Human and Robot Interaction based on safety zones in a shared work environment

Svante Augustsson
The work explores the possibility to increase the automation along a production line by introducing robots without reducing the safety of the operator.

The introduction of a robot to a workstation often demands a redesign of the workstation and traditionally the introduction of physical safety solutions that can limit the access to the work area and object on the production line.

This work aims to find a general solution that can be used not only in the construction industry, but also in other types of industries to allow for an increased Human and Robot Interaction (HRI) without physical safety solution.

A concept solution of a dynamic and flexible robot cell is presented to allow for HRI based on safety zones in a shared work environment. The concepts are based on one robot and the usage of a 3D camera system allowing for the design of virtual safety zones, used to control the HRI. When an operator approaches the robots work area and triggers a safety zone the robot stops its work and moves away from the operator. Based on the safety requirements and triggered zones the robot will continue to work in a new area or wait until the operator leaves the work area and then continue with the interrupted work task. This will allow the operator and the robot to work together, where the operator location controls the robots workspace.

Testing and validation of the presented concept showed that the wanted functionality could be obtained. It also showed limitations to the equipment and the system used during tests and raised additional aspects of the safety for HRI. Of the detected limitations the most crucial when looking at up-time for the production line, is the camera system need of a relatively dust free environment, good and constant lighting. For the safety of the system the limitation lies in the size and placing of the safety zones in combination with the disturbance from surrounding equipment.

The presented concept has proven to work, and can be applied not only for the construction industry but for all industries with manufacturing alongside production lines with large components.
This thesis works have been written as a part of the examination for the Master program in Robotics at University West.

This work have been interesting and educational, both in the area of studying the latest technologies for Human and Robot Interaction (HRI) and especially to have the opportunity to design and present a HRI concept and later test the solution in a physical robot cell.

The work has given me a wider knowledge to different models of robots and new safety solutions and allowing me to see new ways to solve problems connected to HRI. The work has also been good in the way that it has connected knowledge from all parts of the education into one project.

I want to thank Anders Appelgren at University West for the help and discussions during the literature study and the project planning. I also want to thank Anders Nilsson at University West for the introduction to the robot cell and the patience with all the questions connected to the hardware, configuration and system design in the robot cell.
This master degree report, *Human and Robot Interaction based on safety zones in a shared work environment*, was written as part of the master degree work needed to obtain a Master of Science with specialization in Robotics degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

Signature by the author

Svante Augustsson

2013-06-19
Date
Contents

Preface
SUMMARY ..................................................................................................................II
PREFACE ..................................................................................................................III
AFFIRMATION..........................................................................................................IV
CONTENTS ...............................................................................................................V
SYMBOLS AND GLOSSARY.....................................................................................VII

Main Chapters
1  INTRODUCTION ....................................................................................................1
  1.1  PROBLEM DESCRIPTION .................................................................................1
  1.2  AIM..................................................................................................................1
2  LITERATURE STUDY ..........................................................................................2
  2.1  AN INTRODUCTION TO THE AUTOMATION OF HOUSE PRODUCTION ..........2
  2.2  AUTOMATION AND FACTORS THAT AFFECT THE OUTCOME .......................3
  2.3  AUTOMATION AND SAFETY .........................................................................4
  2.4  HUMAN AND ROBOT INTERACTION ..............................................................5
  2.5  NEW RESEARCH SAFETY FOR SAFE HRI .....................................................7
  2.6  SAFE AUTOMATIC OBSTACLE AVOIDANCE AND PATH GENERATION ........9
  2.7  CONCLUSION LITERATURE STUDY ............................................................10
  2.8  FURTHER WORK ..........................................................................................10
3  METHOD ...........................................................................................................11
  3.1  LITERATURE STUDY ....................................................................................11
  3.2  ANALYSE OF HARDWARE IN THE ROBOT CELL AT PTC .........................11
  3.3  CONCEPT DESIGN AND APPROACH FOR TESTING ......................................11
  3.4  ROBOT CELL CONFIGURATION ..................................................................11
  3.5  ANALYSE OF RESULTS .............................................................................12
4  WORK ..............................................................................................................13
  4.1  CONCEPT DECLARATION FOR HRI BASED ON SAFETY ZONES IN A SHARED WORK ENVIRONMENT ..........................................................13
  4.2  EQUIPMENT ..................................................................................................15
  4.3  ROBOT PROGRAMMING ...............................................................................15
  4.4  SELECTION OF STATIC OR DYNAMIC SAFETY ZONES AND SAFETY EYE SYSTEM CONFIGURATION .........................................................17
  4.5  SAFETY PLC PROGRAMMING ...................................................................19
5  SYSTEM EVALUATION ......................................................................................20
  5.1  DIMENSION AND PLACING OF SAFETY ZONES ............................................21
  5.2  ZONE ARRANGEMENT USED DURING TEST ................................................21
  5.3  CONCEPT TEST ON DIFFERENT MATERIALS AND SURFACES ......................22
6  RESULTS AND DISCUSSION ............................................................................23

