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KBS-3H

Upgrading the deposition machine for the Multi Purpose Test

Markku Ojala, Thomas von Numers
Navitec Systems

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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Keywords: Horizontal deposition machine, Instrumentation improvement, Actuation system enhancement, Control system development, Software restructuring, Control method improvement, Error handling, Error recovery, Improved automation level.

Summary

The control system of the horizontal deposition machine has not been fully functional. The incomplete software application has suffered from unexpected functional stops and the system has not been able to fully control the balancing of the load. In order to ensure reliable deposition of the components in the Multi Purpose Test (MPT) experiment the control system of the horizontal deposition machine had to be further developed.

The project was initiated by a control system investigation in order to assess the required correction work. Development plans were made for instrumentation of the machine, correction of the software structure and development of the control method.

As the structural shortcomings in the control application were corrected and most of the communication problems between the modules were solved, a basis for further development was laid. By a thorough instrumentation of the machine and an efficient logging system the machine behavior could be investigated. The control method was then enhanced by developing further all interacting functions one by one. The functionality was improved, but not completely solved. The mechanics of the machine was not completely controllable by the functions in use. Introduction of a new actuation system for steering the front of the sliding plate and lifting pallet produced satisfying control stability. Finally a composite control method utilizing all improved controls was developed.

The automation level of the machine was increased in order to avoid manual operation. New control functionality was developed to handle deposition of units of various lengths as well as the special cases of approaching the drift end and a previous component in the drift. All functions required in a complete deposition were tested with satisfying results both with Supercontainer dummy, distance block dummy and a real bentonite distance block prior to the final MPT deposition.

The bentonite distance block structure with binding rods and foot modules, sensor mounting, sensor cabling solution and a cable block for protecting the sensor cabling during deposition were also tested with satisfying results. The instrumented distance block was deposited and retrieved with good results.

Based on these tests, the machine was considered sufficiently reliable and adequate for the deposition tasks in the MPT experiment.

In the MPT experiment all components could be deposited with good accuracy and good final results, though it also revealed how sensitive the current machine design is to small variations in circumstances. The remaining problems can be solved, but mechanical modifications are required before the control can be further developed.

Large Underground Concept Experiments
This Project has received funding from EuroAtom/FP7 under grant agreement n°269905

Sammanfattning

Den horisontella deponeringsmaskinens styrsystem har inte fungerat tillfredsställande. En ofullständig programstruktur har lett till oförklarliga avbrott i styrningen och ofullbordade kontrollfunktioner har förorsakat problem med balanseringen av lasten. För att säkerställa en tillförlitlig deponering av komponenterna i MPT-experimentet behövde maskinens styrsystem vidareutvecklas.

För att fastsälla korrigeringsbehovet och dess omfattning föregicks utvecklingsprojektet av en systemundersökning. På basen av undersökningsresultaten gjordes planer för komplettering av maskinens instrumentering, korrigering av styrsystemets programstruktur och vidareutveckling av kontrollmetodiken.

Genom att korrigera de strukturella problemen i kontrollprogrammet och förbättra kommunikationen mellan de olika modulerna i styrsystemet lades grunden för vidareutveckling av kontrollmetoderna. En grundlig instrumentering av maskinens frihetsgrader och ett effektivt loggningssystem möjliggjorde noggrann undersökning av maskinens beteende. Därefter utvecklades maskinkontrollen genom att analysera och förbättra alla samverkande kontrollmetoder en och en. Maskinkontrollen förbättrades avsevärt, men löstes inte helt på grund av att maskinens mekanik inte var helt styrbar med de tillgängliga kontrollmetoderna. En stabil kontroll uppnåddes först då ett system för aktiv inbördes styrning av glidplåtens och palettens fronter togs i bruk. Slutligen utformades en sammansatt kontrollalgoritm som enligt behov utnyttjar olika kombinationer av alla de utvecklade kontrollmetoderna.

Maskinens automationsnivå utökades för att så långt som möjligt undvika manuell styrning. Nya kontrollfunktioner utvecklades för deponering av komponenter av varierande längd, för deponering av en komponent mot stuff eller deponering av en komponent mot en tidigare deponerad komponent. Alla kontrollfunktioner som krävs för en komplett automatisk deponering testades före MPT-experimentet med tillfredsställande resultat. Tester gjordes med Supercontainer-dummy, distansblocks-dummy och ett komplett distansblock i bentonit.

Distansblockskonstruktionen med sammanhållande stänger, fotmoduler, sensormontage, sensorkablage och kabelblock för skyddande av sensorkablaget under deponeringen testades i sin helhet med tillfredsställande resultat. Ett distansblock i bentonit med dummysensorer deponerades och återtogs med goda resultat. På basen av dessa test ansågs maskinen vara ändamålsenlig och tillräckligt tillförlitlig för utförandet av deponeringarna i MPT-experimentet.

Under MPT-experimentet kunde alla komponenter deponeras med god noggrannhet och ett gott helhetsresultat. Trots detta visade experimentet också att maskinen i sin nuvarande utformning är relativt känslig för variationer i omständigheterna. De återstående problemen kan lösas, men en vidareutveckling av kontrollmetodiken förutsätter också mekaniska modifikationer.

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1 Introduction

1.1 General

The common goal of SKB and Posiva is disposal of spent nuclear fuel from Swedish and Finnish nuclear power plants at depth in crystalline bedrock to ensure the safety of human beings and the environment for long periods of time. The method selected for the final repository is the KBS-3 method, Figure 1-1. The reference design is KBS-3V employing vertical disposal of the waste canisters, where horizontal disposal of the canisters, KBS-3H, is a possible alternative which is being elaborated by the two organisations. SKB´s and Posiva´s current programmes for KBS-3 are detailed in SKB´s RD&D-Programme (SKB 2013) and in Posiva´s TKS-2009 (Posiva 2010).

The so called Multi Purpose Test (MPT) is carried out at the Äspö HRL starting 2011 and is part of the KBS-3H project development (SKB 2012). The MPT is also part of the LucoeX project and is partly funded by the European Commission.

The test is basically a shortened non-heated installation of the KBS-3H reference design, Drainage, Artificial Watering and air Evacuation (DAWE), and includes the main KBS-3H components, see Figure 1-2. The installation is carried out according to DAWE after which the test conditions are monitored. Dismantling and analysis will be carried out at a later stage and the timing for this will be dependent on the measured data.

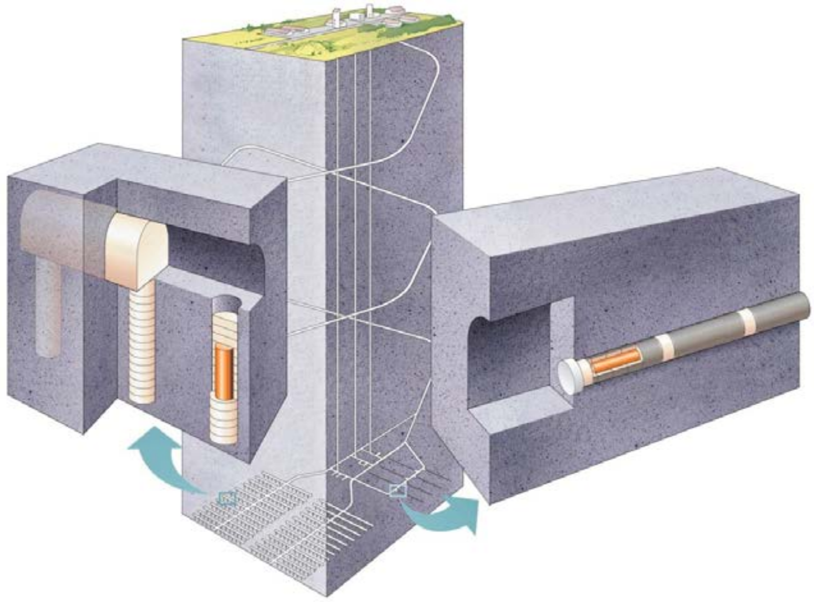

Figure 1-1. *Schematic illustration of the KBS-3 method with its three barriers: the canister, the buffer and the rock. The vertical reference design is illustrated to the left and the horizontal alternative to the right.*

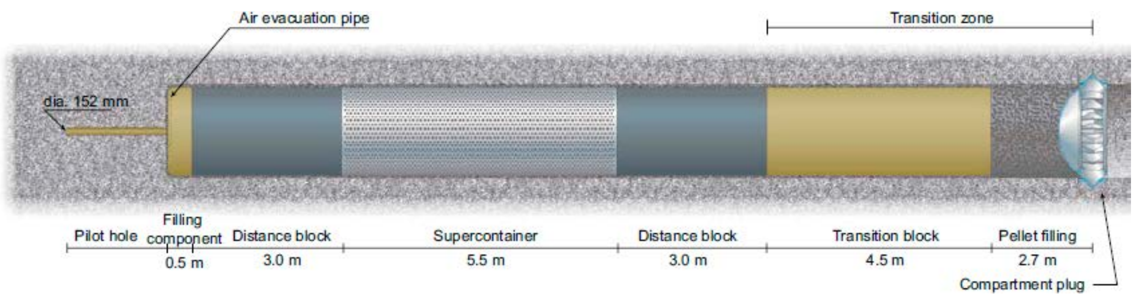

Figure 1-2. *The main KBS-3H components, a Supercontainer, two distance blocks and a compartment plug with it´s transition zone.*

1.2 Background

The KBS-3H deposition machine is a first prototype for demonstration of horizontal deposition in full scale. The machine was jointly designed by SKB and Posiva and manufactured by ECA in 2005–2006 within the 6th Framework programme "ESDRED" of the European Commission. The machine was first demonstrated in full scale tests in the Äspö HRL in 2007.

The water cushion based transportation principle and the heavy load makes the control of the machine challenging. Previous machine testing has been troublesome due to limited control ability and an incomplete software application. The purpose of this work was to develop the control system of the KBS-3H deposition machine to such a functional level, that the depositions in the MPT experiment could be reliably performed and the horizontal deposition concept could be evaluated as a whole. The project was initiated by a machine system analysis in order to determine the needs for corrective actions on the machine hardware and the control system software.

1.3 Purpose and scope of this report

This report describes the work done to develop the control system of the horizontal deposition machine to its' current state of maturity. The development work has focused on three main areas.

- Redesign of the control software to remove structural problems and to enhance reliability and functionality in general to an acceptable level.
- Improvement of the instrumentation of the machine to provide more information of the machine behaviour and enhancement of the actuation system for better machine control.
- Improvement of the control methods to avoid previously occurring machine balancing problems and increasing the automation degree to allow deposition of Supercontainers, distance blocks and transition blocks of various lengths without manual control.

The report discusses the motivations for the development steps, evaluates their effects and finally makes an assessment of the overall functionality of the control system. The control system is evaluated by extensive deposition testing with Supercontainer dummy, distance block dummy and real bentonite components. The application of a logging system saving all measurement and control signals enables comprehensive and reliable test analysis.

Further the report describes deposition of several different bentonite components. Bentonite components have not been deposited with the machine before and topics of special interest were their endurance against the physical stresses and wetting conditions caused by the deposition.

2 KBS-3H deposition machine

2.1 General

The KBS-3H deposition machine is a prototype machine based on a water cushion technique for lifting and transporting the Supercontainer in stepwise movements inside the drift. The lifting and pushing sequence is repeated until the Supercontainer reaches its' destination in the drift.

The deposition machine forms a complete unit with the lifting pallet and the sliding plate, Figure 2-1. The lifting pallet and sliding plate are moved in turns to make the stepwise motion. The machine body runs on wheels while moving the sliding plate which is directly attached to the machine body. The lifting pallet which is attached to the radiation shield is moved using linear actuators between the machine body and the radiation shield as the machine is standing still.

The lifting pallet is guided on the sliding plate by guiding profiles on the sides of the sliding plate, keeping the whole unit lined in the drift. The lifted Supercontainer is kept in balance by a counter-force produced by the masses of the machine body and a counterweight ballast that can be adjusted sideways. The balancing force is brought to the lifting pallet as a torsional force over the linear actuators between the machine body and the shield. The machine body is centered in the drift by steering with the wheels. The wheel axles are interconnected and mounted to the machine body on spherical bearings allowing active steering of the body by turning the axles. The steering is actuated by driving the wheels on each side with different speeds to adjust the angle of the interconnected axles relative to the machine body.

The deposition machine is parked on a start tube outside the deposition drift while not in operation. Between the start tube and the drift there is a space for the transport tube in which Supercontainers and distance blocks are transported to the deposition site, Figure 2-2. To be able to move the transport tube to the drift opening the start tube with the deposition machine must first be moved aside. The machine is longer than the start tube and therefore the sliding plate and lifting pallet are detached and pushed under the machine before the start tube can be moved. When the transport tube and start tube are placed in position for deposition, they are aligned with the drift using adjustable position blocks. Finally the sliding plate and lifting pallet are pulled forwards and attached to the machine again. Alignment of the tubes is important for the sliding plate and machine to pass the transition points from start tube to transport tube and the transport tube to the drift.

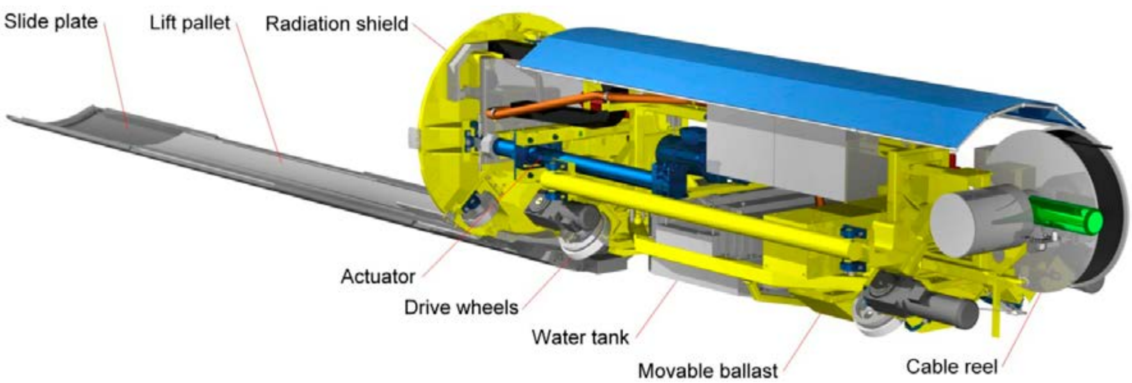

Figure 2-1. *The main functional parts of the horizontal deposition machine.*

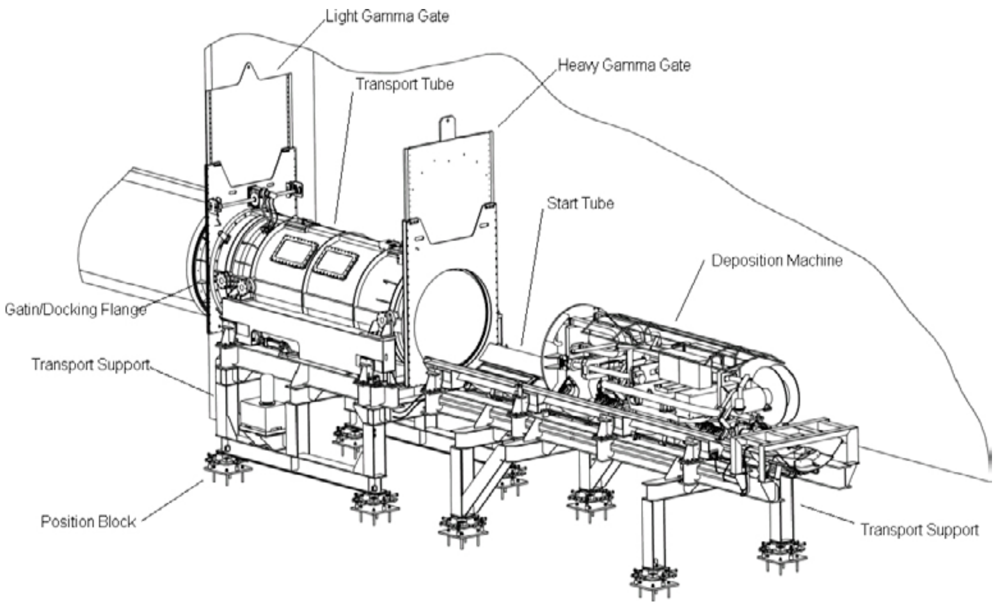

Figure 2-2. *Placing of transport tube and start tube outside the drift. The tubes stand on transport supports which are adjusted into correct position and height with the position blocks on the ground.*

During functional testing of the KBS-3H deposition machine in 2007–2009 it became apparent that the machine was not ready for performance evaluation of the horizontal deposition concept. The operators daily logs mainly reporting interrupted drives, system disturbances and machine balancing problems. Some mechanical enhancements were done in parallel with previous testing (Halvarsson 2008) but it was clear that the machine suffered from greater control problems than mechanical enhancements could solve. A software analysis project was conducted in 2010, which resulted in a set of corrective recommendations.

- Correction of the control software structure.
- Instrumenting the machine to gain complete knowledge of its' behaviour.
- Investigation of machine behaviour by testing and datalogging.
- Designing an actuation system to gain complete controllability.
- Development of a new control method for the machine balancing.

It was discovered that the distributed control software was built together from software modules with an inadequate overall view resulting in an overcomplex structure, partially overlapping functions and discontinuous functional sequences. The software was also not finalised in terms of functional exceptions, error handling and error recovery which often led to unexpected and irrecoverable jamming situations. Since the operators could not see the reasons for the stops on the user interface, they soon adapted to error handling by experimental manual operation and consequently the error reports contained assumptions that were of limited value.

