

7.7.4. State finished

The second state is finished when the counter force of the pile reaches 70 bar. This is measured on the positive lift cylinder pressure sensor, because in principal all counter force is summed up on it in the current situation.

7.8. State 3

State 3 applies pressure on the front axis of the machine by lifting the bucket while translating further into the pile. This state is crucial for the avoidance of wheel slip.

7.8.1. Lift control

When the state is entered, the machine starts to lift the boom. The lift angle is calculated as a function of the translation. The bucket tip shall follow a straight line with an adjustable angle towards the ground. The angle is typically in the range 14-15 degrees.

7.8.2. Tilt control

The tilt control is again the same as the previous state. Keep the bucket at the current angle.

7.8.3. Throttle control

During this state the counter force from the pile will build up even more despite that the lift manoeuvre gives some relief.

Translation:
The speed regulator in this state is a copy of the previous state’s regulator with a small but important difference. This regulator uses a function known as bumpless transfer. It inherits the previous states I-part and sets it at initiation. This ensures a smooth and unnoticeable transition between the states.

Hydraulic pressure:
The hydraulic system might need more power during this state but the required force is directly connected to the counter force from the pile. The counter force is in turn directly connected to the translation speed which will be regulated to be kept constant. If the hydraulics need more power, the translation also need more power and the translation regulator will provide that.

7.8.4. State finished

State 3 finishes on two different conditions. The reason for both is to introduce an increased robustness towards material differences. The first condition is the lift cylinder pressure. When it reaches 130 bar, it is time to change state.

The other condition is translation distance. If the material is light it can be hard or even impossible to reach the pressure threshold, and therefore a translation distance limit is set to 0.8 meters. When this distance has been reached, the bucket has reached a minimum height of 0.2 meters and the pressure on the front axis is considered to be sufficient.

7.9. State 4

The previous three states task is to set a good starting point for state four, which is the state that actually fills the bucket.

The goal of the state is to get material in the entire bucket. The machine control during this time emanate from the J-curve.

7.9.1. J-curve

When the state is entered the current location, the translation distance since state 2 and the pile angle input parameter is used to calculate the J-curve.

7.9.1.1. J-curve calculation

All three points are calculated when state 4 is initiated. This only happens once. They are calculated in meters in a global XY coordinate system with origin in the X-direction at the bucket tip position on state entrance. The origin in the Y-direction is set to the ground level. Point 2 and 3 are currently set manually.

Point 1: This point is set as the bucket tip's global position the moment state 4 is entered. It is calculated from the sensor feedback from the machine. The X-coordinate of this point is set to 0 as this is the leftmost point of the bucket tip during state 4.

$$P1_x = 0$$

The Y-coordinate is calculated from the boom and tilt sensor feedback.

Calculating Point 1 Y-coordinate:
The joint where the boom is attached to the machine is approximately at a constant height during the entire bucket fill procedure. Therefore this point is used as the starting point for the calculation of the Y-coordinate.

The relevant constants on the TP-linkage and the bucket are presented here:

- Length of boom: $|OA|$ = 2.675 m
- Boom/machine joint height above ground: O_y = 2.034 m
- Bucket length from attachment to tip: B_x = 1.448 m
- Bucket height from attachment to tip: B_y = 0.302 m
- Distance between bucket attachment and tip: $|B| = \sqrt{B_x^2 + B_y^2}$ m
- Angle between bucket bottom and bucket attachment to tip vector: $\beta = \arctan\left(\frac{B_y}{B_x}\right)$

With these constants and the angle definitions in figure 1 it is possible to calculate the bucket tip height using the angle feedback signals from the machine:

First convert the GDF-link angle, ψ_{tilt} , to the attachment angle, ψ_{att} . This is performed with a lookup table. Both angles are given relative to the boom:

$$\psi_{att} = lookup(\psi_{tilt})$$

Subtract the bucket angle (θ_{att}) and add the boom angle (ϕ_{lift}) to get the global bucket bottom angle (ϕ_{att}):

$$\phi_{att} = (\psi_{att} - \theta_{att}) + \phi_{Lift}$$

With the global bucket angle and the boom angle it is possible to calculate the bucket tip position on the Y-axis starting at O_y .

Calculate the height of joint A, shown in Figure 20:

$$A_y = O_y + |OA| * \sin(\phi_{lift})$$

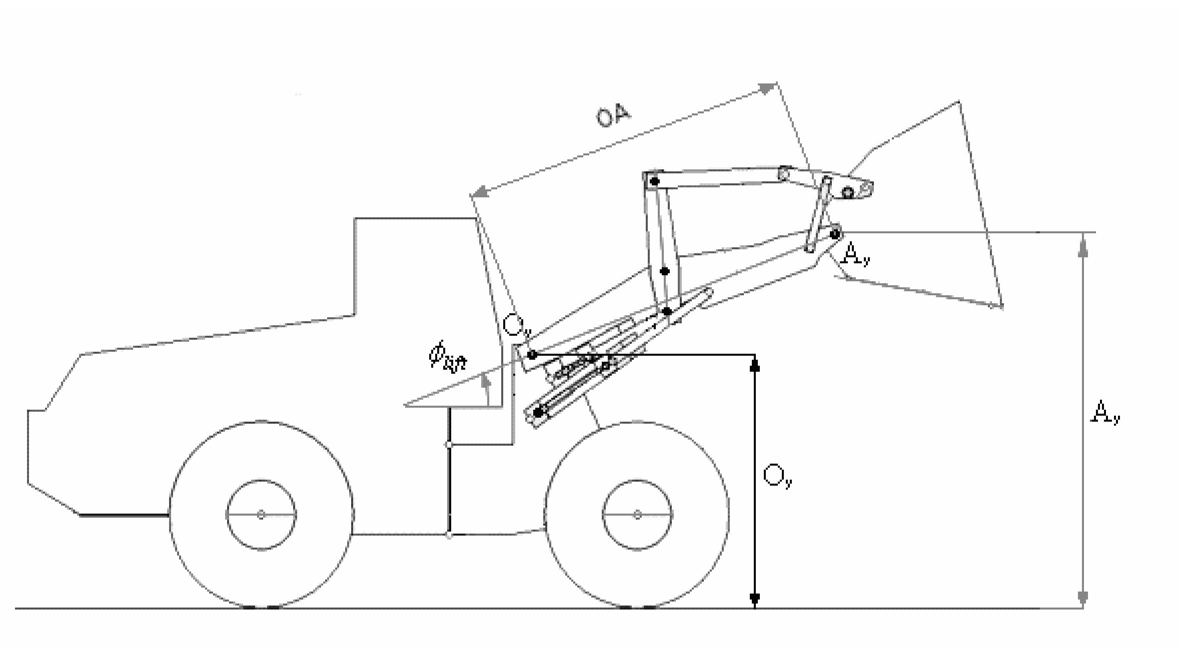

Figure 20, Calculation of height of A

Use the bucket bottom angle and the height of A to calculate the bucket tip height P1 shown in Figure 21:

$$P1_y = A_y + |B| * \sin((\psi_{att} - \theta_{att}) - \beta)$$

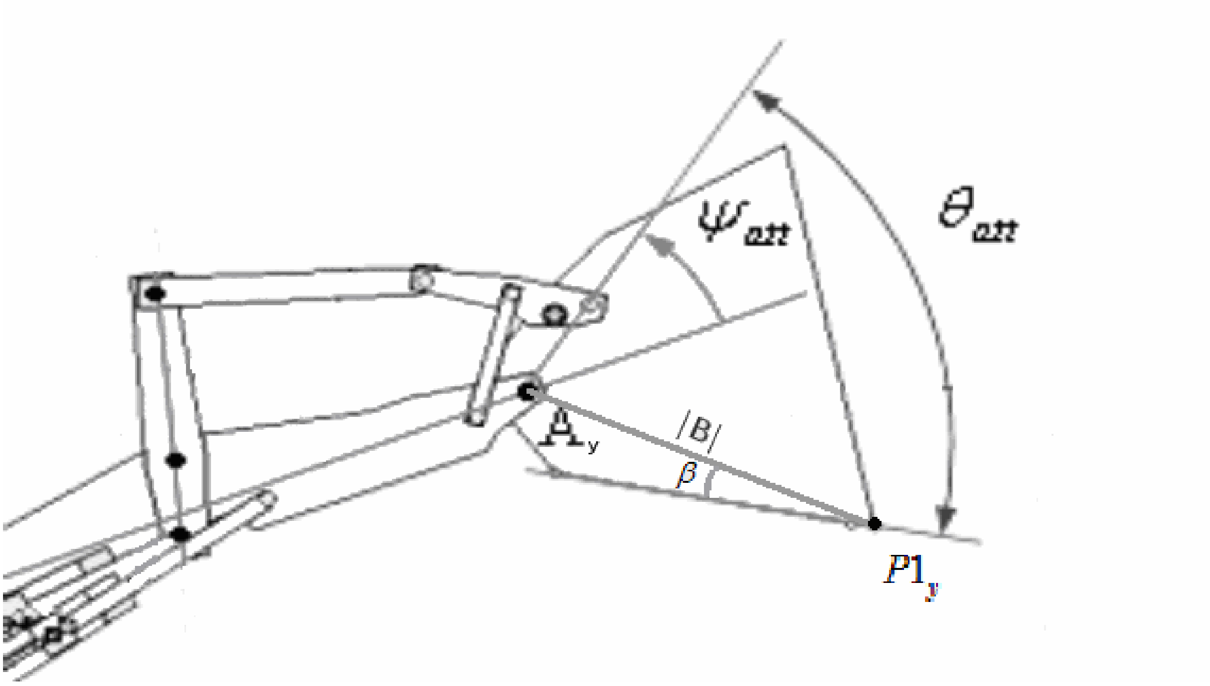

Figure 21, Calculation of height of bucket tip

Calculating point 3:
Point 2 is calculated from point 1 and 3, therefore it must be calculated last. Point 3 lies, as mentioned earlier, on the pile surface, so it is confined to a line in the two dimensional XY-plane. Point 3 is also restricted in the Y-direction; the boom is not allowed to be raised above 0 degrees in a bucket fill. If that is required to fill the bucket completely, then the procedure is carried out wrong. The starting point of the pile profile line in the XY-plane is the position where state 2 was entered, and this information is saved through state 2 and 3. The angle of the pile is an input parameter to the bucket fill system and with these two values it is an easy task to calculate the pile profile line.
Calculate the pile profile line: To get the X-coordinate for the zero-crossing of the pile profile in the Y-direction the distance travelled since state 2 is used. The X-coordinate for state 4 is defined with 0 at the bucket tip entry position. The pile start X-coordinate is therefore:

$$X_{pile} = 0 - X_{transS2}$$

The pile profile line, $Y_{pile}(x)$ is then simply calculated with the pile angle, α_{pile} shown in Figure 22:

$$Y_{pile}(x) = (X_{transS4} - X_{pile}) * \tan(\alpha_{pile})$$

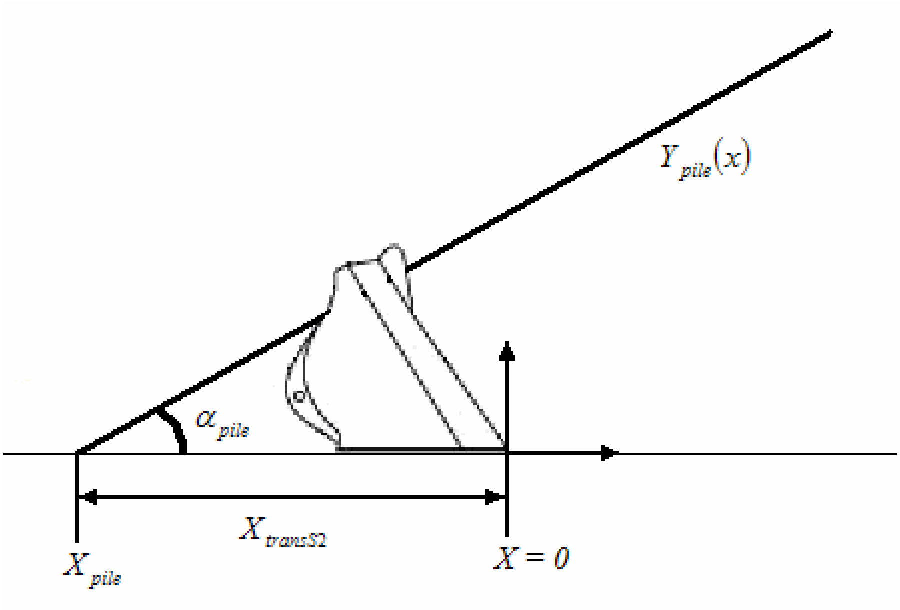

Figure 22, Pile profile calculation

Calculate point 3:

The X-coordinate for point 3 is located at the maximum reach of the bucket tip when the bucket is fully tilted. The wheels of the wheel loader are not supposed to enter the pile at any time. Therefore the maximum reach equals the length of the boom and bucket minus the distance travelled since state 2. The X-coordinate for point three is:

$$P3_x = X_{reach} - X_{transS2}$$

The Y-coordinate is then calculated from the pile profile line formula:

$$P3_y = (P3_x - X_{pile}) * \tan(\alpha_{pile})$$

Point 2: This point decides the covered profile area of the pile. The deeper it is located into the pile; the more material is enclosed by the J-curve. Its placement is restricted to the triangle formed by the right-angled triangle formed by point 1 and point 3 as shown in figure 23.

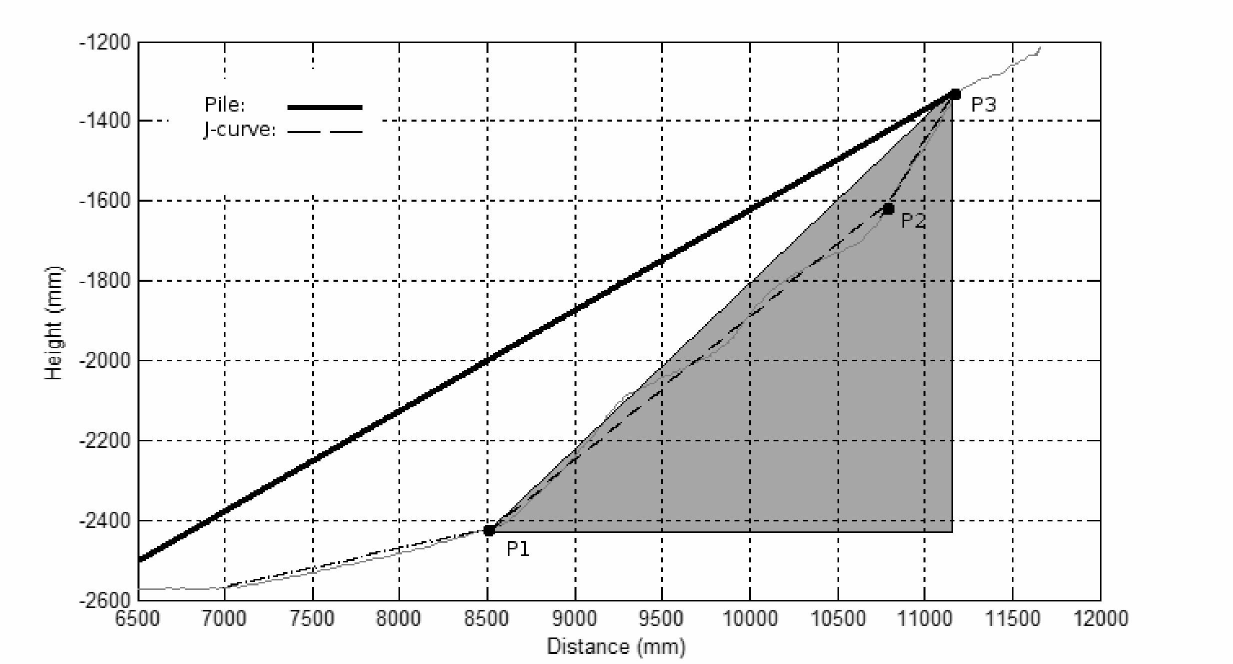

Figure 23, Allowed placement of P2 (shaded area)

If point 2 is not located inside this triangle, the bucket or boom might move downwards during some part of the bucket fill procedure. This could cause the front wheels to loose traction and increase the risk for wheel spin or translation stall.