V
6.1 EQUIPMENT ................................................................. 23
6.2 PLC SIGNALS ............................................................. 23
6.3 PLC PROGRAMMING .................................................. 23
6.4 LIMITATION IN THE INTERRUPT FUNCTIONALITY .......... 24
6.5 CAMERA SYSTEM SENSITIVITY/LIMITATIONS ............. 24
6.6 SAFETY .................................................................. 25

7 CONCLUSION .................................................................. 27
  7.1 FUTURE WORK AND RESEARCH ............................... 27
  7.2 CRITICAL DISCUSSION ........................................... 27
  7.3 GENERALIZATION OF THE RESULT ......................... 28

8 REFERENCES ................................................................. 29

Appendices
  A. KUKA KR 180R2500 EXTRA PROGRAMMING
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMI</td>
<td>Human-Machine Interface can refer to both a display on a screen and to a device for controlling a machine or robot. Common for the HMI is that it allows the human to respond to information provided from the equipment.</td>
</tr>
<tr>
<td>HRI</td>
<td>Human and Robot Interaction refer to the interaction between the human and the robot that accrue either by a physical interaction or through other interfaces.</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization. Is an organization that develops and publishes international standards to ensure that products that follow this standard is safe, reliable and of good quality.</td>
</tr>
<tr>
<td>Payload</td>
<td>The weight a robot can carry and still stay within the limits of its other specifications.</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller or Programmable Controller is a small digital computer used for controlling electromechanical processes, in and between machinery. The computer is designed to process multiple in and output signals in real time.</td>
</tr>
<tr>
<td>Work space</td>
<td>Is commonly described as a sphere around a robot, where the edge of the sphere is the limit of where a robot can reach and work.</td>
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1 Introduction

This work has been performed as a part of a collaboration project between University west, A-hus and Randek. That aims to develop methods and techniques to increase the usage of robots in the manufacturing process of small family houses in wood.

1.1 Problem description

A-hus is a construction company of small family houses in Sweden. The company is interested in automated parts of the production line and are considering introducing robots to the production line. The production and assembly of the houses is today mostly done manual and semi-automated by the personal.

A-hus produces a wide range of house models for the customers to select from. The customer also has the option to decide upon a wide range of changes to the selected house model such as the size and the position of windows and doors. It is also possible to make small changes to the layout in the houses.

The houses produced at the factory are so called module houses. This means that the houses are built as wall modules on stations along a production line. Along the production line a small number of portal robots already exist to aid with nailing and screwing of cladding to the walls modules and placing insulation into the walls.

When all wall modules of the house are produced, it is transported out to the customer’s house plot and there assembled on site.

This give that every house produced in the factory is unique, and demands good flexibility in the production.

Looking at the production of the wall modules, no module is the same as the previous one in the line. This makes the automation of a production line problematic, regardless if it is the construction industries or other industries.

1.2 Aim

This thesis work will be performed with A-hus as the original owner of the problem of increasing the level of automation of the production line with robots. The work will be performed with the aim of finding a general solution, to increase the automation of the production line with the help of introducing robots to the production line without reducing the safety for the operator.