Beside the structural problems in the control system, a more serious problem was the recurring imbalance of the machine. As the machine could not keep the load in balance in all situations, but drifted into irrecoverable imbalance from time to time it did obviously not fulfil the design objectives. The machine could work well for certain periods after calibration of pallet and sliding plate, but situations would eventually come when the machine could not maintain the balance. Understanding of this problem was not clear and the operators did also not have any rules for correct calibration of the machine. As a consequence the operators again adapted to the problem by experimenting how to manually bring back the machine into balance. A normal balancing operation being a few strokes of reverse driving in hope of returning into balance. Clearly, solving this problem was the main challenge of this project as the machine was supposed to work automatically without repeated manual intervention.

Based on previous observations of the balancing problem (Halvarsson 2008) it was concluded that alignment of the sliding plate and the lifting pallet with the drift is of high importance for the balancing. Further, it was found that the cushions are sensitive to load variations and a too uneven weight distribution would lead to unmanageable problems. It was concluded that it is of highest importance that the lifting pallet is accurately placed underneath the Supercontainer and the proposed corrective actions were better fixation of the lifting pallet and sliding plate to the machine for a more rigid and straight machine structure. However, based on the software analysis in 2010 it was concluded that the insufficient ability of the control system to control the mechanics was a more severe problem than the lack of rigidity in the mechanics.

By the start of this project it was decided that the old software, despite many flaws, contained much useful code and should be corrected instead of writing an entirely new application. The project was therefore started by further investigating the structure of the software and documenting the starting point of the code before doing the rebuilding work. Simultaneously the instrumentation of the machine was expanded to cover its' behaviour as comprehensively as possible and an efficient logging system was applied to enable thorough functional investigation. Mechanically the deposition machine was considered well suited for the work, though somewhat worn or deformed in some parts so no significant changes were planned, only minor repair and overhaul tasks.

2.2 Requirements

The requirements set in the project were primarily to ensure a consistent and reliable function of the horizontal deposition machine. The reliability should be on such a level that repetitive driving could be performed to demonstrate that the horizontal deposition principle is working and that a realistic performance evaluation and safety analysis could be done. The functionality should be on such a level that deposition of the Supercontainer and distance blocks in the MPT demonstration could be safely carried out within the time restrictions posed by the project schedule.

The original functional requirements for the machine were given as reference for this project. It was soon realized that the machine control software was not fully corresponding to the requirement specifications and that all requirements could not be completely met. The project therefore started by matching the software to the specifications in order to define and prioritize the required corrective actions.

High priority was given to requirements on:

- Control ability from the operators interface.
- Feedback to the operators interface.
- Automation level of the machine.
- Functional reliability of the system.
- Functional safety of the system.
- Fulfilment of all occurring deposition situations.

Since these requirements strongly affect the usability of the machine and are directly related to the software application. Lower priority was given to requirements on:

- Load capacity.
- Deposition speed.
- Powering adequacy.
- Other physical or mechanical requirements.

As these requirements are more related with the mechanics and components of the machine and mainly fall outside the software scope of this project.

3 Updates

3.1 Hardware updates

The mechanical overhaul of the machine was planned simply to get rid of troublesome disturbances caused by wear and deformation as well as corrosion and dirt. Only a few mechanical changes were planned with functional enhancement in mind. The main hardware update aimed at instrumenting the machine for a complete behavioural investigation focussing on solving the balancing problem. A hardware work not anticipated beforehand, but necessary in order to ensure reliable operation was a partial rebuild of the electrical system.

3.1.1 Basic mechanical updates

Straightening the start tube

The start tube had been deformed so that it was shaped somewhat like a hammock. The result was that the path of the machine over the transport tube and start tube into the drift did not constitute a straight line. As a result, the height and angle of the start tube could not be adjusted to eliminate a harmful step between the transport tube and start tube. The machine always jammed in one way or the other when attempting to drive in under the Supercontainer in the transport tube.

Since the start tube is a rather complicated welded structure with unknown internal strains and the shape is difficult to measure and verify on site it was decided not to modify the structure itself. Instead, the distance between the wheel tracks of the start tube and a straight liner were measured over the whole start tube and the wheel tracks were straightened by adding steel plates of different thicknesses along the wheel tracks. Steel plates of 2 and 3 mm thickness were combined in one to four layers on top of each other in order to form straight wheel tracks. The plates were mounted onto the start tube with countersunk screws for easy removal and further adjustment. The shapes of the wheel tracks before straightening and consequently the amount of filling are presented in Figure 3-1.

The work resulted in a reasonably straight start tube and the jamming problems when driving the sliding plate and pallet in under a Supercontainer in the transport tube could be reduced remarkably.

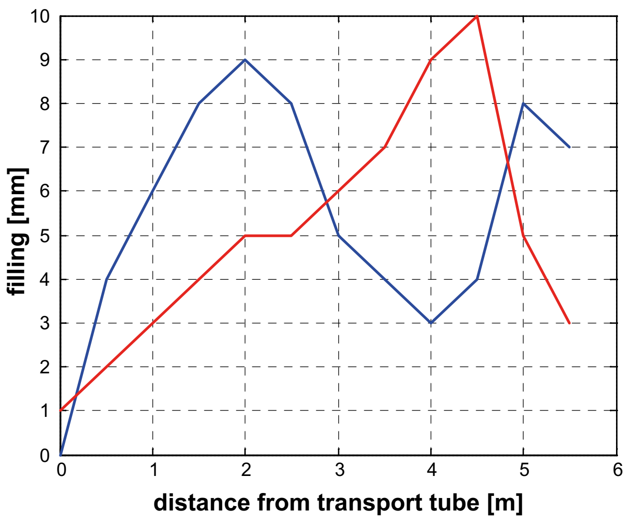

Figure 3-1. *Thickness of steel filling on wheel tracks of start tube, blue – right track, red – left track.*

Sliding plate overhaul

The sliding plate is constantly dragged on the rock surface of the drift and then kind of rolled by the sliding Supercontainer. During every stroke the sliding plate is differently supported by the drift bottom and therefore the rolling forces deform the plate in different ways. Since the lifting cushions slide on the middle part and the sliding plate has stiff box type structures in each end the plate is slowly deformed into a hammock shape. Figure 3-2 shows the two cushion tracks on the plate. Since the front end of the sliding plate is a stiff box-type structure it keeps its' shape. As a result the sliding plate tends to lift its' front end from the drift bottom causing an extra space requirement between the drift bottom and the Supercontainer. Another result is that the front end of the sliding plate is not stably supported over its' whole width by the drift bottom and tends to wiggle somewhat depending on which side the main weight lies on. This is causing some inaccuracy in the angle detection of the front of the sliding plate. It was therefore planned that the sliding plate should be reshaped as part of the machine upgrade. However, the sliding plate is a very large structure and reshaping of the macro deformation could not be done at site. Instead some local deformations caused by stones or local bending caused by the step between the start tube and the transport tube were repaired, Figure 3-3. To avoid excessive wear of the cushions scratches on the upper sliding surface of the plate were removed by polishing.

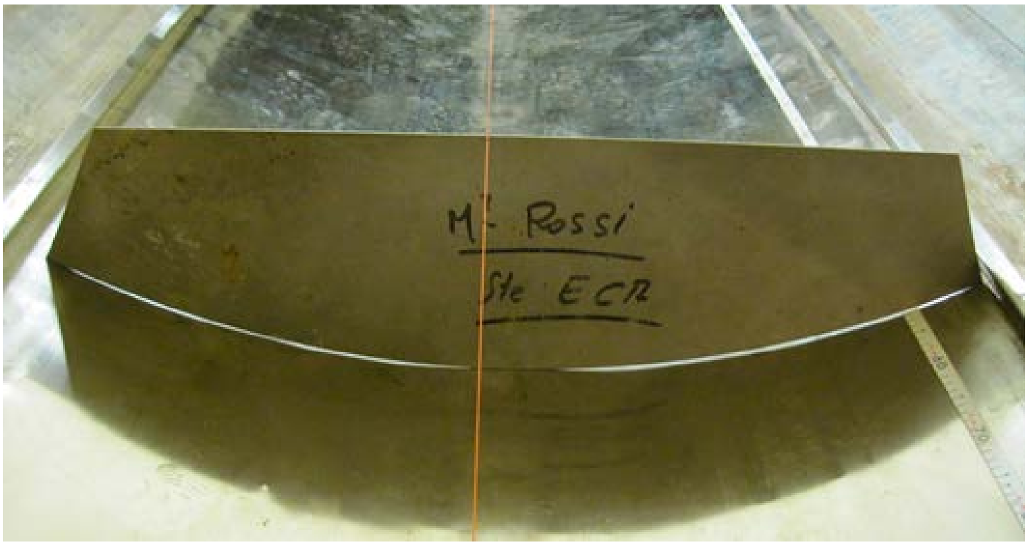

Figure 3-2. *The sliding plate is deformed by the pressure from the cushions. The metal sheet is clearly stretched at the two cushion tracks.*

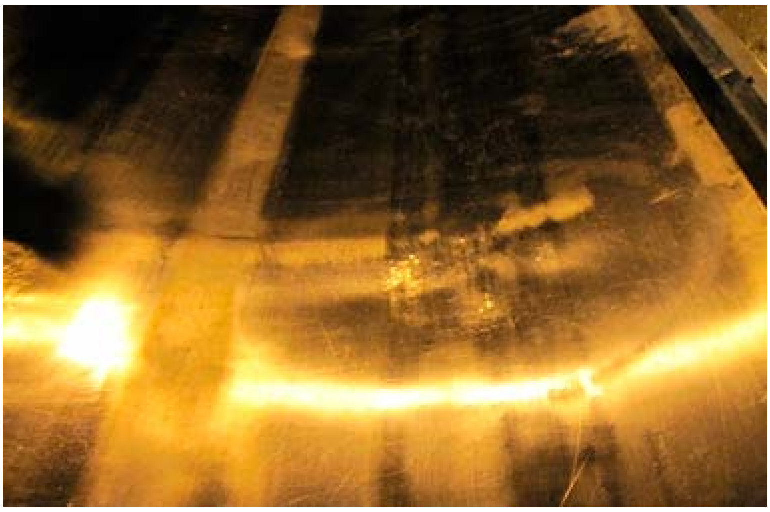

Figure 3-3. *A heavy load has stamped the shape of the underneath drift surface into the metal sheet.*

Assembly of sliding plate collision sensor protection

The framework in the front of the sliding plate keeps the front part of the plate rounded and serves as a housing for several sensors. The radius of the framework is somewhat smaller than the radius of the drift causing some wiggling during operation, see Figure 3-4. Collision sensors are mounted on each front corner of the framework to stop the machine if the sliding plate would push against a foot of the Supercontainer. Due to the wiggling of the framework the collision sensors must not only withstand horizontal forces but also vertical forces as shown in Figure 3-5. Since the contact body of the sensor has been designed to withstand only horizontal forces it is bent by the vertical wiggling. The bending destroyed several inductive switches inside the contact body.

The design of the sensor was not changed, but the contact body was protected from vertical forces by mounting triangular guides forcing down the sliding plate if in contact with the Supercontainer, Figure 3-6.

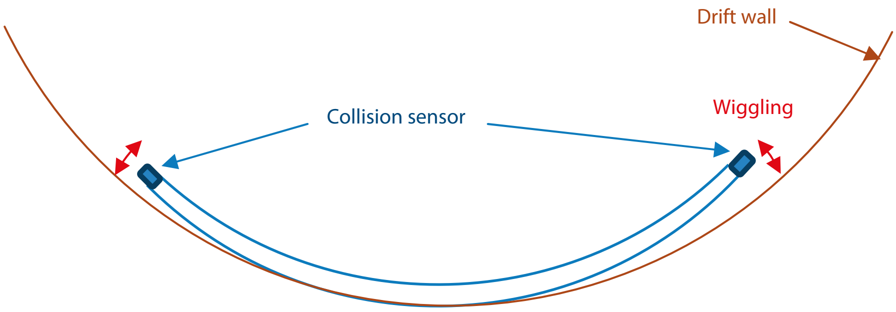

Figure 3-4. *The wiggling motion of thefront part of the sliding plate caused by a too small radius.*

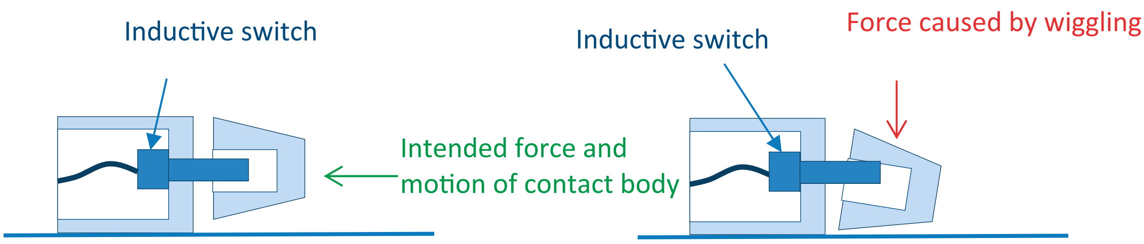

Figure 3-5. *Guides forcing down the sliding plate to protect the collision sensors from vertical bending forces.*

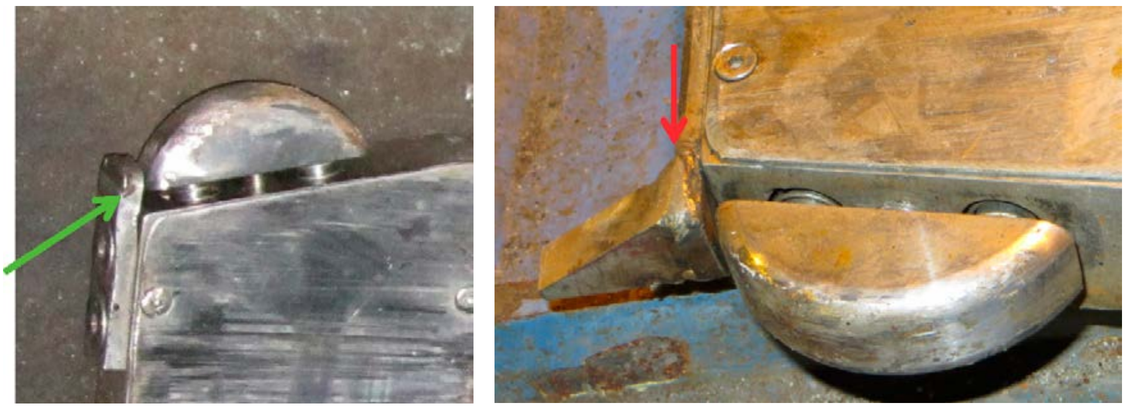

Figure 3-6. *To the left the old collision sensor protection consisting of a plate. To the right the new collision sensor protection guiding the sliding plate down.*

Renewal of the guiding edges of the sliding plate

In order to keep the Supercontainer balanced and in line with the tunnel the sliding plate is provided with guiding edges along each side of the plate. These edges are high enough to support the lifting pallet when lifted and they guide the pallet when it is pushed along the sliding plate. The original edges were manufactured in carbon steel and were heavily corroded. Their corroded surface caused a large friction against the plastic counteredges on the pallet and consequently unnecessarily high variations in pushing force of the Supercontainer. It also caused both wear on the pallet edges and lots of particles in the water system of the machine. The steel edges were therefore replaced by polyacetal plastic edges.

The old steel edges only covered a part of the sliding plate corresponding to the stroke length, but the new edges cover the entire side of the sliding plate to form a tightening surface for a splashing sealing to be mounted on the pallet.

The gap between the new edges is dimensioned so that the lifting pallet has approximately 6–7 mm of free space on each side. Thus, the Supercontainer is allowed to float freely within an inclination range of ±0.5 degrees between the edges. A narrower space would not allow for directional corrections during the transportation and a wider space would allow a too large inclination of the Supercontainer if the weight of the machine is insufficient for balancing.

Assembly of filters in the water return line

Wear between the guiding edges on the sliding plate and the pallet as well as abrasion of the concrete elements in the Supercontainer dummy have caused contamination of the water returning from the lifting cushions. Since the return water was not filtered, all particles have been able to circulate in the water system. The result has been clogging of lifting cushion valves leading to uneven lifting and sometimes very slow emptying of cushions causing excessive strains on cushions. Since the concrete blocks in the Supercontainer dummy were to be replaced by more brittle bentonite, it was assumed that the amount of particles would increase in real deposition.

Two water filters were therefore mounted in the water return line before the main tank, Figure 3-7. Clogging of valves has not been a problem after this arrangement.

Figure 3-7 . *Black chips from the guiding edges of the sliding plate in the water filter.*

Cushion overhaul

Cushion overhaul seems to be standard procedure every now and then on the machine. A major difficulty in cushion service is that the result of the work cannot be tested without connecting the lifting pallet to the machine and perform a lift of the Supercontainer for verification. Just a lift without a load will not prove anything since the working pressure threshold is never reached in the cushions. Cushion problems that have occurred are:

- Slow pressure release in some cushions. This phenomenon slows down the deposition cycle since no motion is allowed until all cushions are pressureless. No cushions have bursted due to excessive pressure which means that the water release anyway works though it is slow from time to time. Clogged valves have previously been reported to cause this type of problems.
- Some cushions don't reach the threshold pressure due to a leakage between the feeding pipe and the distribution block of the cushion.
- Some cushions don't reach the threshold pressure due to a leakage in the sensor pipe. In this case the cushion is actually working even though the control system reports a pressure failure.
- Uneven lifting speed and lifting height even though all cushions work normally. This is a major reason for the bad controllability of the machine since uneven lifting is causing imbalance of the Supercontainer and a changing behaviour of the machine. The controllability issue will be discussed further in later chapters.
- Leaking cushions, usually due to wear or a very small hole in a sharp bend of the rubber.
- Remarkable wear of the anti friction layer of the cushions. Four cushions were tested with a special anti friction layer. This cushion model proved to be unsuitable for this application due to fast shedding of the layer.