Point 2 strategies: There are two different strategies for positioning point 2. The common part is, as mentioned above, that the J-curve shall enclose 115% of the bucket profile area in the pile. The first strategy is aimed at exiting the pile as low as possible, thereby lifting the material as little as possible. This strategy though requires deep penetration into the pile which requires a lot of translation force. The second strategy is aimed at penetrating the pile as little as possible and exit the pile at the limitations of point 3, i.e. the maximum reach or the boom horizontal, whichever occurs first.

Calculating point 2: Point 2 is currently calculated and set manually. No function for calculating the correct placement depending on choice of strategy has been developed. The current value of point 1 is calculated with emphasis on the second strategy.

Bucket tip position: The bucket tip is supposed to follow the J-curve as accurately as possible. The current position of the bucket tip is decided by the translated distance during state 4. The translation distance gives the X-coordinate of the bucket tip and the J-curve in turn gives the Y-coordinate.

7.9.2. Tilt and lift strategy

The lift and tilt control in this state is much different from the previous states because of the complexity of the calculations.

7.9.2.1. Tilt strategy

The current approach on the bucket fill procedure is aimed at a smooth movement of the bucket through the pile. Therefore a straightforward strategy is used for the bucket tilt during state 4. The reference bucket bottom angle is calculated as a second order function of the translation distance. It starts at zero degrees when state 4 is initiated and it reaches 45 degrees, which corresponds to almost fully tilted, at the end of state 4. The constants in the function are directly dependant on the J-curve point 3, since it determines the translation distance during state 4:

$$\phi_{att} = X_{transS2}^{2} * \frac{\pi}{9}$$

This is used as the reference value for the tilt regulator after conversion from global bucket bottom angle to the GDF-link angle (ψ_{tilt}) relative to the boom.

7.9.2.2. Lift strategy:

The lift reference value is calculated from the reference values of the bucket tip position and the bucket bottom angle:

First calculate the angle between the bucket tip and A:

$$\alpha_{AB} = \phi_{att} - \beta$$

Then calculate the global Y-coordinate for A, shown in Figure 24:

$$A_y = Tip_y - |B| * \sin(\alpha_{AB})$$

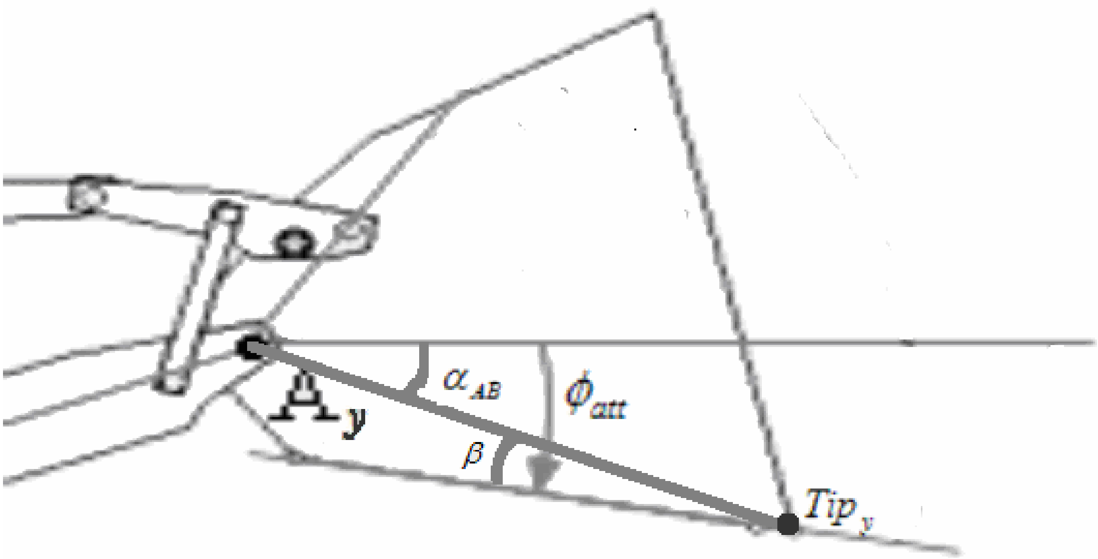

Figure 24, Reference value for A point calculation

Recalculate to the distance from O to A:

$$OA_y = A_y - O_y$$

Finally use the distance from O to A to calculate the boom angle shown in Figure 25:

$$\phi_{ref} = \arcsin\left(\frac{OA_y}{\overline{OA}}\right)$$

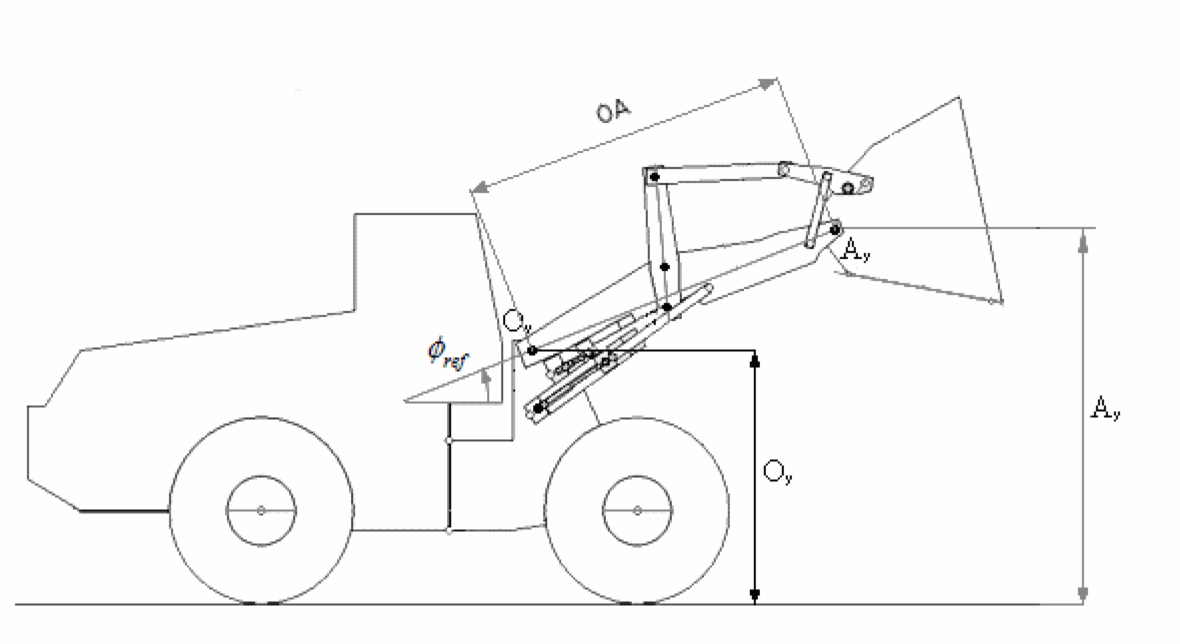

Figure 25, ϕ_{ref} calculation

7.9.3. Throttle strategy

It is important not to get any stall tendencies during state 4. It is here that the experience shines through mostly. Both translation and lift stall is most likely to occur during state 4. To avoid them it is important to always supply the machine with a correct RPM. The difficulty evokes from the fact that if the machine receives too high RPM it will press it iself too far into the pile and get stuck. Further, because of the geometry of the linkage, too much translation force will jam the boom because the lift manoeuvre is moving the bucket forward as well as upward during the bucket fill.