- Find a solution to increase automation and production without this having an impact on the quality of the product.
- Find knowledge on Human and Robot Interaction (HRI) and how to use this to increase automation.
- Find a safe solution for HRI in a shared environment.
- Usage of existing equipment on the market.
- Find a solution that can be applied to the industry today.
- Testing and simulation of methods/solution to be performed at University West’s facilities at Production technology Center (PTC) in Trollhättan.
2 Literature study

This literature study is divided into three sections. The first section is a short introduction and history of the construction industry. The second part looks at the different aspects that affect the result of automation in the industries. The third part looks at safety solutions, ideas and research for HRI within the industries.

2.1 An introduction to the automation of house production

Looking at the construction industry today, the industry is in comparison to other industries very traditional and has generally speaking a low level of automation in the production processes. This comes from the tradition of building single houses on sight with craftsmen and local material. Professions such as carpenters and masons have a long history of producing products of high quality by hand and the knowledge and methods were transferred from the master to his apprentice for a long time.

It is also possible to see similarities in the construction of houses in other industries such as the shipbuilding industries when looking at the level of automation. Both houses and boats have been built by hand and by skilled craftsmen. Resulting in a unique product and at the same time often similar to the product build before. A house is a house even if the size and model are changed. However, modern shipbuilding has developed into highly automated facilities during the last decades giving a dramatic increase in productivity. Then the question is why the construction industry has not been able to reach the same level of automation and productivity, when there is a constant need of new economical affordable and safe houses all over the globe.

During the last 100 years there has been some more successful tries to automate the production of small house in the same ways as cars are produced on a production line. One early example is the Dom-in-o House from 1914 [1].“The Dom-in-o House was one of the most influential, with its simple, standardized, slender frame, slab floors, flexible floor layout independent of structure, lightweight movable internal walls, and external non-load bearing cladding.” This house is also a good example of how to use standardized parts that makes automation of production easier.

Looking at the construction industry it is possible to see some different approaches of the manufacturing of houses, in the industry depending on where in the world you look and the type of house produced. Looking at the material used when building small houses there is two main differences depending on where in the world the house is built. In the northern parts of the northern hemisphere wood is the most command material. Around the equator and the southern hemisphere stones and bricks are the most common material. This can also be a reason that the industry not yet has reached a common approach of producing houses. Like other industries such as the car or boat industry, where the same material and production methods are applicable all over the world regardless of the location. For example in the Japan market people prefer the benefits of a good duality and the little lower price that comes with a higher level of standardisation of a house [1]. This can also be depending of the need of new houses due to increased population and a good economical situation in the country.
2.2 Automation and factors that affect the outcome

When looking at the possibility to automate the production of a product, either it is a production line or a work cell there will always be a numeral of conditions to the product and factory that will affect the level and success of automation.

Factors connected to the product that affects the automation level.

- Type of products.
  - Variation of the product.
  - Design and manufacturing complexity.
- Production lifetime of a product.
- Number of units/batch size.

Factors connected to the production.

- Cell/station design.
- Selection of Robot.
- Safety of the operator.

Factors connected to the investment.

- Cost of automation.
- Cost for production time.
- Payback time.

In all the above conditions the environmental and ethical aspect is important to consider and should be included in the decision process of automation. This aspect has become more important during the last decade. This can be connected to two main reasons, an increase awareness from the manufactures on the market and the growing interest of environmental and sustainable products from the consumers.

2.2.1 Standard, semi-standard or custom made products.

Products can be divided into three types of categories based on of product design, usage, pricing, etc. Regardless of this classification all products can be categorised into three groups that will affect the approach and outcome of an automation of a product.

- Standard products can be categorised by some of the following conditions, high turnover, always the same product properties, optimised production time, large product batches, high automation level and normally kept in stock.
- Semi-standard products can be categorised by some of the following conditions, small variations in product properties compared to the standard product, moderate size of product batches, high and flexible automation level, stock varies from small volumes to available by order.
- Custom products can be categories by some of the following conditions, small batch sizes or single production, higher unit price and often only available by ordering.

A high automation of custom or semi-standard products requires good planning and great flexibility in production system.
2.2.2 Factory, Cell, Station design and product life time and manufacturing volume

In the best case, a production line only needs to be reprogrammed and optimised to reach a higher level of automation.