Extension ring for the transport tube

The transport tube cannot be transported in the Äspö ramp tunnel with the gamma gates mounted due to the height limitation. In order to save time in the final MPT experiment, the use of gamma gates at the deposition drift was avoided by designing a replacement ring, Figure 3-8. By mounting this ring in one end of the transport tube the tube is lengthened about as much as the removal of the gammagates shortens it.

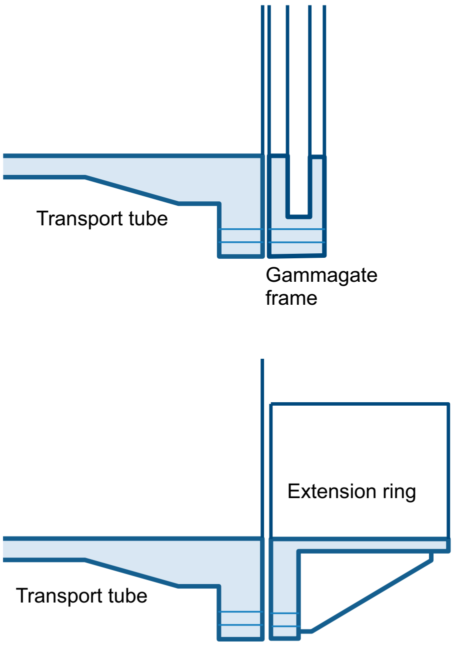

Figure 3-8. *Left upper drawing shows the end of the transport tube with the frame of the open gammagate. Below the extension ring replacing the two gammagates. To the right a photo with the extension ring mounted to the transport tube and the end of the start tube adjusted towards the ring.*

3.1.2 New instrumentation

New lifting height sensors

The lifting height of the lifting pallet was previously measured with sensors consisiting of a turning head and three inductive sensors indicating its' position. The old lifting height sensors merely indicated that the lifting is occurring rather than giving an actual height measurement. In order to get a better picture of how the pallet lifting proceeds and how good the balance between the corners of the pallet is, a new linear lifting height sensor type was developed. This sensor utilizes a rod type sensor measuring the rotation of a permanent magnet. The rod-type sensor is placed in the rotational axis of the turning head and the permanent magnet in the bracket of the turning head. The result is a linear height measurement with a very good resolution. The new sensor design is shown in Figure 3-9.

When combined with an efficient logging system the lifting could be investigated in terms of variations in lifting height and speed during the entire lifting sequence, differences between pallet corners, differences in lifting behaviour with changing lifting parameters and so on. Since most factors leading to imbalance of the Supercontainer can be seen in the lifting behaviour of the pallet this sensor system played a key role in the process of working out the balancing control of the machine. Some examples are given in Figure 3-10.

Distance laser for longitudinal Supercontainer and distance block positioning on pallet

Originally the deposition machine was designed to transport only Supercontainers or distance blocks of one specific size. Distance blocks could be transported either two at a time or one distance block on the front end of the lifting pallet with a mechanical extension piece between the shield and the distance block. Since the size of the distance blocks must vary depending on the conditions in the drift a basic requirement was that the machine must be able to transport distance blocks of different lengths (equal to or shorter than a Supercontainer). The mechanical extension piece was abandoned as a too inflexible and laborous tool. Instead it was planned that by measuring the longitudinal position of the load on the lifting pallet it should be possible for the control system to keep the load balanced wherever the load would be on the pallet. For this balancing two inputs would be needed; the size of the distance block would be requested from the operator and the distance between the shield and the distance block would be measured with a laser distance meter.

A SICK DT50 laser distance meter was mounted behind the radiation protection shield and a hole in the shield was drilled for the laser beam, figures 3-11 a and b. Not a final solution in terms of radiation protection, but good enough for proof of concept. The laser is directed forwards and measures the position of the rear end of the distance block. If a Supercontainer has a perforated end plate the measurement varies somewhat depending on whether the laser beam hits the shell or the bentonite. This was considered a negligible error in this process but has been completely avoided now, as the reference design of the Supercontainer for other reasons has been changed to solid end plates.

The laser distance measurement brings an additional process stability as it produces a verification of the load position even if the Supercontainer contact switch loses contact. This is preventing unnecessary stops in certain problem situations, though the process anyhow tries to keep the switch in contact. This functionality proved very useful when testing deposition of a bentonite distance block with a cable block designed for storing the sensor cabling required in the MPT experiment. Due to the design of the cable block the shield contact could not be achieved, but the test could anyway be performed thanks to the laser measurement.

The distance laser has been verified to measure the position of a Supercontainer beyond the lifting pallet and it can therefore also be used for approaching a Supercontainer for retrieval.

The use of the distance laser will be further discussed in chapter 4.2.1 Automatic handling of distance blocks of warious lengths.

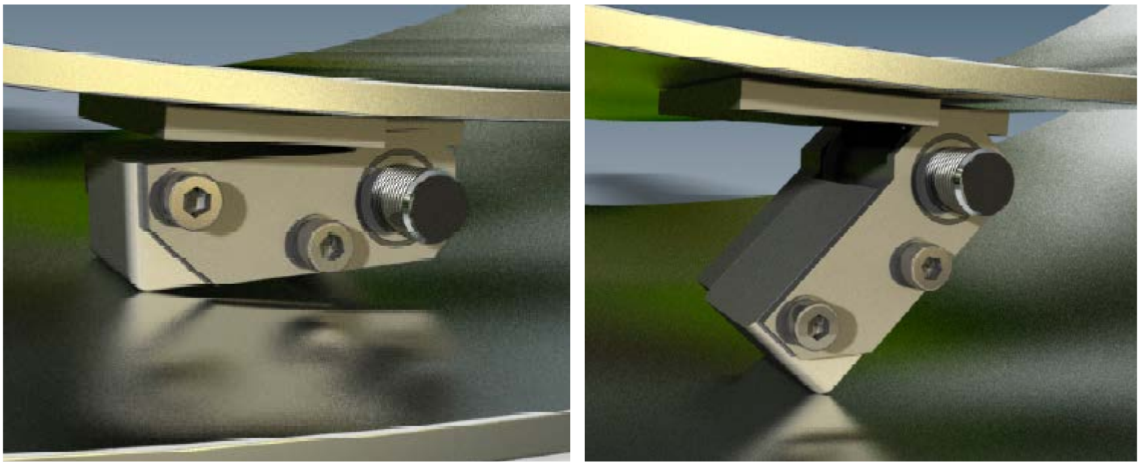

***Figure 3-9.** The design of the new pallet height sensor.*

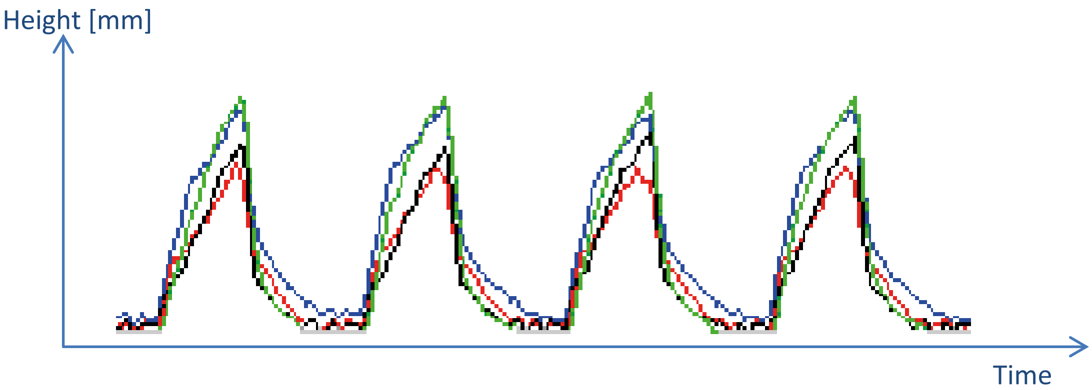

***Figure 3-10.** Typical lifting height logging results. Different corners (blue/green/black/red) have lifted with different speeds and to different heights. The blue graph also showing slow emptying of the cushions.*

***Figure 3-11.** a) Laser distance sensor mounted behind the main plate of the radiation protection shield and the hole for the beam machined into the shield. b) The laser beam in the hole seen from the lifting pallet side.*

Two axis inclinometer on the radiation shield

The radiation shield inclinometer is the basic input for the balancing of the Supercontainer. This basic measurement works well and has not been changed. However, a second axis of inclination was added in order to get information on changes in forward tilt angle of the shield. This was intended for driving belt failure detection of the third linear actuator since asynchronous motion of that rod relative to the other rods could cause mechanical damage by tilting the shield, Figure 3-12. The monitoring responsibility is left to the operator as no automatic stopping of the machine is implemented. The inclinometer also helps in adjusting the belt to the original position by adjusting the shield back to the original inclination.

Inclinometer on the machine body

The transversal inclination of the machine body is important for verification of several functions. Firstly, it is valuable to know when the machine body starts tilting along with the Supercontainer as this is one way of detecting when the balancing action starts to fail. Secondly, the difference between the shield inclination and machine body inclination gives information on how much the linear actuators are twisted by the torsional forces and how much the length of the linear actuators affects the balancing. Thirdly, it is necessary for investigation of how much the axle steering affects the body inclination and thereby how much the axle steering influences the Supercontainer balance.

Inclinometers in both ends of the sliding plate

As the sliding plate is flexibly mounted to the machine and the frame structure of the machine inevitably has some play, the position of the sliding plate is neither constant nor known by the control system. In order to get information on how the sliding plate moves during deposition and further on gain knowledge on how this motion affects the behaviour of the machine, both ends of the sliding plate were instrumented with inclinometers. Since the sliding plate moves in a cylindrical drift, a side shift of the sliding plate is visible as an inclination change in both ends. What is even more important is that a directional deviation is visible as an inclination difference between the front and rear ends of the plate, since this is the unwanted situation that must be detected.

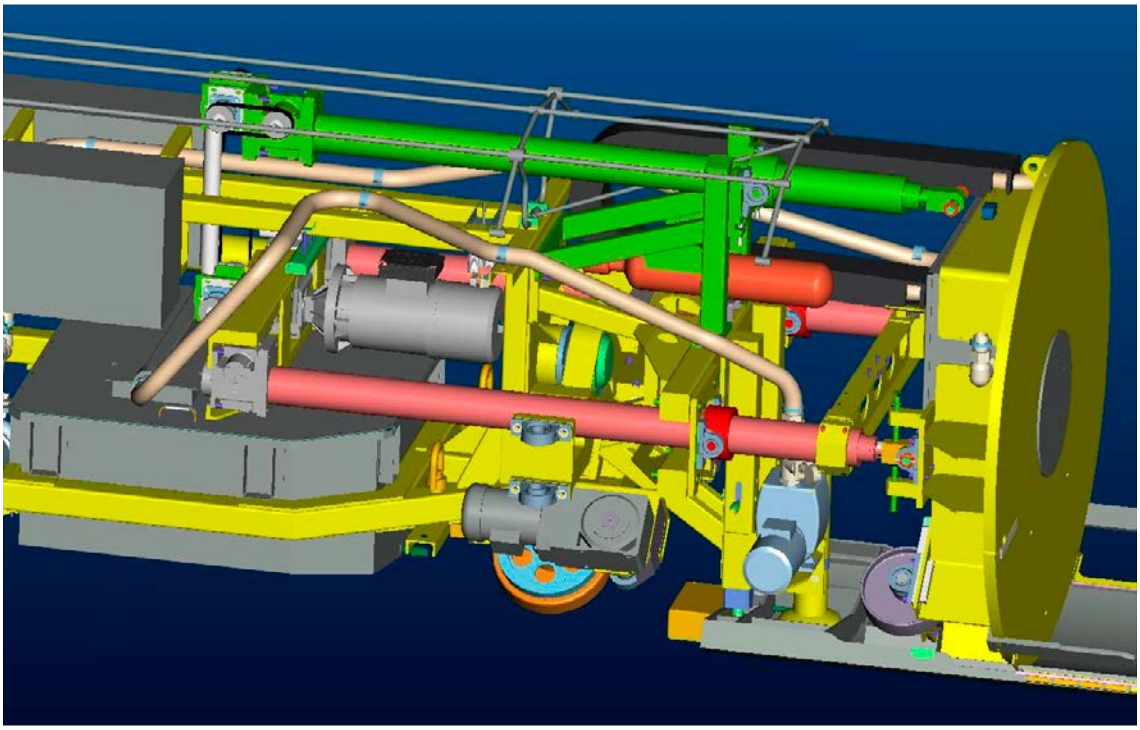

Figure 3-12. *The two lower actuators (pink) are driven directly by axles between the gearboxes. The third upper actuator (green) is driven by a belt. If the belt jumps the shield turns around the attachment points of the two lower actuators.*

Side laser for measuring the transversal pallet position on the sliding plate

Knowing the position of the sliding plate by the front and rear inclination measurements and the inclination of the Supercontainer by the shield inclination measurement does not give the whole controllability picture. In order to know the controllability of the machine the relative position between the sliding plate and the pallet must be measured since this limits the range of the control actions. The pallet can obviously only be balanced in the gap between the guiding edges of the sliding plate.

This measurement was realised by mounting a laser distance meter in the front end of the pallet measuring the sidewise distance to the guiding edge of the sliding plate. The assembly was not completely straightforward:

- The water release from the lifting cushions set high demands on the protection class of the sensor. In practice the sensor must be submersible.
- The small detection distance sets high accuracy demands on the measurement.
- The angled guiding edge surface sets high demands on vertical position stability of the sensor despite the lifting of the pallet. In practice, the sensor must slide flat on the sliding plate despite of the pallet elevation.

A mounting bracket, Figure 3-13, was designed as a parallellogram with a strong spring pushing the sliding base of the sensor holder towards the sliding plate. The sensor holder worked very well, but despite of that the measurement was unstable. The reason proved to be the poor reflectivity of the laser beam from the black plastic guiding edge. After the black edge was replaced with a white edge, the measurement has worked consistently.

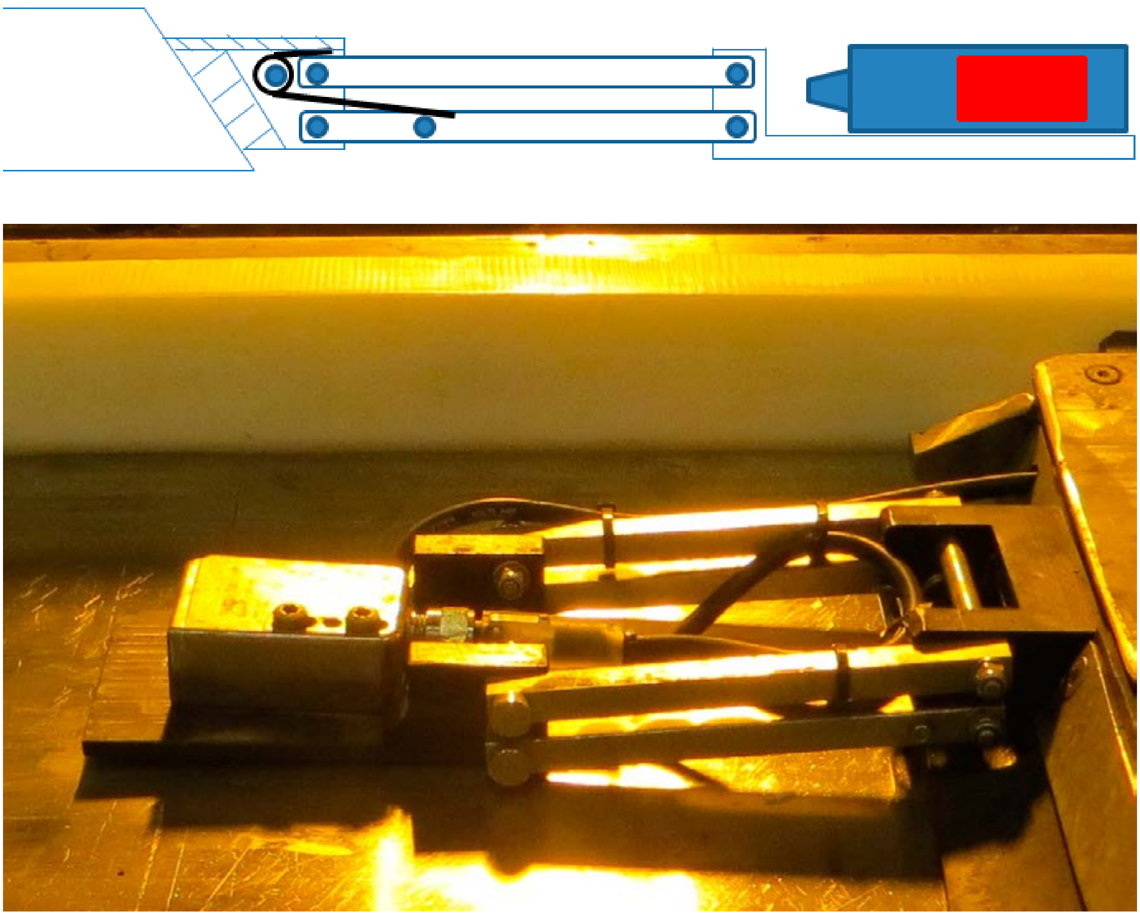

***Figure 3-13.** The design and realisation of the pallet position sensor.*

Displacement sensors for measuring sliding plate position relative to machine body

The sliding plate is mounted to the support legs of the machine body by flexible rubber pads in the transversal direction. When the machine is lifting the Supercontainer the sliding plate is solidly pressed against the drift bottom by the lifting cushions. When the machine gets inclined by the imbalance in the load it is not only balanced by the counterweight ballast in Figure 2-1, but also by the support from the attachment to the sliding plate. This supporting force can be evaluated by measuring the transversal displacement in the attachment pads. LVDT (Linear Variable Differential Transformer) displacement sensors were mounted to the machine body in order to measure this displacement.