Translation:
The speed PI-regulator from state 3 is kept, but the reference value for the speed is lowered from 4 km/h to 3km/h. Because of the change in reference value, the I-part is not inherited.

Hydraulic pressures:
The hydraulic system will require maximum force during state 4. It reaches it is peak force at 1400 RPM. Further increase of the engine speed will only increase the flow speed in the system. Therefore a lower limit is introduced on the RPM after the speed regulator. This limit is set to approximately 1400. This could be a potential problem source for the speed regulator but experience shows that the pile counterforce in the current set up will keep the speed down so that the regulator can function normally.

7.9.4. State finished

State 4 is finished when there is no way of getting more material into the bucket, i.e. when the bucket passes through point 3 in the J-curve. This is monitored via the translation distance and the boom and tilt angles; when one of them reaches point 3 the state is finished.

7.10. State 5

State 5 is an important addition in the strive to imitate expert drivers. An inexperienced driver often considers himself finished after state 4, but an experienced driver knows better. It is very important to position the material evenly in the bucket, especially in applications where there are long translation distances between the pile and the drop off point. This states only task is to adjust the material as good as possible.

7.10.1. Lift control

The lift has no tasks during this state. The reference value is set to the sensor value to keep it is position.

7.10.2. Tilt control

The tilt is used to throw the material into the centre of the bucket. This is accomplished by slamming the tilt into the mechanical stop position of the linkage. This is a quite brutal manoeuvre and is also accomplished brutally. To ensure a fast movement, a constant positive value is added to the sensor feedback value of the tilt angle. This sum is used as the reference value for the tilt angle. This simulates pulling the tilt lever to the end position. When the tilt has slammed into the mechanical stop, the sole feedback value is set to the reference value to avoid further movement.

7.10.3. Throttle control

The throttle is set to 0 and the gear lever is put in neutral in this state since no further translation is needed. The brakes are applied slightly to avoid uncontrolled rolling of the machine.

7.10.4. State finished

The state, and the entire bucket fill, is finished as soon as the tilt manoeuvre is finished. As soon as the sole tilt feedback value is set as reference value, the state exit is and the entire system returns to the hold state, giving back control of the machine to the C++ application.

8. Synthesis

This chapter describes the actual system as it is synthesised. First the changes made to the interface are presented. Thereafter follows a description of important parts of the Simulink model and the C++ model.

8.1. Interface

The interface provided by the previous thesis workers has been modified to include controls for the bucket fill functions.

8.1.1. Laptop

Some extra functions have been added to the manual mode window. The additions are: a button to initiate the bucket fill sequence and a button to stop the bucket fill before one sequence is finished. Two input fields have been added, one for the pile angle and one for the distance from the machine to the pile. The modifications can be seen in the square in the lower right corner in Figure 26.

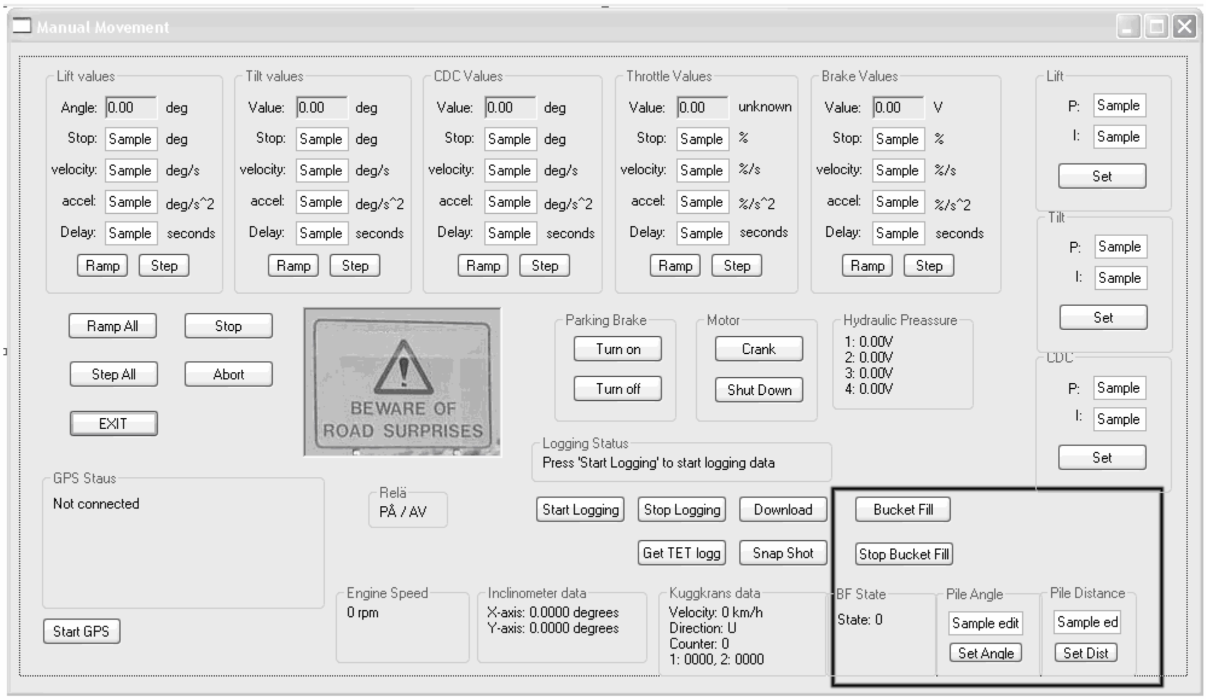

Figure 26, The new manual window

8.1.2. C++ to pip8

To distribute the bucket fill commands from the laptop to the Pip8, two extra parameters have been added. The parameters are global variables in the Simulink model and can be modified by the C++ application. The first parameter is called “BucketFill” and activates the bucket fill procedure when the bucket fill button is pressed in the C++ application. The second parameter is called “StopBucketFill” and aborts the bucket fill if it is pressed during operation.

A new internal signal has also been added to the manual operation window in the C++ application. This signal tells the user which state the bucket fill procedure is currently in.

8.2. Simulink

The original Simulink model is where most of the development has taken place. The bucket fill procedure it iself is added as a subsystem and apart from that it has been heavily modified and a great number of new features have been added. In this part, the most important features of the Simulink model will be described in detail.

The main window has been expanded with the bucket fill subsystem and an interface for adding more modules during the development process as shown in Figure 27. The control signals to the PI-regulators and the subsystem activation signals are distributed here.