In the more common case a reconfiguration is needed based on detailed controls of the existing production line and the wanted level of automating. Resulting in the need of adding new marching and robots and apply smaller changes to the design and reprogramming of equipment. In worst case a major redesign of the production line or a new factory is needed to be able to reach the wanted level of automation.

When planning for a new production line or modification of an existing line for automation of the production two more aspects are important to look at, from an economic perspective.

- Product life time for how long time is the product planned to be produced: weeks, months or years.
- Product volume what is the planned number of units for this product.

These two points are very important when calculating the payback time of the investment. The cost that needs to be invested is not only referring to new equipment and installation but also to invested work time, education of personal, stopped production and optimization time.

When looking at the automation investment, cost for equipment and rebuilding, is it important to consider if it is economically a good decision to do this automation? In some cases it might be more beneficial to look at possible process improvement rather than automation of the process.

An example of extremely complex automation over short time is the cell phone industry, where the product life normally is 6-12 months, and the volume is more than millions of units of a standard model. In this example the automation needs to be or close to 100% and the payback time of the investment needs to be short due to the lifetime [2].

2.3 Automation and Safety

A higher level of automation will almost guarantee an increase of robots and automated machines into the production line. This will also bring the problem of safe HRI to a new level.

By looking at Newton's second law of forces Force = Mass * Acceleration and what forces the human body can handle without getting damaged [3] [4]. This gives a simple and good image of the importance of the safety for HRI.

There exist today a wide range of solutions to protect the human from robots and machines that are approved in the global ISO standard for industrial robots. In addition to this, there is on-going research and production development on new solutions in the field of safety. When designing a work station where the interaction of a high-speed and high-powered robot and a human can occur, a risk analysis is needs to be performed [3]. Depending of the outcome of the risk analysis provided in ISO/TR14121-2 Safety of machinery – Risk assessment and ISO13849-1 Safety of machinery – Safety-related parts of control systems. There are several steps and implementations of safety measures that can be implemented to lower the risk and even eliminate the risk completely for a human working alongside a robot [5].
The following sub-sections will introduce ways to decrease the risk of working with robots available today and in the field of research.

2.3.1 Selection of robot

When looking at the safety in a robot cell and the knowledge of Newton’s second law, some companies go for the solution of implementing small robots that are approved for working alongside humans. This is common for assembly work within the electronic industries. Within many industry segments it is not possible to implement small robots due to the lack of payload and work space that are needed to perform the tasks assigned to the robot.

An interesting aspect of the safety for human and robot interaction is the selection of robots, and how the operators sees the robot and trust it to perform its tasks correctly based on the design of the robot.

Now when robots are getting more common in both private homes and in the industry, new designs are introduced on the market such as the humanoid robots that are designed to reflect emotions and human like behaviour [6]. There is an indication that humans within the industry prefer the more traditional design of an industry robot. [7] “Non-humanoid forms can be perceived as having better personality and friendlier than humanoids, possibly because they are viewed more as machines than as independent actors”. However, this conclusion is not the view of all robot manufactures. There are some companies that today are trying to introduce a new type of robot on the market, which is a combination of the traditional industrial robot and a humanoid. Specially designed for interaction with humans alongside assembly- and picking lines.

2.4 Human and Robot Interaction

In 1941 the science fiction author Isaac Asimov defined three laws for robotics that still today can be used as guidelines when working and studying safe HRI.

Isaac Asimov laws of robotics [8].

1. “A robot may not injure a human being or, through inaction, allow a human being to come to harm”

2. “A robot must obey the order given by human beings, except when such order would conflict with the first law”.

3. “A robot must protect its own existence, as long as such protection does not conflict with the first or second law”.

The HRI can today be separated into two main areas. The first is a separation of the human and the robot work areas from each other. And the second is when the human and the robot share the same work area.

2.4.1 Separation of humans and robots

The most common solution within the industry today is to separate robots and humans from working in the same work area at the same time. Interactions is handled through gates, in/out loading bays or conveyers controlled by safety measures to make sure that the human and the robot do not access the same work areas at the same time.

This separation of humans and Robots can be performed in many ways and by many techniques, each with its advantages and disadvantages. Safety solutions commonly used today are based on [4] [9].