This measurement gives a displacement relative to the inclination change, but it also reveals other phenomena in the machine behaviour. If the imbalance in the load is larger than the counterweight can balance the lifting pallet leans against the guiding edges of the sliding plate. If the sliding plate is badly aligned with the machine the transversal displacement increases during the stroke as the guiding edge steers the pallet towards bigger imbalance.

Further, if the load is leaning forcefully towards the guiding edges of the sliding plate during the stroke the displacement tends to decrease suddenly when the load is lowered due to the release of the sliding plate from the drift bottom. Supposedly, at this time the sliding plate slides away somewhat from the lifting pallet allowing the pallet to get more inclined during the next stroke. This is why the imbalance inevitably increases when the sliding plate is misaligned and the inclination has overcome the balancing force of the counterweight.

3.1.3 Basic electrical updates

New Analog I/O module and implementation of new measurements

As several new measurements have been added to the system, a new analog I/O module was needed. This new I/O module was selected to be similar to those existing in the system; Siemens 6ES7331-7KF02-0AB0, SIMATIC S7-300, ANALOG INPUT SM 331. This module along with fused I/O powering was added to the system and configured for mA measurements.

Some old measurements have also been removed and replaced by new ones. Sensors/measurements that have been removed include water and air temperature sensors (RT100/RT101) and the non-fuctional rear laser (D104). During testing it was detected that scaling for many old sensors was erroneous. Therefore scaling of all existing as well as new sensors was checked and (re)defined. Generic routines (i.e. common functions) have been implemented for scaling and error diagnostics. In addition to analog measurements, the system includes an absolute encoder for linear actuator position measurement and a relative wheel encoder for machine position, plus dozens of digital switches/sensors. Most changes and additions involve only the analog I/O. All analog I/O connections after the modifications are listed in Table 3-1.

Partial renewal of the powering system

Main cabinet BO100

A failed 3AC 400V to 24VDC power transformer (Siemens 6EP1 437-3BA00) in the main cabinet has been replaced with a new one. This unit provides all 24 V power on-board except to the PLC's which are supplied from the battery back-up system.

Top cabinet BO103

Several changes have been made to the powering system in the top cabinet BO103. This cabinet is supplied with the 3AC 400V input and it takes care of the charging and supply of the battery back up system and transforms multiple supply voltages:

- 220VAC for the machine lighting.
- 24VAC for the dome camera.
- 24VDC for the main cabinet PLC.
- 12 VDC for the sliding plate cameras.
- 5 VDC for the communication interface (Profibus/video to optical cable multiplexer board).

Table 3-1. Modifications of analog I/O on the machine

Color codes

- Black – no modification
- Red – removed
- Green – new

Analog inputs – addresses 350…365, 370…385, 390…405			
4-20 mA x 8	**Address**	**Symbol**	**Description**
4DMU 4-20mA	350	I103	Inclinometer upper frame
4DMU 4-20mA	352	I101	Inclinometer wheels, front
4DMU 4-20mA	354	I102	Inclinometer wheels, rear
4DMU 4-20mA	356	P140	M110 pressure
2DMU 4-20mA	358	RT100/ LVDT1	Water temperature/ LVDT – plate side position right
2DMU 4-20mA	360	RT101/ LVDTR	Air temperature/ LVDT – Rear boogey
2DMU 4-20mA	362	P130	Water tank pressure/level
2DMU 4-20mA	364	LVDTF	LVDT – Front boogey
0-10V x 8	**Address**	**Symbol**	**Description**
E +/– 10V	370	D104	"Laser back"; non-functional
E +/– 10V	372	D105	"Laser front"…truly UltraSonic
E +/– 10V	374	LS106	Ballast position
E +/– 10V	376	M101	Linear actuator motor current
E +/– 10V/ +/– 5V	378	I104	Inclinometer sliding plate front
E +/– 10V/ +/– 5V	380	I105	Inclinometer sliding plate rear
—	382		
—	384		
New AI-module 6ES7331-7KF02-0AB0			
4-20 mA x 8	**Address**	**Symbol**	**Description**
4DMU 4-20mA	390	HFR	Palette Height Front Right
4DMU 4-20mA	392	HFL	Palette Height Front Left
4DMU 4-20mA	394	HRR	Palette Height Rear Right
4DMU 4-20mA	396	HRL	Palette Height Rear Left
4DMU 4-20mA	398	DIS100	Sick DT50 laser
4DMU 4-20mA	400	I100	Inclinometer shield – transverse
4DMU 4-20mA	402	I110	Inclinometer shield – long/tilt
4DMU 4-20mA	404	DIS111	Palette side laser

The main reasons for the changes were excessive temperature inside the cabinet and several transducer failures due to short circuited loads.

The cabinet had previously a triple output (5/12/24VDC) power transformer CONV101 that was burned twice due to missing short-circuit protection and missing fuses on loads. This transformer was replaced by more "standard" kind of DIN-rail power modules with outputs of 5VDC, 12VDC and 24 VDC. The main source for the heat was the CONV100 providing 230VAC from battery power. This transformer was simply removed. One functional change after these modifications (mainly removal of CONV100) is that machine lighting and video cameras are not powered any more when the 400VAC power is lost or disconnected. This means that the back-up batteries provide power to the PLC system and communication modules only.

Even though the new transformer models were better protected by nature, all power outputs were also protected by fuses. As a result the whole power system is less complex, better protected and the temperature inside the cabinet is clearly lower. Therefore it is fair to say that both reliability and powering component life expectance have been clearly increased.

Camera system repair

Two cameras were mounted in the front box of the sliding plate for monitoring of the deposition process. The right hand camera had not been functional for some time when this project started and was also not considered necessary. The left hand camera is used for monitoring the space in front of the sliding plate and is essential especially when driving in under a Supercontainer or when approaching a previously deposited component in the drift. No actions were planned for the cameras, but some incidents led to a rather extensive repair session.

Though the right hand camera was unused it was still powered. As the deterioration of the camera housing reached a critical state, Figure 3-14, it caused a short circuit destroying part of the powering system of the deposition machine. It was discovered that the power lines to the lights and cameras were not fused and therefore a whole multi output transformer unit was destroyed. The camera was removed and in conjunction with renewal of the powering system all sourcing cables were fused.

The second camera also stopped working. When opening the camera enclosure it was discovered that some wires between the connector and the electronics were loose due to oxidation and shaking, Figure 3-15. The electronics inside the housing was not documented, and too many wires were loose to try reasoning how they had been connected. Nonetheless, by comparison of the wiring in the two broken cameras the connections could be solved and one functioning camera could be built.

If testing shall continue for a longer time a new camera unit should either be purchased or built. If it is decided to build a new unit some attention must be taken regarding the heat from the lighting. The heat from the power LED's warms up the protecting glass which cracks when water is splashing on it, Figure 3-14. When the glasses fall apart water penetrates into the casing causing oxidation.

A recurring problem in the camera system is the coupling of the coaxial cables between the machine and the sliding plate. The couplings are in hard use because they have to be opened and closed every time the plate is detached from the machine, i.e. for every deposition. Furthermore they are located at the end of the sliding plate where the conditions are always wet.

The middle camera which is used for monitoring the pressure gauge window on the shield cabinet has connection problems in the couplings between the protective housing and the camera unit frame inside the housing. Vibrations often destroy the picture because the connectors are not firmly attached to each other. The camera frame only stands on the connectors and thus the connecting force is only the weight of the camera and the frame.

Figure 3-14. *The camera unit with two power LED's for lighting and a camera in the middle. Protective glass cracked and fallen apart.*

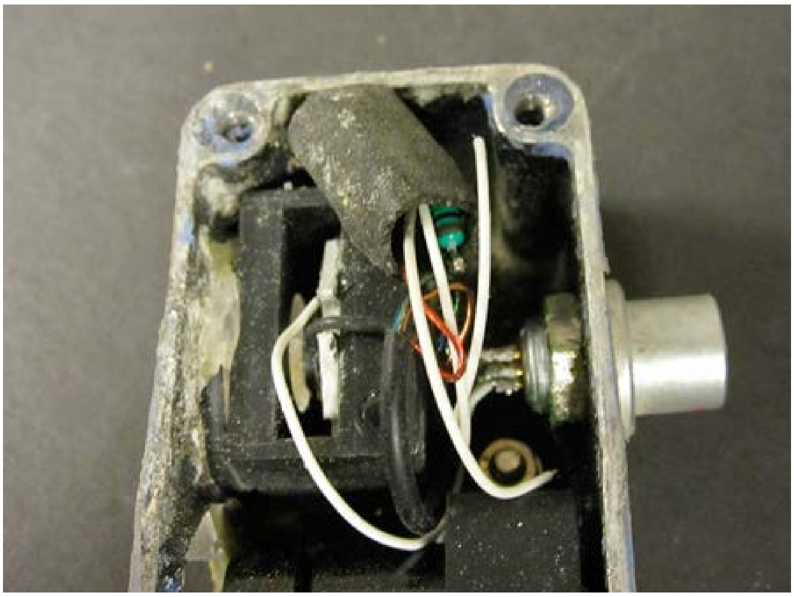

Figure 3-15. The camera unit internal connections with loose wires, the electronics are inside a piece of crimp tube.

Other

The Leroy Somer motor drive controlling the main supply pump was broken and has been replaced by a ABB ACS310 unit. Functionality and electrical connections remained the same. No changes were made to the PLC code because of this component change.

In the past there has been lots of problems with communication and electric drives, both causing the machine to stop quite often. Both of these were later realized to be more or less software related problems and are thefore discussed in chapter **3.2 Software updates**.

3.1.4 New actuation system

The machine seems to be built either with the assumption that the connection between the machine, lifting pallet and sliding plate is stiff enough to stay aligned with the drift or that a possible misalignment could not grow beyond the balancing ability of the counterbalancing. During the machine testing this proved not to be the case. It soon became obvious that some means to actively correct the lifting pallet and sliding plate positions must be developed in addition to the balancing control. The motivations for this are discussed in chapter **3.3 Control method improvement**.

The difficulty in designing this system was to match the high force requirements with the constraints of low water pressure. Directing the sliding plate with longitudinal actuation at the base attachment would have been a natural solution, but had required great forces due to the length and weight of the sliding plate. Any actuation in the front of the sliding plate on the other hand was restricted by the limited space in the pallet and sliding plate on one hand and the lack of support for a counterforce on the other. However a great advantage for the front is a lower power requirement since the further away from the turning point at the base attachment, the less power is needed. Finally, a sidewise actuation was designed between the front of the lifting pallet and the sliding plate. As the pallet and sliding plate are moved at different times it was assumed that the stationary part has higher friction working as counterforce for sideshifting the moving part.

The best actuation power was achieved by filling the space between the two frontmost cushions in the pallet with water cylinders pushing out the sliding edge of the pallet against the guiding edge of the sliding plate, Figure 3-16. The cylinders are powered by a high pressure water pump using the same water as the main cushion pump. Due to a rather small expansion tank the water pressure fluctuates between 15 and 30 bars, but this pressure has been sufficient. The cylinders are actuated through two on/off valves in the radiation protection shield.

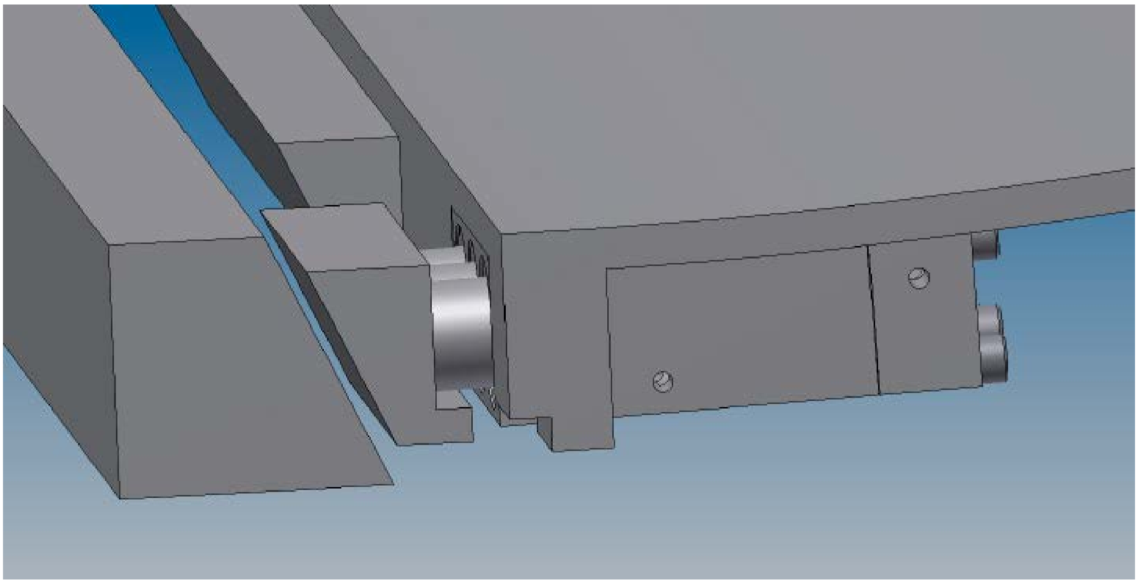

Figure 3-16. *The actuation cylinders of the pallet and sliding plate steering system.*

3.2 Software updates

3.2.1 General

The situation before the project was actually worse than evaluated in the preceding software analysis project. In addition to major problems in balancing performance, the control software had numerous errors causing hang-ups and erroneous behaviour. It was also realized that some functions documented in the requirement specification were missing. Most implemented functions required the operator to know how to prepare the machine for each task by means of manual driving. All these problems resulted in the machine not being really automatically operated, but driven quite often manually. Problem solving was also based on operator experience and manual manouvering rather than actions based on error messages.

In addition to clear software problems there were major problems especially with communication and the electric drives, both causing the machine to stop quite often. Both of these were later realized to be more or less software related problems as well.

The control system consists of three different software modules; Machine PLC software, Fixed PLC software and HMI. The main scope in the project was on providing a stable machine control, a less error-sensitive control software structure and a better structured operator interface; the operator interface however being the least prioritised issue.

First priority has been a software implementation having the functionality and reliability needed for truly automatic operation for the specified task. Therefore most of the work has been concentrated on the Machine PLC software taking care of the automated functionality. Even though many improvements were planned for the HMI as well, at the end many "look and feel" kind of HMI issues have been put aside. Code and functionality of the fixed PLC has not been in the scope of the software project.

3.2.2 Documentation

Documentation concerning the software was very limited, the only documents being state machine diagrams for automatic states and the User Manual. The state machine diagrams were out-of-date and the User Manual proved to be erroneous in several details. Therefore the old implementation had to be documented first to cover the most important parts, like the state machines and the memory map.

3.2.3 Software project

The KBS-3H deposition machine is a first prototype for horizontal deposition and implements a lot of known technology but in a new application and it was not fully functional and not fully in line with the requirements when the purchase of the machine was being finalised. There were lots of discussions between the client and the manufacturer and eventually a compromise had to be reached to enable a close of the purchase. The software suffered the most in this compromise as the delivery was done knowing that there was a lack of functionality, mixed language and several other shortcomings.

For some reason the software project had been split into pieces at some stage of the original development. Due to this there was no logic connection between the Machine PLC, Fixed PLC and HMI softwares and the project could not be further developed. As a first thing the software project had to be reintegrated and the project errors fixed. It was never completely clear which software versions were the correct or latest ones as the latest software version provided by ECA was not quite identical to the one found in the Machine PLC. The differences between the versions were not very big however, just leaving a question mark. The main language was also changed from french to english. French symbolic names and comments were naturally not modified by this action. All new definitions, descriptions and comments are written in English only. Some of the existing French-based terminology is also translated into English but not all, so unfortunately we have a mixed language system for now. All symbols visible to the operator and messages on the HMI have been translated into English though. The multi-language selection and support from the HMI has been removed (it was never really properly implemented). So, from now on English is the only language supported on the HMI.

3.2.4 Software structure

The control software has suffered from bad structure, scattered code, hang-ups, uninitialized variables, dead-locks in state machines and other shortcomings that have been identified and corrected piece by piece.

Deadlocks have been identified and removed as much as could be found. Numerous other known or found errors have been fixed in the code and lots of unnessasary or erroneous code and variables have been removed.

The Machine PLC control software has been partially redesigned. Typically targeting to more straightforward implementation with less code. For example all state machines and the way they are driven have been changed. Also all sensor data handling has been rewritten. Whenever possible, the same code has been used for similar kinds of tasks. As an example, many routine tasks that had earlier been copied into many places of the implementation have been turned into single reusable functions.