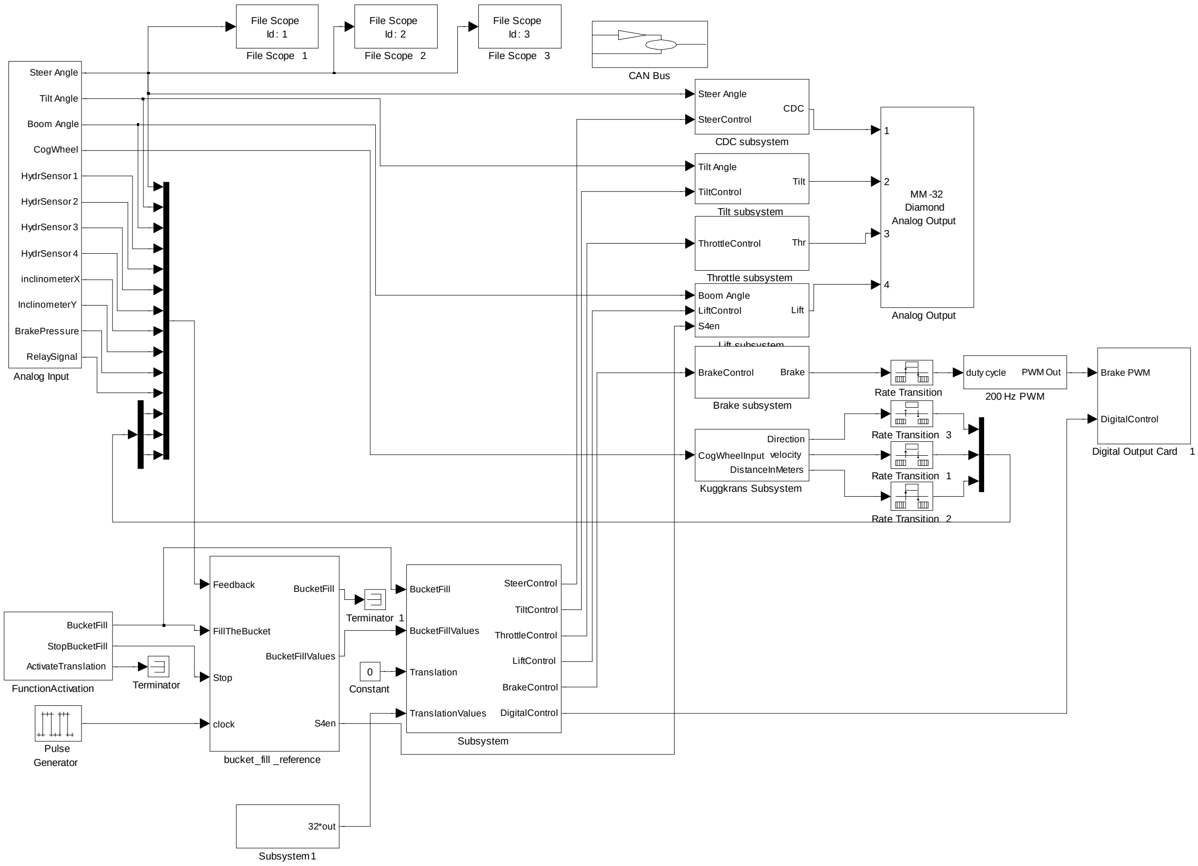

Figure 27, New Simulink main structure

The bucket fill subsystem consists of a state machine and regulators, shown in Figure 28. The state machine controls the regulators and decides when to activate and deactivate them according to the feedback given from the supervisor laptop and the regulators themselves.

The currently unused block "exception detector" will in the future detect and handle stall situations by disconnecting the regulator block momentarily and solve the stall problem before returning control to the regulators.

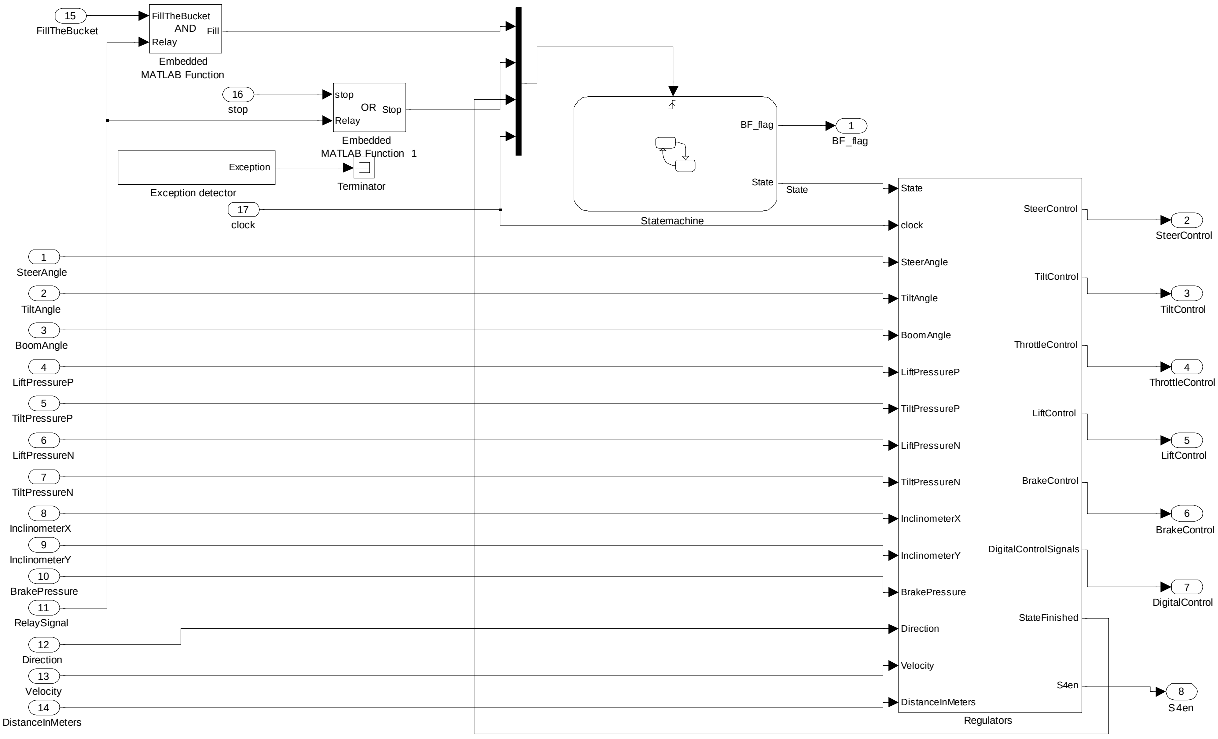

Figure 28, Bucket fill subsystem

The regulator block contains enabled subsystems for each state, shown in Figure 29. The state machine on the previous level activates and deactivates the state subsystems and selects the correct output signals. Some of the state subsystems forward signals to the next state to keep the machine moving smoothly.