Fences/gates:
Degree Project for Master of Science with specialization in Robotics

Human and Robot Interaction based on safety zones in a shared work environment - Literature study

+ Provides a physical obstacle that protects from both parts and light.
+ Controls the access in a physical way.
- Limits access to the robot.
- Time consuming to change.

Light curtain:
+ Provides access control to an area without being a physical obstacle.
+ Provides easy access.
+ Easy to change and redesign.
- Easy to trigger by mistake.

Sensors:
Exist in many configurations and with a wide range of purposes such as range, proximity, touch, vision, sound, temperature, force, motion, and so on. The sensors can be used to control a specific task or for monitoring motion up to 360 degrees from the sensor.

Safety mat:
+ Places on the floor to control access and is a physical obstacle that is easy to see.
- Sensitive for heavy loads and often limited to small areas.

Clothing:
The robot is covered in a viscous-elastic material to absorb the initial energy in a collision or to remove sharp edges.
+ Prohibit visual inspection and can hide leakage and damages.
- Low cost.

2.4.2 Shared work areas of robots and humans

The safety when humans and robot share a work environment is strictly regulated by laws to protect the operator from getting harmed. Creating a safe environment and to allow the interaction demands a high and reliable safety solution. The basic principle for doing this is in many areas similar to the solutions used for separating humans from the robot.

The HRI are in many industries often limited to a specific area such as a shared workbench or similar. Work scenarios could include the robot performing a task alone, supporting the human in tasks like holding material or hand-guided to allow the human to perform work with higher precision in a work task such as welding or helping to lift heavy loads.

There exist today solutions to lower and even completely eliminate the risk during the HRI. Solutions used today often include the usage of speed, force monitoring, cameras, light curtains and usage of potential fields to detect an obstacle and guide the robot away [3] [5] [10].

The research in this area is constant growing and new or modified products are classified as safe and released out on the market.

One product on the market today that can make the interaction between humans and robots more flexible and easy is the SafetyEYE [11] [12]. It is more of a system solution then a single product. The system includes a 3D colour camera and software for monitoring an area. With the help of 3D technology it is possible to define multiple zones not only in a 2D plane in a cell and thereby control access to different zones depending on where in the process the robot is.
It is being more and more common to combine a number of different safety solutions into a so called safety network to guarantee the safety and get the best features from each product and solution on the market. This has the main advantage that the safety can be well adapted to the HRI. It also has the disadvantage of needing an advanced control system that needs to be configured to handle and control the signals from the network. The control system also needs to be classified and risk evaluated before taken into production.

2.4.3 New types of robots in the industry
There are a handful robot manufactures on the market that have introduced robots that are a combination of traditional industrial robots and humanoids [6] [13]. To meet the new demands in the industry, with focus on safety, easy programmability, automation, assembly work and close human interaction. These robots have been designed for [6]“Work elbow to elbow with people” in a safe way along the assembly or sorting line. To make the robots safe, they have been limitations to the speed (1 m/s or slower) and the force (80 W or less) of the robots. Even the design of the robots has been remade to remove sharp edges and hard surfaces have been equipped with plastic shell cladding to protect the human. The robot has also been equipped with a wide range of sensors, cameras, etc. to support a high level safety.

2.5 New research Safety for safe HRI
There is a lot of research on-going related to safe HRI. The research stretches from new interventions only tested in a controlled lab environment to continuing development of old technologies.

2.5.1 Wireless control and HMI
One example of continuing development is the development of wireless teach pendants and Human Machine Interfaces (HMI) devices.

Today the majority of teach pendants for robots and machines are physically connected to each other due to safety regulations. There is today on-going research of how to make the teach pendants more secure when used in wireless mode and increase the functionality [14].

Benefits with the new solutions are that the operator always can have direct access to the control for the robot at all time and more important to the emergency stop for the robot. There is also on-going research of implementing gyroscopes into the teach pendants to detect motions. This technique will allow a self-trigger of the emergency stop, if it is dropt on the floor or an unexpected motion is detected. These solutions provide the possibility to always have direct access to an emergency stop and will support increased safety if the operator is slips inside the work area or gets hit by the robot.