The mode handling of the control system has been changed. In the past the operator (using the HMI) and the control system were both modifying the operating mode directly and asynchronously. Now the actual operating mode and the mode requested by the operator are different things. The Machine PLC is always defining the operating mode while the operator can only make requests to change the mode. In this way the mode is changed in a controlled way without causing deadlocks.

All alarms and errors have been reconsidered. Some old ones have been removed and lots of new ones have been defined.

The PLC memory map has been partially optimized for improved communication throughput. The PLC memory map for symbolic variables, including HMI tags, was scattered over the memory address space, making it impossible for the system to optimize data transfer between the PLC and the HMI. The old code had lots of symbolic variables having overlapping memory areas and sometimes even absolute memory addressing. Modifying the memory map in this kind of system is therefore very error prone and time consuming. Therefore it has not been done for all existing variables, rather as long as it seemed to be worth the "expense".

3.2.5 Communication

The Profibus communication has been one of the big problems – stopping the machine operation frequently. These errors were in old reports quite often reported as communication media (optical fiber) related problems.

In this project the reasons for these problems were studied. Profibus analysis was carried out on all levels involved. The hardware level was documented and analyzed using a dedicated Profibus analysis tool, ProfiTrace. Some minor issues were fixed in the cabling, in the cable connectors and in the communication board settings. None of these seemed to be a major issue however. The analysis of the higher level issues then gave more interesting information. The single main reason for communication problems has been the excessive overload on the Profibus, caused by several reasons:

- Bad overall communication design having all HMI-PLC communication on the low level control bus, Profibus DP –not solved as it would require bigger changes in the system.
- Erroneous Profibus hardware configuration and profile for the control system – fixed.
- Very low data speed of 93.75 kbit/s on the Profibus – increased to 1.5 Mbit/s, which is the maximum for the current hardware installation.
- The PLC memory map being scattered, having a negative impact on the Profibus performance – the memory map has been partially optimized having a significant effect on the data throughput.
- Lots of unnecessary data transferred over the bus – the amount of data transferred has been reduced; on the other hand lots of new data (new sensors, missing functionality, new alarms, etc.) has been added in stead.
- Tag configurations on the HMI have been poorly selected, having up to 100ms update cycles – these have been modified.

A speed increase by a factor of 15 is never a fully safe thing to do. Especially speeds exceeding 1 Mbit/s tend to be sensitive for cabling, bus topology and many other bus details. In this case the speed increase has not caused any problems. Even though the data throughput is now clearly better, it is not however quite at the level the project would like it to be. Without major changes in hardware, the only way to further decrease the bus load is by software means; still reducing the amount of data transferred and further memory map optimatization. In addition to improvements in data throughput many other improvements have been carried out in order to improve communication reliability as well.

The functional requirements document states that the Profibus load shall be 30 % during normal operation. Even with the improvements made, that has not been reached.

3.2.6 Electric drives

Alongside the communication problems, another major problem has been the electric drive errors. These errors occurring so frequently is a problem itself, but the lack of a recovery scheme made it a big problem. The only way to clear any such error has earlier been to swithch off the power from the the drives – in other words rebooting the drives.

The problems were studied and the first priority target was a successful error avoidance. It seemed evident that the problems were caused by a combination of device configuration and the way the devices were controlled. It was realized that the main source for electric drive problems were too large or fast changes in motor load or speed. It is important that electric drives are in all conditions and in all situations decelerated and accelerated in a reasonable way, by the drive itself or by the PLC. For wheel and actuator drives the accleration and decelaration has been handled by the software. The reasons behind this are supposedly the synchronized driving and accurate and immediate control of wheels and actuators.

After studying the PLC acceleration control it was realized that:

- Acceleration/decelaration calculation simply failed; values supposed to be between 0–100% were most of the time > 100% and limited to 100% and therefore resulting in full speed.
- Acceleration/decelaration was calculated only on some specific situations.
- Acceleration/decelaration was calculated separately for wheels and linear actuators in synchronized driving.
- Whenever acceleration/decelaration was not calculated, the speed change request was handed out to the electric drives in a single step.
- Wheel steering made 20% stepwise changes to motor speeds.
- Wheel slippage causes errors.
- Excessive Profibus load had potentially a negative effect on acceleration/deceleration calculation, as the linear actuator position comes from a Profibus sensor.

All Machine PLC code for motor drive controls have been thoroughly checked and the acceleration and deceleration calculation has been fixed and added to places where it was missing. This has resulted in smoother driving and a significant decrease in motor drive related errors.

As avoidance of errors can never be fully guaranteed, also a reasonable error recovery method was planned. Each eletric drive has an enable/reset input that has been previously connected to +24VDC. This line was instead connected to the PLC control and as a result the PLC is now able to perform a drive reset. The drive reset clears any non-fatal error and this scheme therefore eliminates the need to “reboot” the drives manually after errors.

After fixing the software errors related to this matter, stops during“normal” driving in the drift have been very rare. Wheel slippage still causes errors however, as the software has no means to detect or prevent this. Wheel slippage happens mainly while driving the machine from the start tube to the transport tube and into the drift. Fortunately other actions, like straightening the start tube, have improved the situation by decreasing the amount of wheel slippage. Still, as future improvment the acceleration and deceleration scheme should be changed so that the electric drive configuration is changed to handle acceleration and deceleration related issues internally, if possible.

3.2.7 Balancing

Balancing the machine is a crucially important function. Overall changes in this area are described later in Chapter **3.3 Control method improvement**. The following shortly lists the modified and added control methods. Balancing the machine has been based on two very simple control methods:

- Counter balance control.
- Wheel control.

Both of these controls had clear problems and both have been rewritten. It was detected quite soon, that these controls alone have no possibility to keep the load balanced in all situations. Therefore new control methods have been implemented, including:

- Supply pump pressure control – the supply pressure has an impact on the palette lifting height.
- Linear actuator stroke lenght control – it was assumed that a shorter stroke means more torsional force for balancing. Anyway, a shorter stroke length means decreased lifting time and therefore decreased lifting height, which is sometimes advantageous.
- Cushion control (really disabling selected cushions) – balances lifting since if either side is lifted higher, the load tends to tilt.

For some time it seemed that all these controls combined could handle the balancing. This however proved to be a false assumption. The controls are effective in many cases, but not in all.

Therefore active steering using water hydraulics was introduced. Also this is described in the later chapter **Control method improvement**. The active steering uses a pump and cylinders on both sides of the lifting pallet. The pump and control cylinders can be controlled both manually and automatically. While driving a load, the cylinders may push only while the palette is unloaded. Therefore cylinder controls are automatically disabled always when the palette lifting height exceeds 4 mm.

3.2.8 Automated sequences

Previously "automatic" sequences required that the machine, actuators and several other conditions should be in a certain state before the sequence could be started. This always required some manual maneuvering and an experienced operator before the automated driving could be started. Sometimes more than one automated sequence was needed to carry out a single task. Special sequences needed by the end of a deposition, like approaching a previously deposited component were incomplete and the very critical "First deposition"-condition was not correctly defined.

In the current software implementation manual task preparations have been automated. If a task requires another task to be carried out first, it is done automatically. Also, the sliding plate is flushed automatically when needed, as the palette must not be moved on a dry sliding plate. As the critical "First deposition"-condition can't really be automatically defined now when an overall planning system is missing, this is asked from the operator prior to starting the driving task.

Fully automated sequences at the end of the drift have been implemented and tested for all tasks needing one:

- Deposit Supercontainer – driving the Supercontainer into contact *) with the previously installed component.
- Retrieve Supercontainer – driving the tip of the sliding plate under the previously installed component in order to have fully balanced lifting from the start
- Install distance block – driving a distance block into contact *) with the previously installed component or close to the drift end; the case is selected based on the "First deposition"-condition. In the last phase the load is moved on the palette without moving the machine and the sliding plate.
- Retrieve distance block – driving the tip of the sliding plate under the previously installed distance block or close to the drift end; the case is selected based on the "First deposition" – condition. In the first phase the load is moved on the palette without moving the machine and the sliding plate.

* The contact is detected using linear actuator current measurement as force feedback, since reaching contact increases the current rapidly.

The concept of driving distance blocks has been changed. Now distance blocks are deposited one assembly at a time without mechanical extension piece, positioned close to the shield during the drive. It is only at the end of the drive that the load is moved forward on the palette, on a need basis.

Distance blocks can also have different lengths and cushion selection is handled automatically by the software in all situations based on the length and position (on the palette) of the distance block.

Now the whole operation is pretty much fully automatic. The operator approval is however required for safety reasons while the machine is driving in under the load in any of the four sequences listed above. This feature is implemented in a dead man's handle kind of way; the machine moves only when the "Authorize Forward Wheels" button is kept pressed down. When the control software needs authorization by the operator, the "Authorize Forward Wheels" button starts flashing on the HMI. The control software automatically detects when this phase is completed, no operator input is needed for that. When this phase is ready, the control software again takes full control and continues automatic operation.

3.2.9 Semi-automatic driving

Previously the machine was operated strictly in automatic or manual control. Now it is possible to drive the machine manually while the steering control and balancing are handled automatically. This helps manual driving as the operator does not have to balance the machine manually and also cannot drive the machine into imbalance by mistake. On the other hand the need for manual driving should be minimised.

3.2.10 Machine position

The position of the machine in the drift has previously been used in decision making in the control system. Since no control decisions shall be made on absolute position, but rather on the position relative to components, drift end or start tube, they have been removed.

Now the machine position is used only for logging and supervision on the HMI, not for control. The machine position is a relative measurement based on a single wheel (wheel encoder RE 105) and therefore a position error may accumulate, for example due to wheel slippage. The machine position reset signal source is RD303 (light gate at the start of the start tube); any change in this signal resets the machine position. The machine position is stored so that it is not lost in case of a PLC restart.

The position could be calculated using both wheels and linear actuators whenever appropriate. This could potentially decrease the cumulative error, but not remove it. As the machine position currently has no functional meaning, this scheme has been left as it was.

3.2.11 Other – PLC

In addition to those changes explained earlier there are numerous other fixes and improvments in the machine PLC code, including:

- Linear actuator motor current is measurable. This current is used for "force feedback control", too high currents stopping the machine. This is used as "contact detector" at the end of deposition. In other situations it is considered as an error and the movement is stopped.
- Security, initial and working conditions checked and fixed.
- Ballast driven automatically to middle position at the end of the ReturnMachine sequence.
- After Reboot PLC the mode goes to None or Pendant (earlier this restored the previous mode, even automatic mode which could lead to an unexpected start of the machine).
- The mode is automatically changed to Pendant when the communication dies; this did not work before.
- A virtual shield contact implemented using the shield laser makes it possible to drive even if the load is not in physical contact with the shield.
- The water suction pump working conditions have been changed – the pump is always running when there is water on the sliding plate. Previously a stop due to an error also stopped the water suction pump causing the water returning from the cushions to flood over into the drift.
- The speed is automatically slowed down whenever the shield is driven close to the load – concerns both linear actuator and wheels.
- Starting the load push/pull was earlier triggered only by a timer – a minimum lifting height has been added to the concept for safer operation.
- The HMI-PLC communication watchdog has been simplified in order to react faster.
- Functions triggered by "single detection" of a sensor or measurement have been modified – kind of filtering – resulting in less unnecessary stops and better reliability.
- The front buffer sensors have been prone to damage and have therefore been made overridable.
- Buzzer added to Fire Alarm.

3.2.12 Other – HMI

- Most known HMI errors have been fixed. Some non-critical issues have been left uncorrected for now. Instead their activation has been prevented to avoid malfunctions; one example being the screen "Reports F10" which is not activating the log reporting anymore.
- Many (not all) none funcional Profibus tags and screen information as well as ghost screen components have been removed.
- The HMI guides the operator more in doing the right things at the right time. The control system prevents the operator from doing unreasonable things, rather than generating errors afterwards. Mode changes and the Start-command being the most obvious examples.
- Predefined cushion selections (Container, Blocks Fwd/back) have been removed; cushion selection is automatic with possibility to manually disable any of the cushions.
- Measurements out of range are visualized with red background.
- The M110 counterweight ballast motor error is visualized with red indicator.
- The Start/Authorize buttons flash in green when the operator is expected/required to do something.
- The remaining distance for the load is calculated and shown by the end of the drive.
- New cushion color – yellow – meaning activated cushion not yet pressurized.
- Numerous minor fixes and improvements.
- Lots of indications of detailed error sources.

Performance requirements

The performance is affected by the drive speed of the wheels and the actuators as well as the implementation of the lifting and balancing processes. So, pretty much all the controls have an effect on the performance figures. The Performance requirements for the deposition machine are:

- Average Transport Speed with Supercontainer Min 20 mm/s.
- Average Transport Speed with Distance Block Min 30 mm/s.
- Transport Speed (only Machine) Min 100 mm/s.

This project has not focussed on the transport speed but rather on the balancing quality and therefore the transport speed is more or less unchanged compared to previous operation. Currently the transport speed differs only a little between Supercontainer (ideally 17 mm/s) and distance block (ideally 20 mm/s). The only difference comes from the longer lifting time of the Supercontainer. Generally balancing problems and cushion depressurizing problems have the biggest effect on the transport speed. An example of this is shown in Figure 3-17 where the load imbalance causes slow lifting of the front right corner delaying the pushing sequence to twice the normal. A big transport speed reduction comes from balancing actions based on shortened stroke length which is causing a transport speed reduction to approximately 75%.

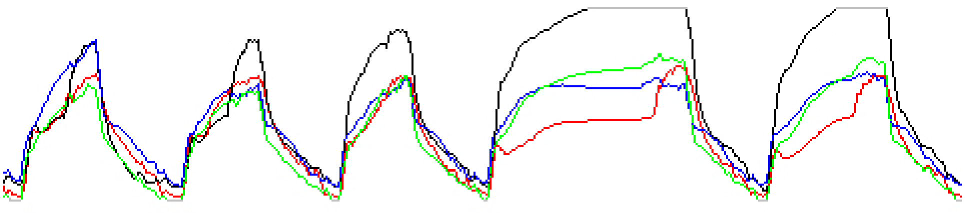

Figure 3-17. *The first lifting sequence is normal, in the second and third sequences the front left corner (black line) starts lifting higher than the others. In the fourth sequence the imbalance is too big and the front right corner (red) has problems reaching pushing height. The fourth stroke therefore takes twice as long as the normal strokes.*

3.2.13 Data logging

A proper data logging system has been a very important part while improving the overall system. PLC Analyzer pro 5 has been used for this purpose. It provides fast enough and even cycle-precise logging of data, without any changes to the control system itself. Logs and log analysis are presented in the MPT result analysis in Chapter 5.

3.2.14 Known issues

The actuator over travel sensors stop the actuator motors directly without feedback to the PLC. This is still a potential functional stop without error message and recovery. The implementation is the safest way to prevent mechanical damage as the stop occurs immediately without any software analysis in between, but the stopping signal should be connected to the PLC for error information.

Uneven lifting of the pallet is a problem when driving short loads, like distance blocks. The problem can be solved by activating the front cushions for some time at start of a lift and then deactivate them before the front rises too much (as there is no weight on those cushions with short loads). This problem is handled by manual control for now.

The HMI can't clearly indicate all different types of Profibus communication problems. The machine PLC on the other hand is aware of all problems, which is the important thing.

3.3 Control method improvement

A control problem often encountered with the horizontal deposition machine has been the drifting of the Supercontainer into irrecoverable imbalance. The imbalance is caused by several different interacting phenomena either singly or in combination leading to the problem. The fact that the interacting phenomena are so many have made the investigation complicated and the construction of a complete balancing solution rather challenging. However, by identifying the causes one by one and by developing effective countermeasures to each of them have slowly led to a composite control strategy that is able to keep the machine in balance.

3.3.1 Transversal sliding prevented by accurately displaced guiding rails

A very low friction between the lifting pallet and the sliding plate is the key to the transportation method of the machine. However useful in the direction of transportation, the low fricition is a problem in the transversal direction. When lifted the Supercontainer floats freely and the slightest imbalance tends to roll it over to either side. The Supercontainer is like an inverse pendulum in two directions. Firstly, the mass centre of the Supercontainer is rather high compared to the width of the lifting pallet resulting in a narrow stability zone. Secondly, the drift is slightly inclined uphills causing a tendency of the Supercontainer to turn to either side. Since the imbalance to either side is carried by an increased pressure on that side and the pressure increase is built up by increased suppression of the lifting cushions the Supercontainer is always allowed to tilt in either direction. In order to keep the Supercontainer in line with the drift the sliding plate has guiding edges limiting the motion of the lifting pallet. If there were no rails the Supercontainer would roll around until the lifting pallet slips away from underneath the container.

The optimal position of the guiding rails was evaluated to be such that the lifting pallet has approximately 6–7 mm of free space on each side. Thus, the Supercontainer is allowed to float freely within a range of ±0.5 degrees of inclination between the rails. A narrower space would not allow for direction corrections during the transportation and a wider space would allow a too large inclination of the Supercontainer.

3.3.2 Enhancing the counter balance control

During transportation of the Supercontainer the surface and the direction of the drift vary somewhat (it is not a perfect cylinder). This is causing a natural tendency of the Supercontainer to roll to either side by the imbalance of its' mass centre. This swinging is counteracted by a torsional force brought by the linear actuators from the machine body. Since the machine body is freely hanging in its' longitudinal centre axis the counterforce is caused by the weight of the machine body and an additional movable counterweight. The counterweight is very small compared to the weight of the Supercontainer, so it can only balance the Supercontainer when the imbalance is within about ±0.7 degrees. If this limit is exceeded the Supercontainer continues tilting even when the counterweight is driven to its limit.