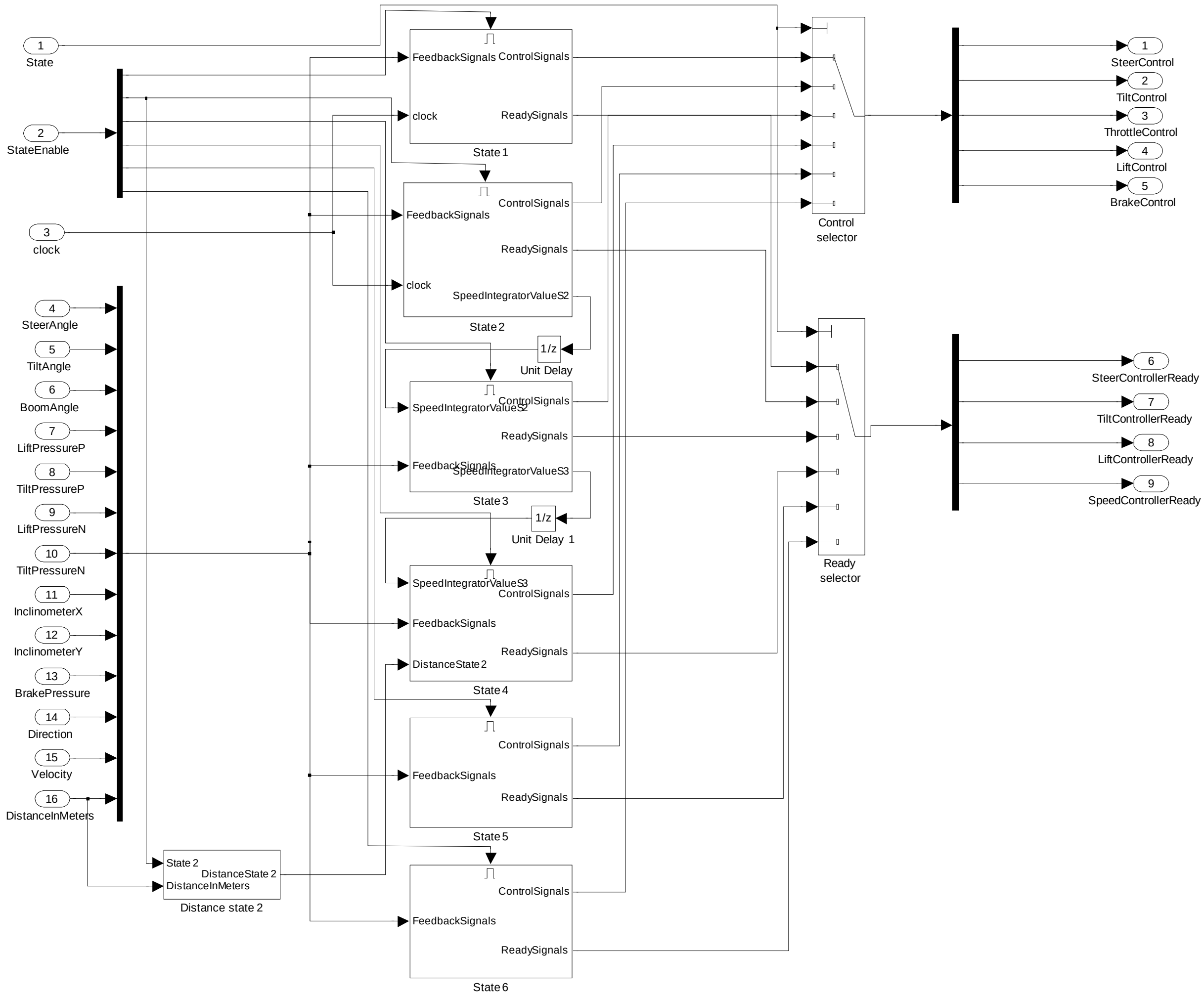

Figure 29, Regulator subsystem

Each state subsystem contains the different functions and regulators that is activated and deactivated during the operation as described in chapter 7.

8.3. C++

Some minor modifications have been made to the C++ model from the previous thesis work. Buttons for starting and stopping the bucket fill procedure has been added as well as a display which continuously shows the current state during a bucket fill.

9. Testing

Some reality testing has been performed to verify the functionality of the bucket fill regulator.

9.1. Field test

The machine has been tested in a real gravel pile. The circumstance during the testing was everything but optimal and very few of the general requirements on the pile and ground were fulfilled. The pile consisted of a mixture of larger rocks, gravel and dirt. The ground was wet and slippery and the pile profile angle wasn't constant.

9.1.1. J-curve test

The first test round took place with the J-curve regulator. As suspected though this test round didn't turn out well since the tilt blocks the lift as described in section 6. The results were so poor that they hardly fulfilled the basic requirements. After 10 tests the fill grade hadn't exceeded 80% any time.

As seen in Figure 30 the tilt performs a continuous movement between 73 and 75 seconds, which corresponds to state 4. The graph is representative for the behaviour in all tests and confirms the continuous use of the tilt during state 4.

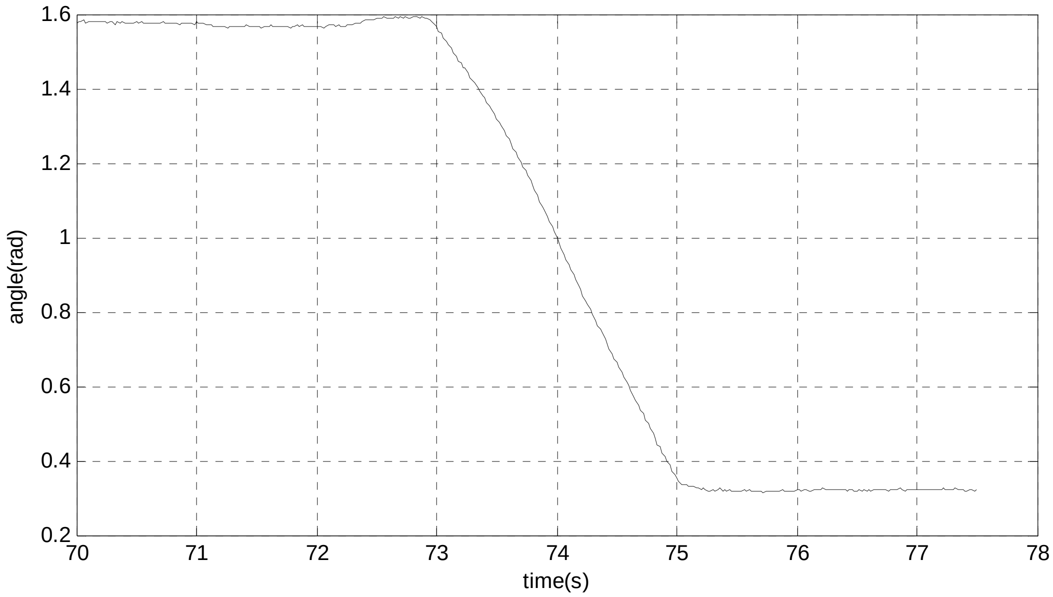

Figure 30, J-curve test tilt angle

In Figure 31 the tilt effect on the lift behaviour is clearly seen as the lift movement is non-existent while the tilt is moving.

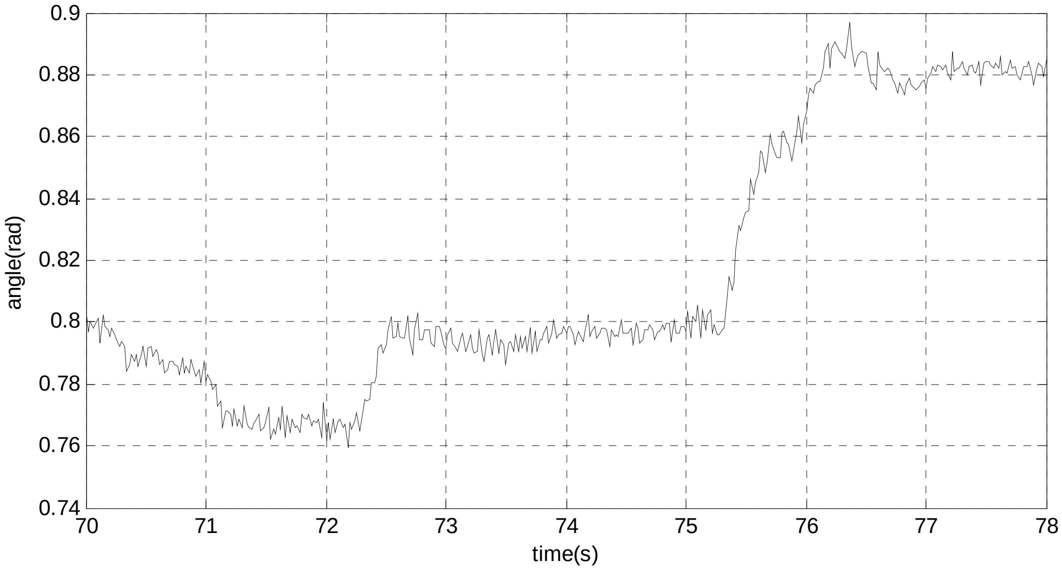

Figure 31, J-curve test lift angle

A quick look on the bucket tip movement in figure 32 shows that the bucket seems to follow a quite good trajectory. But since it is only performed by the tilt, the fill grade is not satisfying. The reason for this is that the bucket lift height is not enough to enclose enough material inside the J-curve.