2.5.2 SafetyMat
Another improvement and redevelopment from existing technologies is the SafetyMat. This is a new solution under development to allow a human to enter a robot cell and stay safe [15]. The new system is using a more advanced safety mat that is equipped with pressure nodes that can be read individually. The mat is then connected to an Artificial Neural Network (ANN) for analyse of the data from the node in the mat. The ANN then calculates the orientation of a human based on the placement
of the feet on the mat. With the help of the orientation in a 2D plane a 3D model is created to represent a human. The system is then predicting a path of the human in the cell.

The system is using both on-line and off-line learning to calculate the path in the cell. The offline programming is used to define normal path patterns connected to normal work and the on-line programming is used to adapt to changes in the environment. This combination allows the system after 2-3 initial steps to predict a path and after 4 steps to have a prediction of a path for the next coming 4 steps. The path prediction is then used together with the robot to detect possible collisions resulting in redirections of the robot to avoid collisions.

2.5.3 New material for a safer robot design

Researchers in other areas like material and construction have introduced new possibilities to the development of robots. As earlier mentioned the design of a robot can be used to lower the risk of injury in a collision, with the help of removing sharp edges and applying shock absorbing material to the robot.

The research within composite material and fibre strengthened plastic has introduced good solutions to replace materials such as steel and aluminium in the robots [4] [9]. These allow the reduction of the mass of the robot and thereby the amount of energy transferred from a robot in collision. These new materials also demands less energy to be processed than steel and especially aluminium. This not only provides environmental benefits such as lowered energy consumption during production of the robot, it also reduces the energy for transports. This opens up for new actors on the market to start to develop and produce robots or parts when the need of heavy production equipment is lowered due to the new materials.

So the usage of new materials in the robotic industry opens the door for safer, lighter, improved designs and cheaper robots to the market that can both increase the safety for interaction and the way the interaction is done.

2.5.4 Potential fields

The research on potential fields has been on-going for the last one and a half decade. There exist a number of products on the market today that are used for increase safety.

The basic idea of a potential field is taken from nature, for instance a charged particle moving through a magnetic field, or a small ball rolling down a hill. The basic idea is that depending on the strength of the field, or the angle of the hill, the particle, or the ball can arrive to the source of the magnetic field the, or the bottom of the hill.

In robotics, this can be simulated in the same way, by creating an artificial potential field that will attract the robot to the goal. [16] "The basic concept of the potential field method is to fill the robot workspace with an artificial potential field in which the robot is attracted to a target position and is repulsed away from the obstacles that can be in the way". The usage of potential fields is a preferred technique due to its simplicity and logical mathematic [10] [16].

Potential fields can be used for finding, avoiding and even following an object. It is also possible to combine several potential fields to achieve a more complex behaviour such as moving to a point and at the same time avoiding an obstacle on the way.

The research around potential fields has almost exclusively been focusing on stationary robots. With some changes it is possible to use the same principle of potential
fields to guide a mobile robot in a dynamic environment [16]. This is an interesting area that can be used for both the industry and home market of robots.

An example of more fun use of the potential fields is the design of small robots that are trying to play soccer. Trying to locate the ball and at the same time avoiding colliding with each other.

2.6 Safe automatic obstacle avoidance and path generation

When studying the different techniques for avoiding collision for HRI. Either if it is the use of potential fields, the principle of the SafetyMat, vision systems or other solutions [15]. The use of safety zones, on-line and off-line programming is needed to controls the behaviour of the robot.

2.6.1 Safety zones

The usage of safety zones can be divided into two types of zones static and dynamic. Selection of type is normally done based on the desired end result. The benefit of a static approach is that it demands less 3D image sensors and can be used to replace safety solutions such as fences and light curtains. There exist already products on the market today that use static safety zones [11]. Looking at the usage of dynamic safety zones, the demand of 3D image sensors and system complicity during installation is increased due to the new demands that come with the dynamic zones. This can in many cases be motivated with the benefits of the flexibility that can be found using a dynamic system. Research in this area is mostly done with focus on mobile robots [17].