The original counterweight control was insufficient in many aspects. Firstly, the maximum speed of the weight adjustment from side to side was too slow. Secondly, the control was a simple bang bang control that added delay into the control. The result was that the counterweight in some situations added to the imbalance instead of counteracting it. It was decided not to build a new actuation system since that would have required a too big hardware update. Instead the counterbalancing control was changed. It was discovered that the imbalance of the Supercontainer was cyclical, repeating the same back and forth swinging pattern during a pushing cycle.

Therefore, instead of trying to control the counterweight according to actual inclination at all times the most representative inclination was saved for one cycle at a time. When using this inclination for counterweight adjustment the control became much more stable and it was not late anymore. Now, despite slow counterweight motion the balancing is smoother and works in the correct direction.

3.3.3 Enhancing the wheel control

As the machine body is freely hanging in its' longitudinal centre axis the front and rear wheel axles can swing independently around the centre axis of the machine. Also here the former control was a bang bang controller trying to keep each axle leveled. The control was hence always late and the axles constantly swinging in the range of ±1.5 degrees. This swinging was not assumed to be of any bigger importance. However, replacing the bang bang control with a proportional control stabilized the behaviour of the machine somewhat and adding a derivative term helped significantly. It seems that the former swinging of the wheel axles somewhat changed the direction of the machine body axis, thereby adding to the unstable machine behaviour.

As discussed earlier, the former bang bang controller used 20% stepwise changes to the motor speeds as steering method. Changing this to a continuous smooth control was important also in order to decrease electric drive problems in general.

3.3.4 Increasing instability with increasing lifting height counteracted with water pressure adjustment and limited lifting time

The higher the Supercontainer is lifted the higher the centre of gravity and consequently the more unstable the Supercontainer gets. During each lifting and pushing cycle the Supercontainer is rising all the time, even during the pushing phase. Thus, the imbalance continuously increases towards the end of the stroke. In order to reduce this imbalance the water pressure was decreased. The imbalance was slightly reduced but this also resulted in uneven initial lifting. Uneven lifting at the start of the pushing cycle could risk the feet of the Supercontainer due to ground contact and therefore only a small reduction could be used. Finally, a scheme with higher water pressure in the beginning of the lifting and lower pressure during the pushing phase was realised. This method allows a longer pushing time before the load is raised too much, but does not completely stop the constant raising of the load during the pushing.

A more efficient solution to this problem was reduction of the stroke length. This reduced the raising time of the Supercontainer and most importantly avoided the highest peak by the end of the lift. In many cases a Supercontainer inclination of about 0.6–0.7 degrees could be solved by simply shortening the stroke.

3.3.5 Weakening torsional force counteracted by limiting stroke length

Supposedly the longer the actuators are the less torsional strength they have, see Figure 3-12. Due to several interacting parameters this could not be verified from the logs, but probably the good results at times encountered by shortening the stroke was not just the decreased lifting height, but also the better balancing force from the actuators.

3.3.6 Uneven lifting counteracted by cushion deactivation

Replacing the old stepwise height sensors of the lifting pallet with continuous linear measurements gave good information on how the weight of the Supercontainer is distributed over the pallet. These sensors gave information on how some corner due to uneven load would raise slower and eventually much less than the others. It could also be verified how this uneven lifting eventually led to an increasing inclination of the Supercontainer. Reasons to uneven lifting can be many. The most significant being the position of the lifting pallet relative to the Supercontainer after the free forward motion. If the front end of the lifting pallet had drifted to either side relative to the Supercontainer it would immediately show as an uneven lifting in the front, see Figure 3-18. The uneven weight would press the front of the lifting pallet even more to the side resulting in an increase in the Supercontainer inclination. With an increasing inclination the whole pallet gets unevenly lifted and the inclination escalates.

To prevent uneven lifting from escalating some lifting cushions on the higher side were deactivated. It was shown that this countermeasure could restore the balance if the imbalance had not gone too far, below 0.6 degrees. At larger angles it could prevent the escalating inclination and bring the system into an angled equilibrium.

3.3.7 Drifting tendency due to misaligned pallet and sliding plate counteracted by accurate pallet calibration

Despite all above balancing actions the machine would some times drift only towards positive inclination and some times only towards negative inclination. A rather obvious reason for this is the attachment angle of the lifting pallet to the machine. This angle is changing frequently since the pallet must be detached from the machine each time a new Supercontainer is to be deposited and after reattachment the angle is never exactly the same as before, see Figure 3-18. In order to minimise this variation a calibration procedure was developed.

The calibration method uses the radiation shield as base for aligning the pallet with the machine. A calibration tool consisting of a ruler with an attached laser transmitter and a target plate was developed, Figure 3-19. The ruler is put against the shield surface and the target plate is centered over the far end of the lifting pallet. The position of the lifting pallet is then shifted until the laser beam hits the middle of the target plate before the lifting pallet is attached to the shield. In this way the lifting pallet is always centered and perpendicular to the shield. The calibration gave good, however not always lasting results, as described in the next chapter.

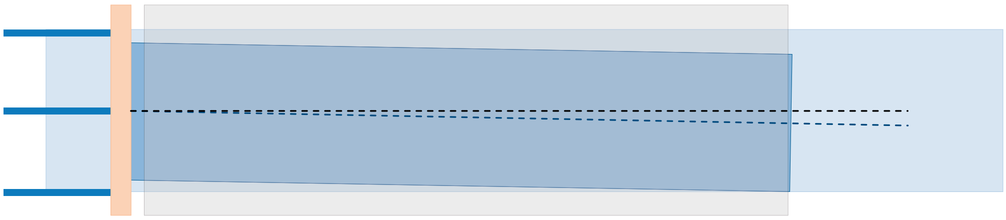

Figure 3-18. *The lifting pallet (darker blue) is inaccurately attached to the shield causing an angular deviation between the centre axis' of the pallet and the Supercontainer (grey). The load of the Supercontainer on the pallet is imbalanced in the front.*

Figure 3-19. *The calibration tool developed for aligning the lifting pallet with the machine. The ruler against the shield on the left and the target plate in front of the Supercontainer on the right.*

3.3.8 Random misalignment of pallet and sliding plate counteracted by active front steering

After calibration the machine would normally behave very consistently for a time, but then suddenly change to strong drifting in either direction. The logs did not show any triggering event, only a sudden disturbance in alignment between the front ends of the sliding plate and pallet. Since the sliding plate is quite flexibly attached to the machine there was no means to force the sliding plate back in line with the pallet. In many cases the drive had to be interrupted as the inclination escalated irresistibly despite all above described countermeasures. A last option to try rescuing the situation was to drive a few strokes backwards to straighten up the system and then continue forwards again, but this was effective only in some cases and after all not an appropriate solution.

As all control means had now been used and these rare but repeated problems were still encountered, what remained was some kind of active steering forcing the sliding plate into position. Turning the sliding plate from the base would require very high power due to the narrow base and the long and heavy plate. Pushing the front part against any external body, like for instance the Supercontainer feet, was considered too risky due to the possibility of getting stuck against the feet during free sliding of the plate. Therefore, pushing cylinders were designed on each side of the lifting pallet to force the gap between the pallet and the sliding plate to either side, see Figure 3-16. It was assumed that the moving part always has less friction and thereby pushing in different states of the motion cycle either the lifting pallet or the sliding plate would move to the side as the other stays in position. In this way, while moving the pallet over the sliding plate the pallet would move to the side by the cylinders and while moving the sliding plate as the pallet is stationary the sliding plate moves to the side. The cylinders were mounted behind a piece of guiding edge in the front of the pallet and are activated by pressurized water.

Naturally, due to the small size of the cylinders they could not be used while the Supercontainer is lifted, but rather to position the pallet evenly under the Supercontainer before lifting.

The function of the cylinders exceeded the expectations. In free tests without Supercontainer the sliding plate and pallet could be moved approximately 1 cm to the side for each stroke. A test with three strokes back and forth yielded a sideshift of 3 cm. During normal depositioning drives just one activation of the cylinders have yielded a balancing action of 0–1 degrees, typically 0.4–0.8 degrees. Even if the balancing action is close to zero, it guarantees that the inclination does not get any worse by removing the gap between the pallet and the sliding plate on the side that could add to the inclination. The good thing with this balancing control is that it works regardless of the original inclination. It can thus be used in cases when no other balancing actions work anymore.

3.3.9 Composite control strategy reacting on machine behaviour and inclination

In order to achieve as constant and balanced behaviour as possible of the machine a control scheme has been developed which is always using the most appropriate balancing action for the situation. For small inclinations the counterbalance and wheel axle controls are used and for somewhat larger inclinations cushion deactivation is added. Stroke length reduction is used as the last traditional balancing method since it slows down the transportation. As a last resort in cases when the inclination escalates over the controllability of the traditional controls the front steering cylinders are used. This combined control has produced very balanced driving and in the current tests no drive has been stopped due to irrecoverable inclination.

Threshold values for activating different control actions are parameterized, so the machine can now be easily tuned if mechanical properties or environmental circumstances change. Currently wheel axle control and balancing is always active, cushion deactivation is activated at around 0.5 degree inclination, active steering at somewhat larger inclination and finally stroke length adjustment at around 1 degree.

For simplicity all controls are using the shield inclination as input, though the cushion deactivation for example could advantageously be activated by the pallet height sensor data. A more refined control can be developed in a future project if considered necessary.

4 Test programme

4.1 Supercontainer dummy tests

The Supercontainer dummy has been used for machine testing since the beginning of the KBS-3H ptoject and was available for machine testing throughout this project. All basic functional development in this project was tested with the same unit and thus all results are comparable with previous results. Since the new instrumentation on the machine was taken into use most of the testing has been logged with an external logging system and saved to enable verificative follow-up examination of the tests, if necessary. All logs don't contain all data though, since different test sessions have had different scopes of investigation and the logging has been narrowed in order to limit the bus load. It must be stressed though, that most logs are datalogs only without any verbal interpretation and therefore require experience of the graphical log data presentation for analysis.

In addition to the functional and control method testing, the Supercontainer dummy was also used for verification of peripheral mechanical properties like the start tube straightening, the adjustment of the start tube and transport tube in line with the drift and required foot height of the units.

4.2 Distance block dummy tests

All general functionality of the deposition machine was developed with the Supercontainer dummy. What remained to develop and test with the distance block dummy was related to its' different physical properties. The main difference being the size raising questions on how to position the distance block on the lifting pallet, firstly during the deposition drive and secondly when approaching the previously deposited component in the drift. Another important question was adjustment of the lifting for the lighter load that was not evenly distributed over the lifting pallet.

A totally different topic of interest was related to the feasibility and durability of the newly designed distance block feet.

4.2.1 Automatic handling of distance blocks of various lengths

In the original design the machine was able to transport either Supercontainers or distance blocks of one specific size. The lifting pallet is dimensioned for the Supercontainer and the size of the distance blocks were determined by an extension piece that together with the distance block constituted a unit of equal length to a Supercontainer. Despite the additional work of lifting the extension onto the machine and the limitations it caused to varying the distance block size it also had a negative impact on the controllability of the machine. Distance blocks were placed on the pallet with the extension between the shield and the distance block and driving the machine all the way through the deposition drift with the distance block weight on the far end of the pallet was not a feasible solution. As all the weight is at the tip of the pallet and the control reacts on inclinations measured at the base of the pallet the control gets delayed and the load gets a too high momentum before the control reacts to it. The more play there is in the mechanics of the machine the more severe this problem gets. Therefore, a method had to be designed allowing the main transportation through the drift to be done with the distance block at the base of the pallet against the shield and then by the end of the drive allow shifting the position of the distance block to the far end of the pallet for tight deposition against the previous unit.

The solution was to skip the extension piece and equip the machine with a distance laser measuring the position of the block on the pallet. The previous way of activating either the whole set of lifting cushions or just the front half of the cushions was replaced by an adaptive cushion deactivation function. This function uses two input parameters; the length of the transported distance block given by the operator or a future production control system, and the distance between the shield and the distance block measured by the laser. The function then calculates which cushions are under the distance block and deactivates the rest of the cushions. In this way a balanced lifting is achieved wherever the distance block is positioned on the pallet.

The new lengthwise pallet balancing function works well as long as cushions can be deactivated accurately outward from the ends of the load. Some problems were encountered due to the pairwise coupling of the cushions which is sometimes preventing cushion deactivation right at either end of the load. In such cases one end of the pallet will raise significantly higher than the other. This can cause the load to either hit the roof of the drift in the higher end or scrape the feet towards the bottom of the drift in the lower end. Optimisation of the stroke length according to the connection pattern of the cushions was considered in order to always have deactivable cushions at the block ends, but not implemented since the cushions are connected pairwise alternately transversally and longitudinally along the pallet. It was also discovered that the maximum stroke of 1,500 mm equals the length of three cushions, so using this stroke the load is positioned equally to the cushion pattern each time. With the current lengths of distance blocks the problem was also not too serious. However, the shorter the load the more significant the problem gets. An enhancement for the future therefore would be to connet all cushions to separate control valves and then adjust the stroke lengths to whole cushion intervals, depending on the situation.

4.2.2 Depositing tight against the drift end or another unit

During the main deposition drive the distance block is always positioned close to the shield for best balance. When the front end of the sliding plate reaches the previously deposited component the control system changes mode to final positioning. The final forward motion of the machine is calculated so that the sliding plate is driven in under the previous block until the front of the lifting pallet barely doesn't reach the previous unit in its' frontmost position. The machine then stops and only moves the pallet back and forth lifting the distance block stepwise forwards on the pallet until the front end of the block extends somewhat over the front end of the pallet. Then, for the last stroke the remaining stroke length is calculated based on the position of the block on the pallet, the pallet position on the sliding plate and the relative position of the sliding plate to the previous unit. The block is then pushed forwards until contact with the previous block is detected by the increase in pushing power (delta-current detection). The last part of the stroke is very slow to avoid damaging the brittle bentonite blocks when the contact is reached.

The same pushing power detection is used when depositing a Supercontainer against a previous component, but since the lifting pallet is dimensioned for the Supercontainer no position shifting along the pallet is needed.

When depositing the end block towards the drift end the deposition scheme is similar to deposition against another block. The difference is that the sliding plate cannot be driven under the previous block which requires the end block to extend quite remarkably over the pallet edge. During the last stroke almost one block segment is completely unsupported by the pallet imposing a great load on the rods binding the block pieces together.

The old control method with the extension piece would have required the end block to be driven all the way through the drift with one segment almost unsupported, being a risky operation. Anyhow, since the block segments are longer but not binded together in the reference design, deposition of the drift end block must be further developed in the future. For the MPT experiment the developed scheme is sufficient.

Depositing units tight together has been done with good results. The units are tight together when the pallet lowering starts. However, due to an uneven lifting angle or uneven lowering the units might get parted some millimeters during lowering.

4.2.3 Functional testing of the distance block feet

A new foot module has been designed for the distance blocks, Figure 4-1. The foot module consists of a perforated metal rim with a circular foot in each end. The foot module is mounted to the distance block with one M30 x 90 mm bolt in the center of each foot. The main concerns were the durability of the feet and their mounting to the blocks. The first tests were actually quite catastrophic, but the remedy was equally simple and effective.

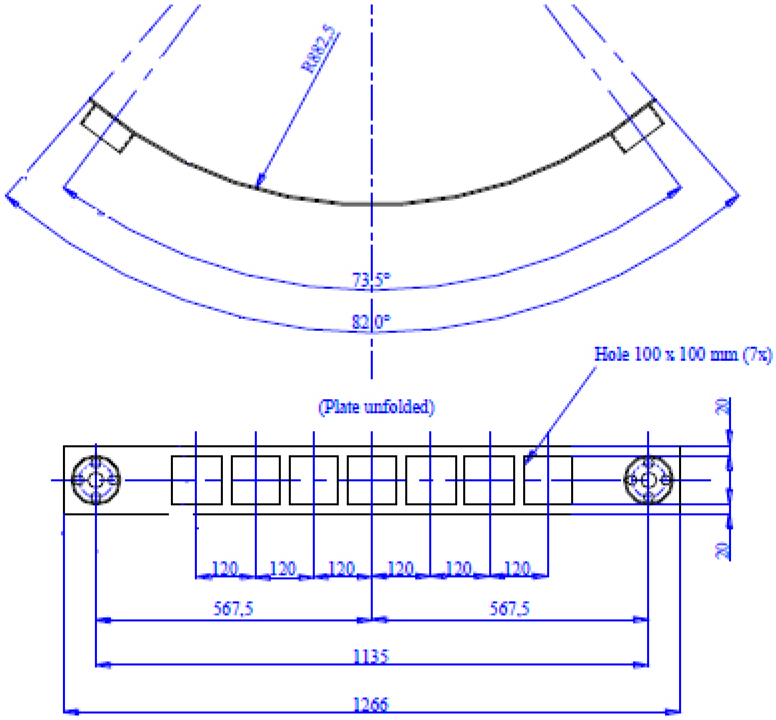

Figure 4-1. *Foot module design for the distance and transition blocks*

During deposition testing several drives were done, many of them also with the distance block extended out over the end of the lifting pallet. As these were the first tests with a distance block the balancing was not yet fully functional allowing the feet to hit the ground during the stroke. Some feet got remarkable deformation, but stayed fastened to the concrete block. The rims of the foot modules were manufactured by punching from sheet metal forming very sharp edges that scraped off material from the plastic guiding edges on the sliding plate. Had the machine not got a new water filtering system had this test resulted in a major water system clean-up. Nonetheless the test ended very suddenly. One of the foot rims was twisted by the scraping force, Figure 4-2, locking the lifting pallet and the sliding plate under the distance block. The jammed deposition machine had to be rescued from the drift by lifting the distance block with separate watertubes.