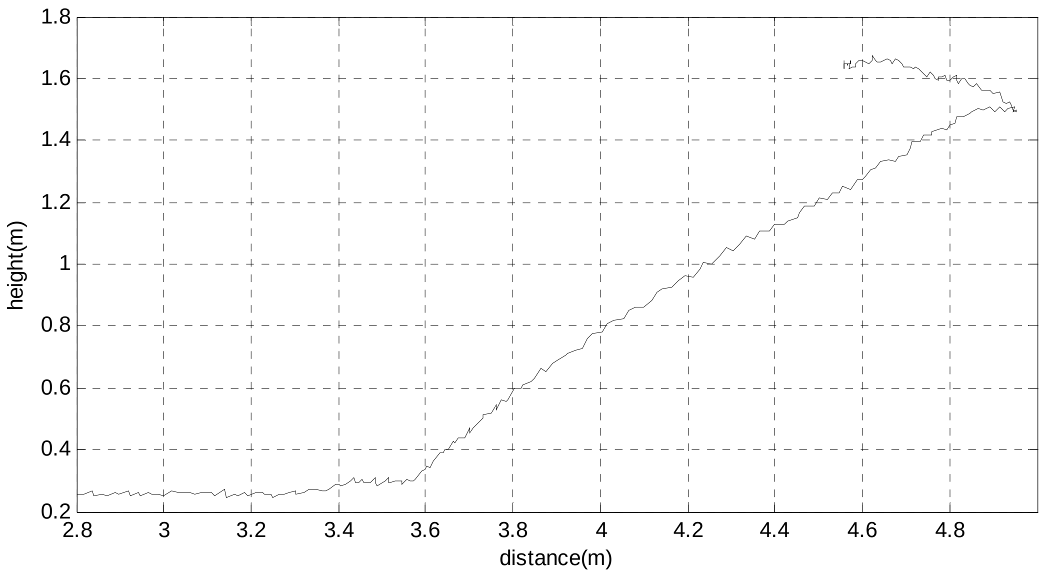

Figure 32, J-curve test bucket tip movement

9.1.2. Simple chic-chic

To quickly improve the performance for the final report, simple chic-chic behaviour was added by decreasing the tilt angle change, which is calculated from the translated distance. This allowed the lift command to be let through more than with the pure J-curve model. The result was satisfying. The combination of the lesser tilt signal and the unevenness of the pile and ground made the machine perform a chic-chic manoeuvre in two steps, filling the bucket approximately to 100% in all runs.

The tilt angle with this setting shows a clear stepwise behaviour in Figure 33.

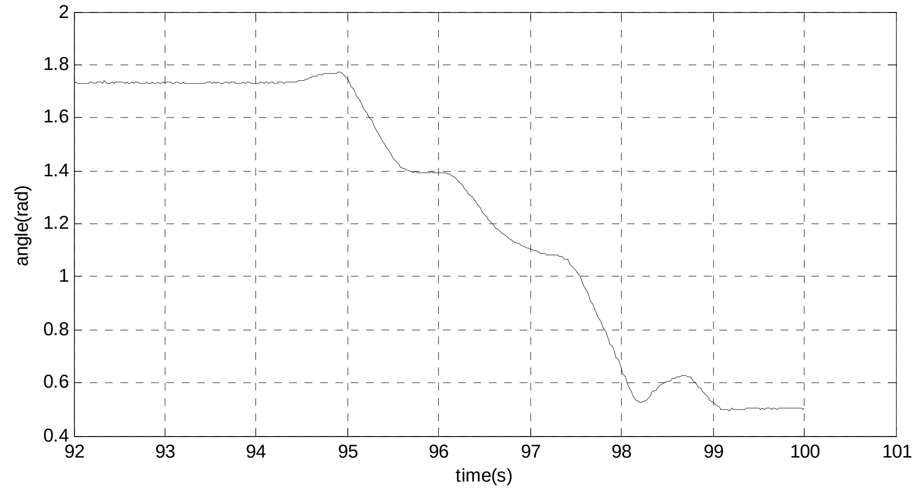

Figure 33, Simple chic-chic tilt angle

The stepwise tilt behaviour is reflected in the lift behaviour in Figure 34. The difference from the pure J-curve test is big; especially the total lift height has increased dramatically.

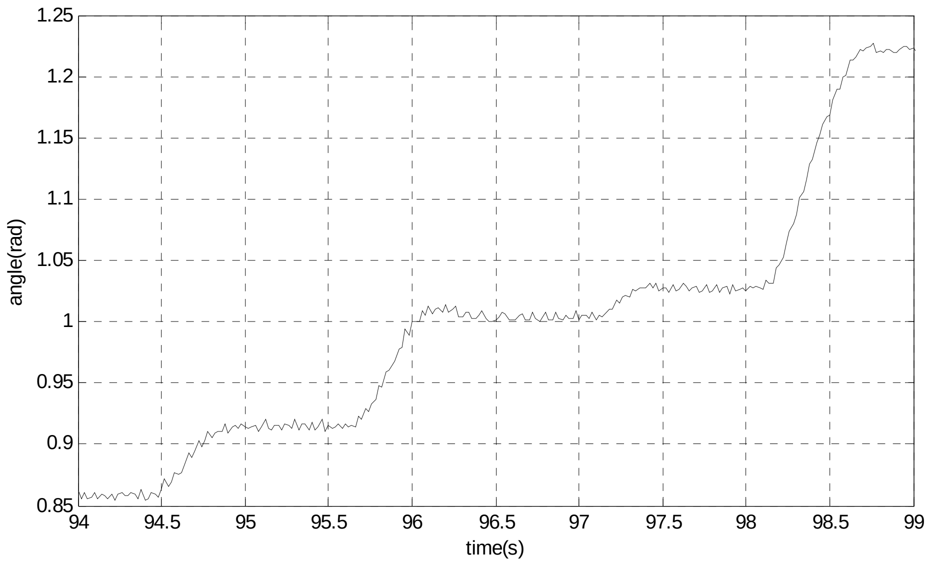

Figure 34, Simple chic-chic lift angle

The engine RPM during the bucket fill, shown in Figure 35, is comparable to a human drivers' performance and fits the description of the RPM-strategy given from the interviews.

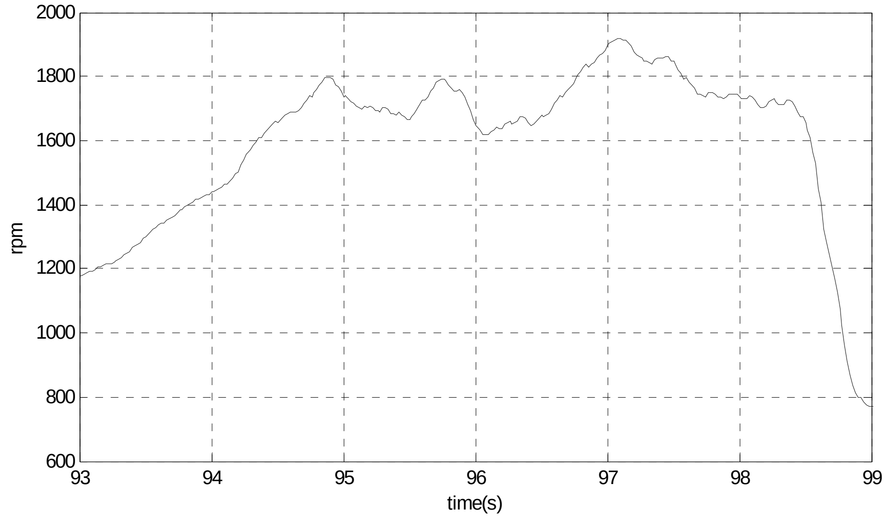

Figure 35, Simple chic-chic engine RPM

Finally the bucket tip movement with the simple chic-chic strategy, seen in Figure 36, shows a huge improvement compared to the J-curve strategy. The lift height is sufficient to reach enough material and the stepwise behaviour is clearly seen. The fill grade reached in this run reflects the improvement; it was approximately 100% of the bucket volume.