Regardless of the usage of static or dynamic safety zones, a three level zone approach to control the safety during interaction is commonly used and it is also the most prompted number of zones within the research [5] [16] [18]. The proposed definition of a three level Safety Zones can be defined in the following way.

- “Safe zone: When the distance between the operator/object and the robot is larger than a pre-imposed boundary threshold”.
- “Warning zone: When the robot could end up in a collision but the relative distance allows the execution of safe avoidance control algorithms”.
- “Danger zone: When the distance is shorter than the one associated to a lover level and an increased collision risk”.

How the robot will perform when detecting an obstacle is depending of in which safety zone it is detected and which safety method that are used in the system.

A common approach is to move the robot away to a new place or to a safe path, reduce the speed of the robot and if this is not possible stop the robot.

2.6.2 Off-line and On-line programming for automated obstacle avoidance

The method of moving away a robot to a safe point or a new safe path to avoid a collision is depending on both on-line and offline processing to guarantee a fast and safe reaction from the control system.

- The off-line processing is necessary to get a fast response time. The system contains a grid of pass-through points to help determine a possible new path adapted to the kinematic properties of the robot and the design of the work...
environment. How close to the pass-through point the new path will be is
determined, based on the safety level that is triggered.

- The on-line processing is used to track the obstacle detected in the work area
  and predict the path of it and search for new obstacles or limitations that can
  arise during the work.

The usage of pass-through points and automatically generating of new paths for a
robot, have two main drawbacks [18].

- “It cannot be easily integrated in industrial robots controls because it needs to
  replace the real-time path planning algorithm already implemented in controls”.
- “The new path followed by the robot cannot be verified and validated before
  execution since it is completely generated in run-time”.

2.7 Conclusion literature study

The literature study showed that there are many ways and aspects to take into consid-
eration before starting to increase the automation level in a factory. It also showed
that an increased level of automation is not always the way to go, to achieve a higher
production level and improved economic situation.

One approach to reach a higher level of automation for the construction indus-
tries is to aim for semi automation or station automation with robots. When these
stations have reached the target level of automation, the focus can then be directed to
the next station or process where the automation can continue.

This will allow for a responsible automation adapted to the type of products, the
economic investment, and the time invested. This will also minimize the stop time for
the production when the reconstruction only affects parts of a station or a single sta-
tion instead of the whole production line or factory.

When introducing new machines and robots to a factory with the aim of increas-
ing the automation level. The selection of the robot and how they will interact with
the operator is connected to available safety solutions on the market or even if the
safety solutions are needed. The market today provides a wide range of solutions to
ensure safety, both for separating the operator from the robot and to allow interaction
between them in different work tasks.

Looking at the research of HRI today the future will provide solutions for even
better interaction between the robot and its environment. Examples are increased
functionality, automatic avoidance of obstacles, adaption to new situations in a dy-
namic environment. This will affect the usage of both mobile and stationary robots
and how they are used in the factories.

2.8 Further work

With the literature study as a base, the further work will focus on the usage of safety
zones, robots and HRI to find a solution to allow for increased automation by intro-
ducing robots to the production line. A solution for introduction of robots at the
workstations at A-hus that can perform harmful and heavy work and at the same time
allow increase automation and a safe work environment.
3 Method

To use one main method for this work is not easy, due to the mix of tasks that needs to be performed to complete the installation, testing and analyse of proposed final solution to allow increased HRI based on safety zones. The main method used for this work is system engineering since it allows for a holistic view of the project.

3.1 Literature study

The literature study was performed with the aim of finding an answer to two questions. How to determine a suitable level of automation in the construction industries in a safe and secure way? And can a more general approach be used to increase automation in a safe and secure way for construction companies in the small house segment.

The literature study provided increased knowledge of aspect affecting the automation and safety for HRI, available safety solutions and product on the market and what might come in the future based on the current research. This helps to see new solutions for HRI to increase the production along a production line.

3.2 Analyse of hardware in the robot cell at PTC

The planned concept testing and analyse is to be performed at Production Technology Center. The Robot cell consists of the following setup of equipment:

- Robot KUKA KR 180R2500 Extra C4 FLR.
- SafetyEYE system.
- JOKAB PLUTO S46 (Safety PLC).