After redesigning the feet with beveled rim edges the feet worked well without any disturbances. Thus, the foot design was solved.

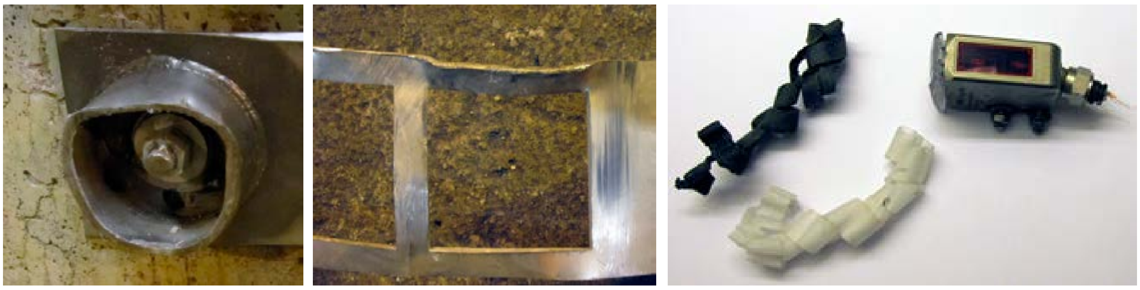

Figure 4-2. *a) Deformed foot due to ground contact during the stroke. b) Bent rim due to scraping against guiding edge. c) Flakes of guiding edge and a sensor torn away by the bent rim (see intact sensor in Figure 3-13).*

4.3 Bentonite distance block tests

As presented above, deposition of a distance block dummy made of concrete had been done prior to testing the deposition of a bentonite distance block. Therefore machine control issues were mainly a verification of previously developed functionality. New issues of interest concerned the stability and durability of the bentonite component. The main concerns regarding the bentonite component were:

- Durability of the feet and their fastening to the bentonite.
  Major problems had been encountered with the feet during the dummy tests. Though the feet had been modified still the stresses on the feet were known to be remarkable if they would scrape against the drift floor while in motion. As the lengthwise balancing was known to be somewhat unstable for short blocks the risk of damaging and loosing feet was evident. In order to have a larger margin against breaking the bentonite at the fastening bolt, the length of the bolts was increased from 90 mm to 150 mm.
- How well the sensors mounted onto the surface of the components would stay in their holes and their cable piping in their grooves.
- How the bentonite would stand the underground environmental conditions with 100% humidity.
- How well the bentonite would stand local wetting due to splashing from the lifting cushions.
- How well the bentonite would stand driving against the Supercontainer at the end of the deposition.
- How tight the bentonite distance block would be deposited against the Supercontainer.
- How well the bentonite distance block would hold together when extended out over the edge of the pallet when deposited at the end of the drift.

The bentonite distance block was first driven back and forth in the drift, then deposited against the Supercontainer a number of times and finally deposited as if the Supercontainer would be the drift end. Inspection of the distance block showed that:

- The feet showed minor scraps and deformation from contact with the drift bottom and the sliding plate, but showed no signs of loosening, Figure 4-3. The bentonite also did not show any signs of cracking around the fastening. After the test one foot element was removed for inspection of the bentonite surrounding the bolts. No visible damage was noted.
- Some loose bentonite was found on the drift bottom, which was assumed to have fallen from the sensor installations, but neither sensors nor cable piping were loose.
- Though the distance block stayed down in the drift for a week, no signs of degradation were found, this is in line with the distance block design where it is expected to stay unaffected for around 10 days.
- The splashing wetted the bentonite on both sides of the lifting pallet, but no damage occurred until the wetted parts dried again after some weeks in the assembly facility. When drying out the wetted parts cracked and fell off, but only to a depth of less than a centimetre.
- No significant deformation was found in the contact surface between the distance block and the Supercontainer
- The pushing force was detected exactly like for the concrete dummy. Tight deposition was achieved.
- The distance block was deposited as if it would be deposited towards the end of the drift, which is the most stressful case. No signs of deformation were found.

As a conlusion the deposition tests with the bentonite distance block were successful regarding both bentonite properties and the feet.

The tests revealed a minor issue with the machine. The distance block made of bentonite had a slightly different mass distribution than the previously tested concrete dummy which caused some longitudinal load balancing problems. These problems indicate that a lift balancing scheme based on the height measurement sensors might anyway be, if not necessary, at least very useful in the future.

Figure 4-3. *Slight deformation of the distance block foot after the deposition test. No cracking in the bentonite and firm fastening after the test.*

5 Results from the MPT deposition

5.1 General deposition results

Though the MPT experiment contained many simplifications in procedures on one hand and test equipment complicating the work on the other, the deposition of four components under rather controlled circumstances gave a good picture of the concept in general. Four bentonite components were deposited without major problems even though some of the bentonite blocks had some surface cracks due to too low humidity in the storage. A rather substantial circular crack had formed in the end surface of the first distance block. Despite this, no major damage was caused to the block during deposition. Overall it seems that the integrity of the components is not jeopardized during the deposition process but this is something that will have to be studied further when continuing development work. The deposition machine has taken a step forward in terms of functionality and reliability but is still a prototype needing further development.

5.1.1 Consistent machine balancing

Generally the depositions done in the MPT experiment were successful. The transversal balancing of the load was considered sufficiently robust to skip calibration of the lifting pallet in order to save time. The deposition logs show that the control system at times utilized all the newly developed transversal balancing methods and despite rather varying conditions never had any problems to fulfil its' task. Figure 5-1 shows a part of the log from the transition block deposition which was the most imbalanced.

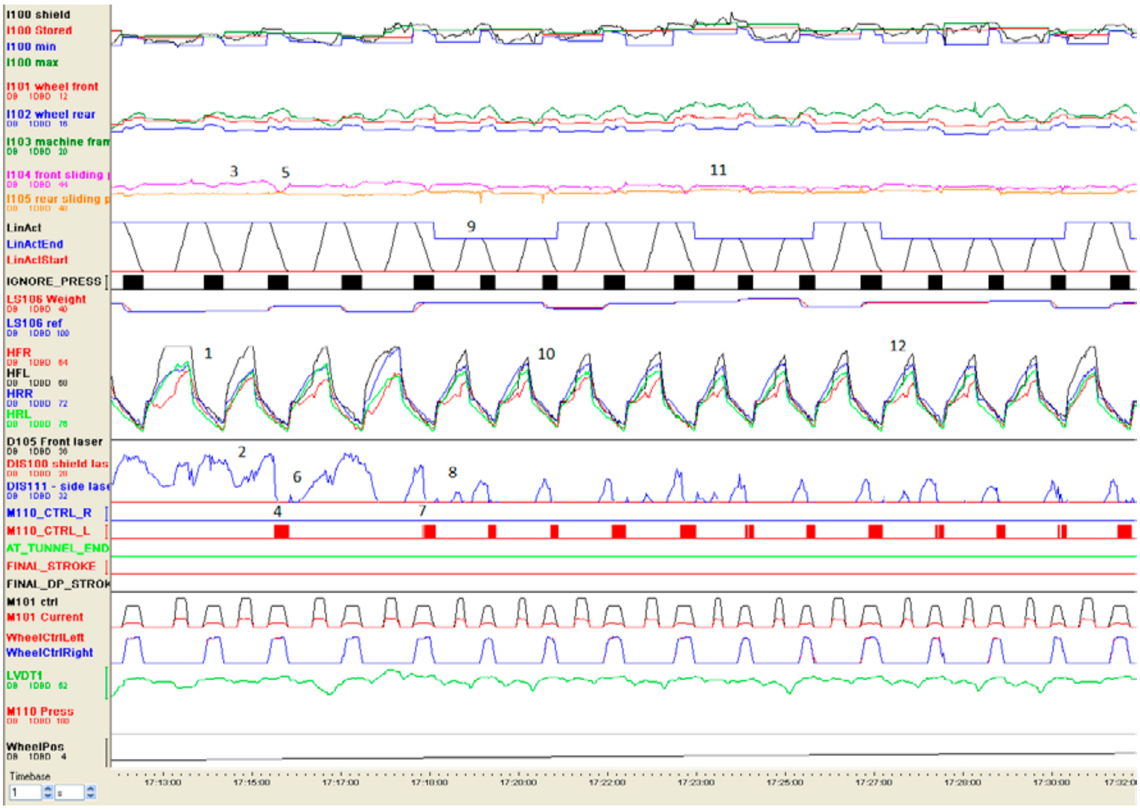

Figure 5-1. Part of the machine log from the transition block deposition.

The log figure is marked with numbers describing phenomena and events of interest.

1. The pallet lifting is extremely uneven with the front left corner (black) raising so high that the graph is cut and the front right corner (red) is having problems even rising high enough for the pushing to start.
2. The uneven lifting is caused by angled mounting of the lifting pallet.The pallet is angled to the left which can be seen from the front laser measurement (blue) constantly showing a large gap on the right side between the lifting pallet and the sliding plate.
3. The increased tilting is possible since the sliding plate front and rear parts (magenta and orange) are not in line and there is always space for the transition block to tilt more.
4. When the inclination reaches a threshold value the front pallet steering is activated (red).
5. The front steering straightens up the sliding plate removing the space for increased tilting.
6. The sideways laser in the front of the pallet also shows that the gap between the pallet and the sliding plate is zeroed. Thus, the pallet leans towards the guiding edge of the sliding plate when the lifting starts and the tilting cannot increase. The lifting is more even.

   During the following lift the active steering is not used allowing the imbalance again to increase and the gap between the pallet and sliding plate to grow.
7. The front pallet steering is thereafter used during every lift and
8. The gap between the pallet and the sliding plate is constantly close to zero. Only small peaks occur.
9. The tilt angle of the load exceeds the threshold value for shortening the stroke producing
10. A lower and more even lifting of the load.
11. The constant use of front active steering keeps the sliding plate aligned.
12. The lifting is well balanced during the rest of the deposition.

5.1.2 Tight deposition results

The new final deposition phase for driving the components into close contact with each other also worked well. The distance from the drift end to the inner surface of the last component differed only 4 mm from the sum of the measured component lengths which is well within the assumed measurement tolerances. The length of each component measured during assembly and the measured overall length of all components after deposition are presented in Figure 5-2.

A machine log describing the final deposition phase of the second distance block is shown in Figure 5-3. The log figure is marked with numbers describing phenomena and events of interest.

1. The front laser (which is actually an ultrasonic sensor) detects the previous component in the drift. The black laser distance detection falls from full detection to a shorter distance and the machine is stopped.
2. The green “at tunnel end” bit is set to indicate the final phase.
3. A short stroke is started (b) to position the lifting pallet in the front for starting the final deposition sequence.
4. Using the measured distance between the sliding plate and the previous component and the distance between the distance block and the shield the final stroke lengths are calculated. The first stroke length limitation is calculated for driving in the sliding plate in under the previous component.
5. The machine is then driven a last time to push the sliding plate under the previous component so that the distance block can reach that component without the lifting pallet hitting it.
   Two strokes (c and d) are done without moving the machine so that the distance block is shifted to the front of the lifting pallet.
6. When the distance block is in the front of the lifting pallet extending somewhat out over the pallet edge the last stroke signal is set (red).
7. The last stroke is very short and slow to prevent that the components hit each other with force.
8. The pushing is stopped when the pushing actuator current (red) raises due to the mechanical contact.
9. During strokes c,d,e the machine has not moved (no red,blue wheel control).

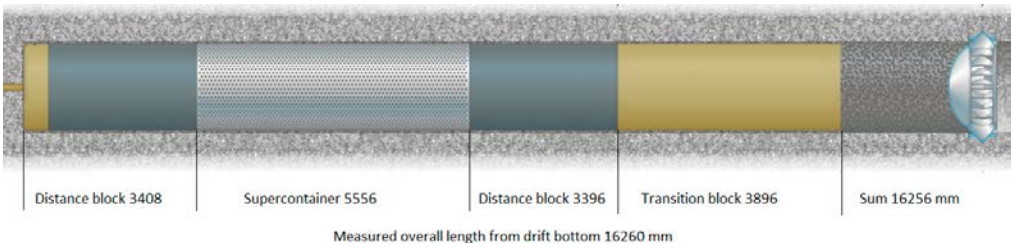

Figure 5-2. *The component lengths measured during final assembly and the overall length of the deposited components measured as the distance of the outer surface of the last component from the drift end.*

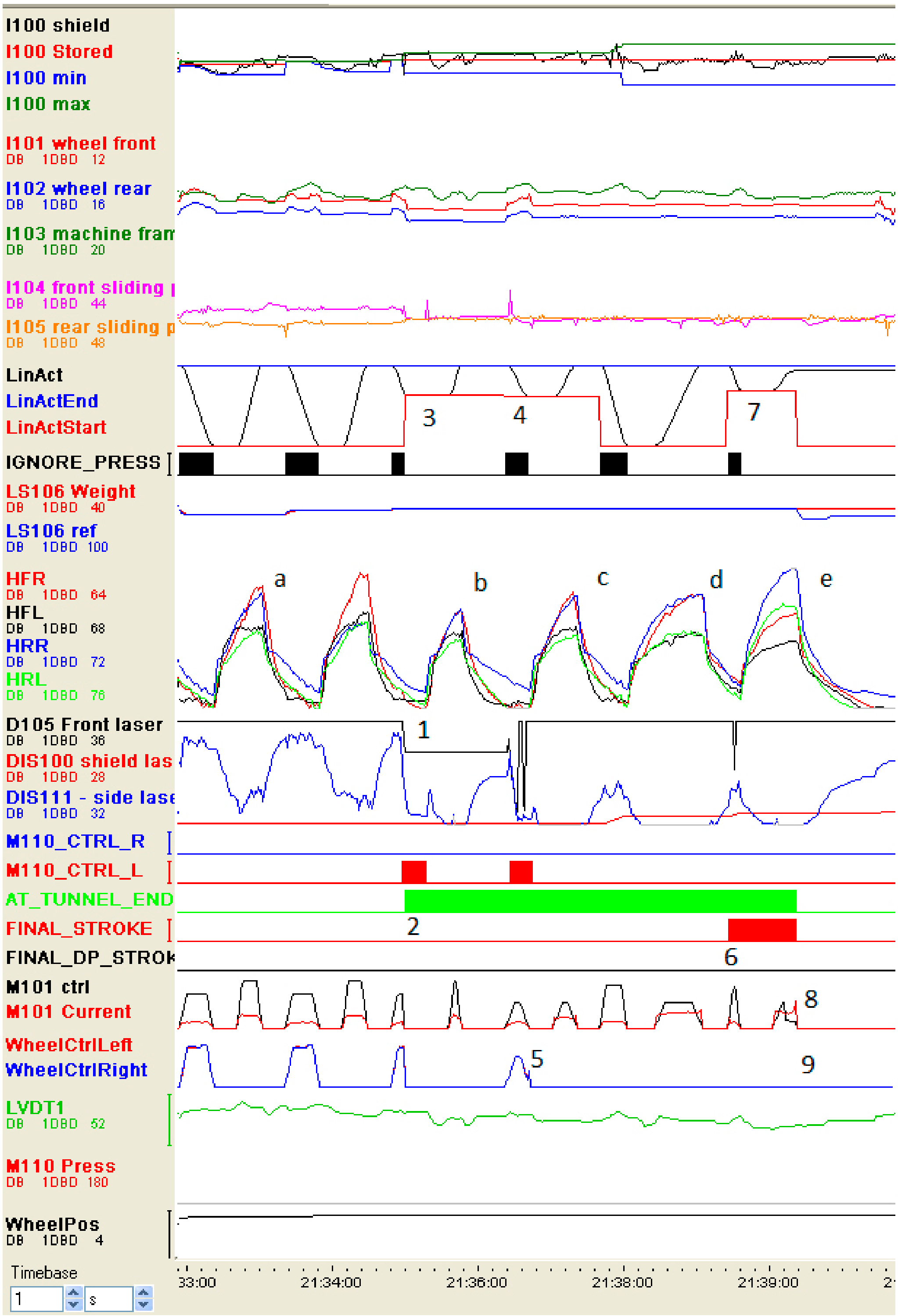

Figure 5-3. *Last part of the machine log from the second distance block deposition.*

The increasing imbalance in lifting during strokes b,c,d,e clearly shows how much more sensitive the system is when the load is in the front of the lifting pallet. The proof is clear as the machine and the sliding plate are standing still and only the distance block is shifted forwards on the lifting pallet. A verification that the use of the mechanical extension piece between the shield and the distance block would have been very challenging.

5.2 Shortcomings of the machine

Some inadequate properties, that had not been attended to because they required too extensive mechanical modifications, proved to need attention in the future. The main things being related to cushion control and splashing prevention. Some occurrences of deficient machine behaviour are noted below. Suggestions for corrective actions are discussed in a later chapter.

5.2.1 Longitudinal balancing of short loads

The distance blocks and transition blocks were shorter than the Supercontainer and the control system automatically deactivated cushions that were not under the load in order to keep the longitudinal balance. For the distance blocks this balancing worked well, but the length of the transition block did not match the pairwise coupling of the cushions and therefore either one cushion row too many or one too few had to be deactivated. This resulted in longitudinal balancing problems with the front end lifting either too much or too little. Especially activating cushions outside the load twisted the free part of the lifting pallet strongly to either side causing excessive balancing problems.