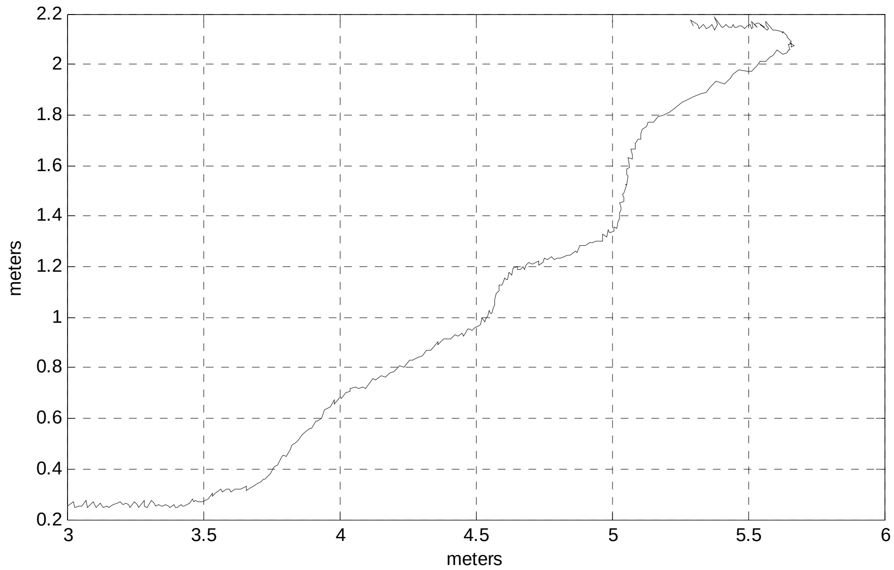

Figure 36, Simple chic-chic bucket tip movement

10. Results

When comparing the field test measurements it is easy to see that the machine simulates an experienced driver quite good. The productivity is at the same level as an experienced driver thanks to the satisfying fill grade reached in the final implementation and the fact that the autonomous machine fills the bucket just as fast as an experienced driver.

The engine RPM comparison in Figure 37 shows that the autonomous machine is comparable to an experienced driver :

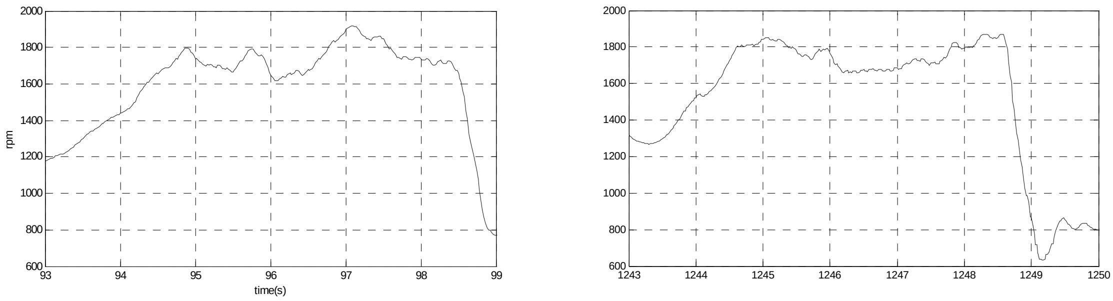

Figure 37, Autonomous machine RPM (left) VS. Human driver RPM (right)

Also the bucket tip movement is quite similar to a human driver as seen in Figure 38. This is a quite good indication that the strategy used is close to human behaviour.

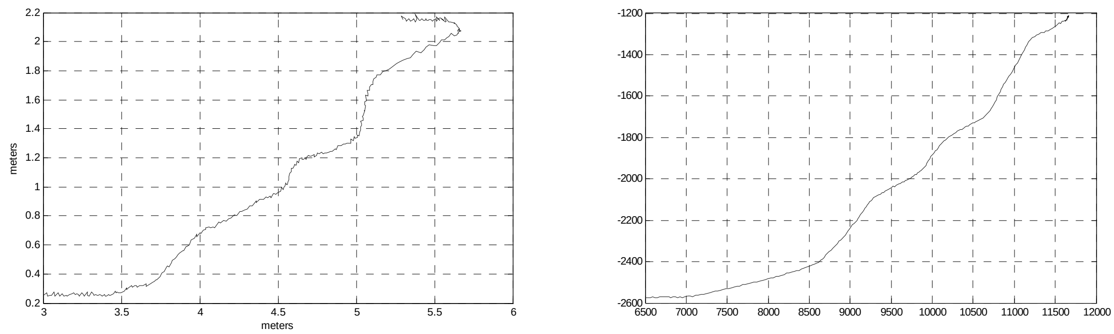

Figure 38, Autonomous machine bucket tip movement (left) VS. Human driver bucket tip movement (right)

10.1. Requirement fulfilments

All basic level requirements that concern the machine and the bucket fill system are fulfilled. The requirements concerning the environment and the pile are not considered here since the machine can complete a bucket fill in a less optimal environment.

Req. no.	Description	Level	Fulfilled
1	The machine shall reach more than 70% productivity compared to an experienced driver.	Basic	Yes
2	The machine shall reach more than 70% efficiency compared to an experienced driver.	Basic	Yes
3	Wheel spin shall not occur.	Basic	Yes
4	Translation stall shall not occur.	Basic	Yes
5	Lift stall shall not occur.	Basic	Yes
6	The machine shall autonomously fill one bucket with gravel at a time.	Basic	Yes
7	The bucket shall attack the pile horizontally and at ground level.	Basic	Yes
8	The machine shall apply pressure on the front axis to counteract wheel slip.	Basic	Yes

9	The machine shall move the bucket through the pile following the J-curve.	Basic	Yes
10	The machine shall move the bucket through the pile with the chic-chic strategy.	Extra	Partially
11	The machine shall handle common stall situations.	Extra	No
12	The machine shall perform a final push with the bucket to position the material.	Extra	No

Table 8, Requirement fulfilments

11. Conclusion

The goal for this project was to make a wheel loader be able to fill one bucket of gravel given the prerequisites listed in Table 2. The wheel loader is able to fill one bucket of gravel with known starting conditions standing in front of a pile. The procedure takes approximately 6 seconds to complete. Thus, the scope of the thesis work is completed.

11.1. Discussion

The analysis of the bucket fill shows that the process is a complex and delicate interplay between different considerations. Some of them are apparent and others are harder to detect and understand. The apparent ones are gathered in the 5 states while the not so apparent are gathered in the 6 problem formulations. It is possible to fill the bucket quite well using only the 5 states and the solution to one or some of the problems. But to perform excellent during long periods of time, all problems must be handled.

This project solves enough problems to manage to complete a good bucket fill, but in an endurance test, the current system will inevitably run into problems. There are also still some black holes which have not been covered by this thesis work, for example calculating the actual forces that affect the machine and the pile. Especially state 4 could benefit a lot if the feedback from the machine can be expanded to incorporate interesting forces.

11.2. Future work

The development of the bucket fill procedure will continue. The next logical step would be to start doing research to understand and develop the chic-chic stage. The aim should be kept at solving the 6 problems and thus creating the robust bucket fill regulator.

Also the addition of more feedback from the machine, like vision systems and force feedback would increase the understanding and possibilities for the autonomous machine.

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