During the end sequence of the deposition of the first distance block the block was extended far over the lifting pallet in order to reach the drift end wall by the end of the stroke. Due to the large overhang in the front the lifting was slow causing dragging of the distance block feet against the drift bottom.

The friction between the feet and the drift required additional pushing force and the increase in actuator current was so large that the control system incorrectly assumed that the component had reached contact with the drift end wall. The last deposition stroke was therefore ended too early and had to be extended manually. Longitudinal balancing must be better managed in the future.

5.2.2 Lifting problems with oversized load

The combination of a Supercontainer with a cable block was longer than the lifting pallet is designed for, which caused a too big load on the front part of the pallet. The front feet of the Supercontainer were not lifted from the dift bottom before the pushing started. The pushing required too high power and was stopped with an error message. Automatic longitudinal balancing of the Supercontainer was not possible despite full water pressure and deactivation of the rear cushions. The only solution was to increase the lifting time. With the longer lifting time the front end was lifted free from ground contact but at the same time the rear part almost reached the roof of the drift. The deposition could be carried out by manually deactivating some extra cushions in the rear when the height increased too much.

5.2.3 Splashing with heavy loads

Splashing was not a problem with any of the distance or transition blocks, Figure 5-4, even when the load was a bit unbalanced longitudinally. However, the big unbalanced load of the Supercontainer with the cable block caused rather severe splashing problems, Figure 5-5 and Figure 5-6. It is difficult to assess how big the influence of the greater load was compared to the imbalance, but splashing was remarkable especially in the rear of the lifting pallet where the cushions reached their maximum lifting height during the long lifting times.

***Figure 5-4.** The bottom of a distance block seen with the camera in the front of the sliding plate after deposition. A small dark spot in the upper left corner probably comes from splashing.*

***Figure 5-5.** The bottom of the Supercontainer after deposition. Splashing has wetted the bentonite so much that it is pouring out of the holes in the steel shell.*

***Figure 5-6.** The lifting pallet after deposition of the Supercontainer. Wetted bentonite was left on the pallet.*

5.2.4 Sensitivity to changing conditions

Mechanical

As a preparation for the final MPT deposition the height and angle of both start tube and transport tube were adjusted as these units were not properly in line with each other and the drift. Before the adjustments the pallet and sliding plate could not be pushed from the start tube in under the component in the transport tube. The machine also got stuck under the component when trying to pass the step between the transport tube and the drift. Adjusting the position blocks was a laborious and time consuming task which should be avoided by changing the design. The adjustment did not last for all four depositions indicating that some means of active adjustment should be applied. The adjustment would then be automatically performed prior to every deposition.

Sensor system

During deposition the previous component in the drift is detected with an ultrasonic sensor in the front of the sliding plate. When detection is received the propagation of the sliding plate is stopped. The deposition control changes to the end sequence moving the component forwards on the lifting pallet until it comes into contact with the previous component. During the MPT depositions, two conditions regarding this detection had changed. Firstly, the foot height of the components had increased somewhat compared to the dummy Supercontainer and secondly the ultrasonic sensor had most probably been pushed somewhat deeper into the mounting hole during service. The result was that the beam was narrower than before and did not detect the somewhat higher corner of the previous component. First the problem was solved by manually driving the component forwards into contact. For the last two depositions a piece of cardboard was mounted on the previous component to ensure detection. In the future such critical detections must have a more robust design and preferably also be doubled.

The cameras onboard the machine, especially the one in the front of the sliding plate, gives very valuable information about the progress of the deposition. For the operator, fail-safe function of the camera system is therefore vital. At certain occasions during the MPT the camera system had severe problems with picture quality. Connecting the sliding plate camera to the system shut down the main camera picture or disturbed it remarkably. The problem was probably caused by disturbances in the sliding plate cabling or the connections between the machine and the sliding plate which are constantly exposed to water. The sliding plate system needs renewal and possibly doubling of the cameras.

6 Safety assessment and evaluation of CE marking validity

A system safety investigation was conducted on the horizontal deposition machine by the Research Centre of Finland (VTT). The investigation consisted of three separate stages:

- In a preliminary hazard analysis (PHA) the focus was on finding all potential hazardous situations related to the use of the machine in its' normal working environment. The whole working cycle including transports in the niche was investigated. A list of prioritized hazard scenarios was presented.
- Next the safety and control functions related to the identified hazards were assessed and their performance levels evaluated. Safety functions needing closer investigation were listed for the next investigation.
- A HAZOP study was conducted for the chosen functions. HAZOP is a standardized risk analysis method focusing on deviations that might occur in a system and on the consequences the identified deviations might cause. The deviations are searched and the consequences are evaluated based on probability and severity.

The HAZOP analysis covered the control system of the deposition machine and the operator controls in the control room. The HAZOP study was mainly focused on personal safety issues and was done to the system when most of the control software corrections were done.

Some deviations with a medium risk level were found. Most of them were to be corrected by better guidelines for the operator. One deviation was related to unintended start in mode changes and has been corrected.

Finally a safety validation according to the Machinery Directive was done. Corrective actions were mainly listed for working in elevated positions, working platform conditions, and personal protection in the vicinity of hydraulics. Since the working platforms were removed for the MPT they were not fixed. Protective covers were built for the transport tube hydraulics.

The validity of the CE marking is a complicated question, since there is not one single party who has complete information on all design aspects and knowledge of the actual implementation. Therefore prototypes and machines under development are normally not CE marked. The CE mark responsibility therefore lies on the machine owner, who has ordered the safety analyses both for the original CE marking and the current modifications. The current modifications were found to be in conformance with applicable European directives.

7 Suggestions for improvements

The machine can still be improved both regarding mechanical properties, the control methods and the control application. How to go further with the development depends on the economics and the scope of the development. The basic problem is the lifting stability and the somewhat inaccurate controllability of the cushion technology which can be only slightly improved by further control system development, but could be more enhanced with concurrent mechanical upgrading.

7.1 Load balancing by separately controlling the lifting of each quarter of the pallet

Many times the imbalance of the load starts by poor lifting in either front corner. During forward pushing the load then tilts towards the lower corner increasing the imbalance. Since the height sensors in each corner of the pallet give an accurate detection of the situation the imbalance could be avoided with better individual pressure control of the lifting cushions. Quite simply, lifting of the pallet would be controllable if any quarter of the pallet could be lifted with increased or decreased pressure, Figure 7-1. However, since distance blocks cover only part of the pallet, lifting should be controllable with individual pressure regulating valves on all cushions. Then the quarterly balancing could be implemented for any size of distance block in any position on the pallet. The piping in the pallet would remain the same, but the valves would have to be replaced and the piping in the valve cabinet would have to be rebuilt.

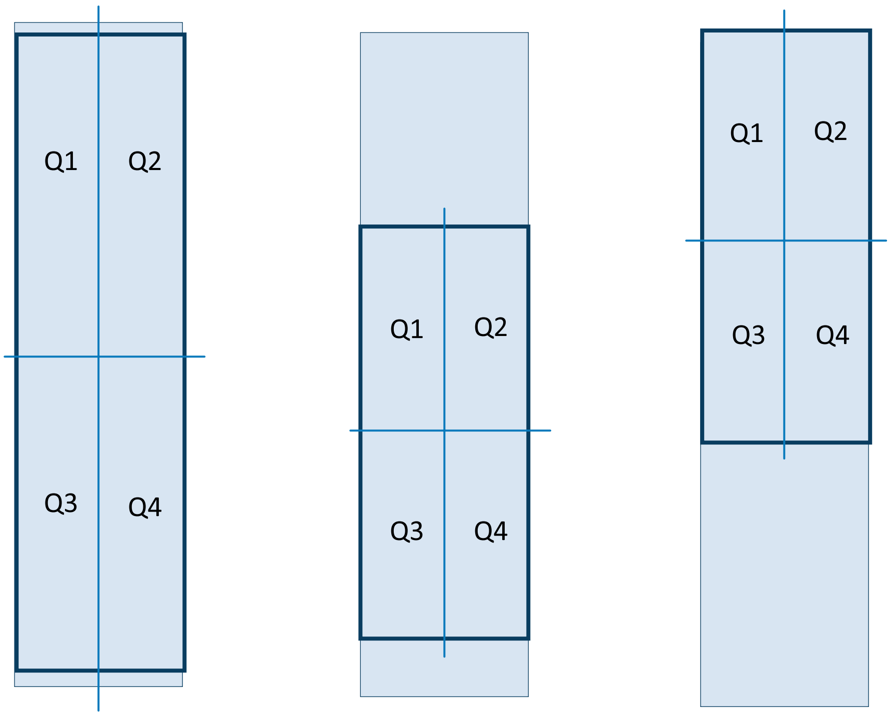

***Figure* 7-1.** *Balanced lifting requires cushion deactivation outside the load and use of different pressures in different quarters of the load.*

7.2 Load balancing by directly controlling the rotational angle

The current instrumentation, actuation and control system is able to detect instability in the transport process with sufficient accuracy to enable balancing actions before the machine gets too imbalanced to control. The active steering applied in the front of the pallet is not strong enough to hold against the imbalancing forces during lifting, but is able to steer the unloaded pallet and sliding plate to return the system into balance or at least to prevent an increase of the imbalance. A more sustainable solution would be to use a control that is forceful enough to keep the load balanced, if not in any inclination, at least in a much wider range than with the current system.

If a more extensive redesign of the machine mechanics is possible, a solution to the problem could be to use a steering system which is forceful enough to control the inclination while the load is lifted. Since lifting the load presses the sliding plate against the drift bottom with the weight of the load the sliding plate can be considered as an absolutely stiff support during the lifting. Therefore, in addition to balancing with the balance weight and transferring the torque over the linear actuators a stronger balancing force could be applied directly to the sliding plate before the load is lowered after the stroke. An example solution is presented in Figure 7-2. Linear actuators 2) are mounted on the shield pushing turn plates 1) underneath the shield. Either turn plate is pushed against the guiding edge of the sliding plate rotating the shield to the other side. Distance sensors must be mounted in the linear actuators to prevent that pushing does not exceed the available space between the guiding edges. The front actuators are still needed for controlling the front end of the lifting pallet while it is slided forwards.

More consistent behaviour of the machine can also be achieved by changing the way the lifting pallet is mounted to the shield. The pallet should always be fixed in the same angle and position by guiding pins and the angle should be adjustable and lockable into position. Such enhancements have been suggested but not realized after the first test period.

7.3 Splashing prevention on the lifting pallet

Though the splashing did not harm the bentonite distance block remarkably a splashing prevention has been prepared by providing guiding edges over the whole length of the sliding plate. The edges are intended as counter surface for a splashing cover on the sides of the lifting pallet. A cover has never been designed though, due to other more prioritized work. A design is shematically presented in the Figure 7-3. The splashing cover material should be flexible but still have an internal tension pushing the outer edge against the guiding edge of the sliding plate despite the elevation of the lifting pallet.

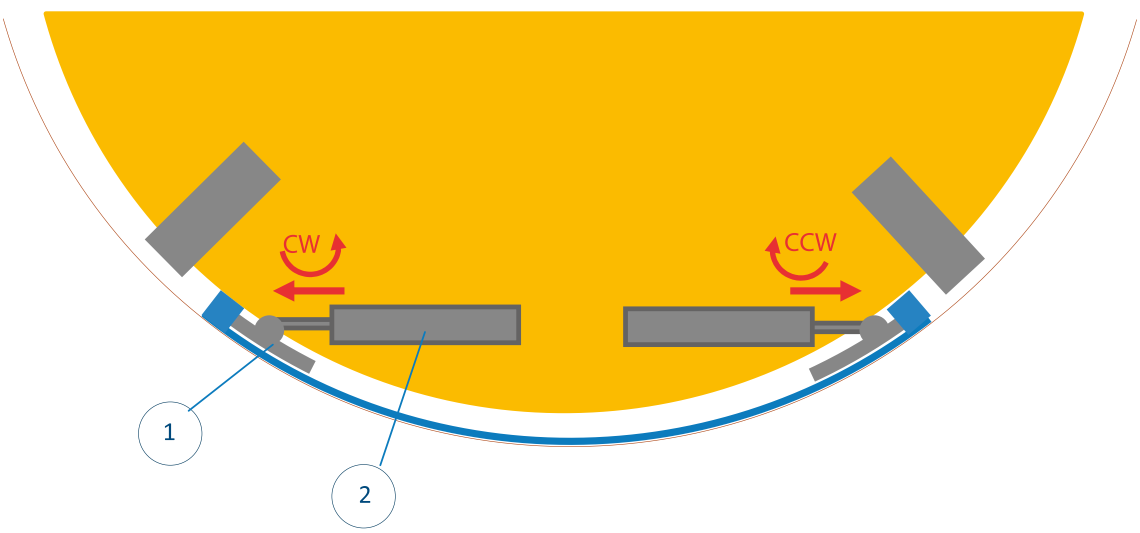

Figure 7-2. *Schematic illustration of turning plates 1) lying on the sliding plate under the shield pushed by linear actuators 2) mounted on the shield towards the guiding edges of the sliding plate.*

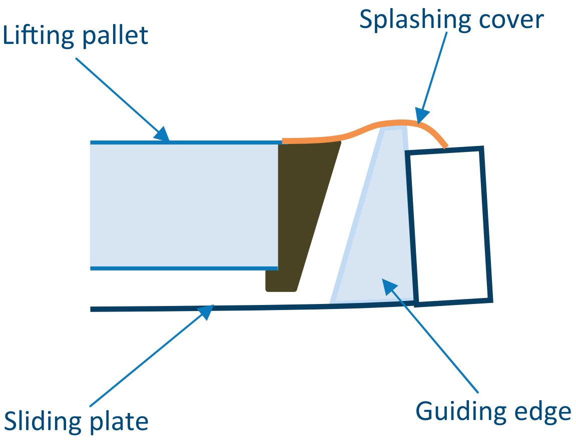

Figure 7-3. *Schematic splashing cover design.*

7.4 Safeguarding work cycles

Some sensors and systems that are very critical for the final deposition result are the sensors for detecting the previous component in the drift, the linear actuator length sensor and the measurement of the distance between the shield and the load on the pallet. If any of these fail the deposition of the component can not be guaranteed to be tight against the previous component. Therefore these sensors should be doubled. The camera in the front of the sliding plate is really necessary for remote monitoring of the process and should therefore be doubled. For all other sensors and actuation controls proper functional monitoring with error messages, remote error resetting and override control should be applied where not yet finalized. These are tasks that could not be fully addressed in this project and are associated with an industrialisation of the prototype machine.

7.5 Automating the transport tube and start tube

In the final repository the use of manually adjustable position blocks for the start tube and transport tube outside every deposition drift should be avoided. This can be done by substituting the static support frames with AGV type of transport vehicles for both transport tube and start tube. The AGV's should have positioning systems for aligning accurately with the drift, supports for leveling respective tube to the drift and adjustable frames for sidewise and angular finetuning. The end ring of the deposition drift should be shaped to guide the levelling.

Self propelled transport tube and start tube machines allow a smoother work cycle. After deposition the start tube unit moves out somewhat giving space for the transport tube unit to move to the side and then pass the start tube unit out into the transport tunnel. As the transport tube unit drives away for loading a new component another transport tube unit can dock to the drift with the next component. The start tube unit then moves in again for the next deposition.

As the machines are self propelled, the power to the deposition machine would be produced on-board the transport vehicle. The control system of the transport vehicle would serve as a supervising system to the control system of the deposition machine. All machines would be controlled by a centralized mission control system over WLAN connections.

The start tube of the machine must be as long as the deposition machine with the sliding plate and lifting pallet attached. Disassembly, assembly and calibration work on the machine can not be part of the deposition process. Such work can only be allowed when the deposition equipment is moved from one drift to another as the tunnels might be too narrow for transporting the whole system in its' full length. However, in order to make the machine easier to transport between drifts both machine design and start tube design can be made more compact.

8 Conclusions

The functionality of the machine control system was enhanced considerably by:

- Restructuring the control software.
- Optimisation of the memory map.
- Optimisation and reconfiguration of Pofibus communication.
- Reconfiguring HMI Tags and interaction functions.

The control and balancing of the machine has been enhanced by:

- Improving counter balance control.
- Improving machine steering by better wheel control.
- Reducing instability by water pressure control, lifting time limitation and stroke length limitation.
- Introducing active balancing by cushion deactivation.
- Preventing imbalance due to misplaced lifting pallet by active pallet steering.

The enhanced controls have all been integrated into a composite control method that proved stable in the deposition tests. Further, manual operation has been minimized by increasing the automation level in all sequences of the deposition.

Though the machine control system had much more structural problems to correct than was initially estimated and a comprehensive solution to the balancing problem was behind a long path of partial solutions, the machine was finally brought to a sufficiently functional level. The machine performance was adequate for carrying out the MPT experiment and can be used for further conceptual validation testing.

Future machine development requires mechanical modification of the machine before the control system can be further developed. Topics needing attention are:

- Longitudinal load balancing which requires individual cushion control before the pallet height sensors can be utilized for control.
- Stronger transversal load balancing which requires utilization of a mechanical force instead of the movable load based balancing.
- A rigid pallet mounting with easily adjustable pallet to shield angle.
- A more compact machine and a stiffer and longer start tube design with better height adjustment capabilities.This should allow transportation of the machine without dismantling it and enable easy alignment of the system to a drift.

A vast number of actions could be taken to enhance the control software in general, the operators interface, information and language matters,error handling, maintainability of the application etc. However, as long as the machine is still a prototype, these matters are of minor importance.

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