The different equipment and connected system in the robot cell will be tested and analysed individually to determine their advantages and disadvantages, to determine how it can be used to its best advantage and what additional knowledge that need to be acquired before the concept preparation and testing can commence.

3.3 Concept design and approach for testing

Based on the literature study, the hardware analyses and knowledge required during the education and work within the manufacturing industries. The concept will be designed to meet the aims presented in chapter 1.2 “Aim”.

The concept testing will be performed in the robot cell at PTC with the aim of proving the concept validation, tests will be performed in a fictive process.

3.4 Robot cell configuration

The configuration of the systems included in the robot cell will follow the guidelines and rules stated by the equipment manufactures for each system. System integrating will follow industrial praxis for the manufacturing industries.
3.5 Analyse of results

The results from the work and testing will be analysed in two ways. First the function for the presented concept meeting the aims stated for this work will be analysed. The second analyse will be to see if the concept is possible to implement in a safe way.
4 Work

The work will be performed with A-hus as the original owner of the problem of increasing the level of automating of the production line with robots. But the work will be performed with the aim of finding a general solution, to increase the automation of the production line with the help of introducing robots to the production line without reducing the safety for the operator.

Based on the literature study, new technologies and new safety solutions available on the market, the work is to program a robot work cell to allow for increase production with a dynamic and flexible solution. Where the HRI will be based on virtual safety zones to allow better interaction and work environment without physical limitation such as fences and gates.

4.1 Concept declaration for HRI based on safety zones in a shared work environment

The Robot cell will be programmed and analysed to prove how new safety solutions can be used to increase the HRI without lowering the safety for the human within the construction industry.

The robot cell will be programmed to allow a robot to replace monotonic and damaging work tasks such as placing of thermal bridge in the insulation of the wall modules. Meanwhile the operator can continue to work with other task on the wall module. The concept is to place a robot on the long sides of the wall to limit the demand of rebuilding of the current productions lines used in the construction industry of small houses.

The wall module will be divided into sections that will be the base for the safe HRI. The wall will be divided into two sections for this concept solution. The number of sections that are used can be adjusted to fit specific demands or changes in the production. Every section will be assigned with a warning and danger zone based on 3D technology to control the HRI.

4.1.1 Concept behaviour step by step

The interaction can be divided into 10 steps to easier explain the solution and how the system is designed to work. This example is based on condition that the robot is working in section one, when the operator is approaching the wall to start to work see Figure 1.

1. The robot is working without any limitations and on full speed on the wall module and no operator are in the close proximity to the wall.
2. The robot is working without any limitations and on full speed on the wall module and a human is approaching and triggers the first warning zone. A decision process is started to determine the action of the robot based on its current position and work task.
3. The robot is stopped and starts to retract back to the second section of the wall with reduced speed to a safe level. And the operator can start to work freely on the first section of the wall.
4. When the robot reaches the new section of the wall, it will continue with its work task at full speed until the task is completed for the section.
5. If the operator triggers the second warning zone the robot will stop work and return to its home position with the speed at a safe level.
6. The robot will wait at its home position until the operator has left the wall section.
7. The robot will then continue to work on the section with full speed until the work is completed.
8. If the operator leaves the first section, and the robot works within the second section the robot will finish working and then move to the first section to complete the started tasks in step1.
9. If the operator returns before the robot has completed its task on the first section the process will repeat in the same way presented from step two.
10. When the robot has completed its work it will return to its home position and wait for the arrival of a new wall module.

Figure 1 Illustration of proposed concept 1: The robot works on the complete wall, 2: The operator enters safety zone and the robot retracts, 3: The robot work in section two and the operator in section one on the wall, 4: The operator works on the wall and the robot waits for the operator to leave, 5: The operator has left section two and robot returns to work on section two, 6: The
4.2 Equipment

The Robot cell consists of the following setup of equipment see Figure 2.

- Robot KUKA KR 180R2500 Extra C4 FLR.
  - KR C4 operating system.
- SafetyEYE system.
  - Sensing device (3D Camera).
  - Analyse unit programmable safety and control system (PSS) SB 3047-3 ETH-2 SE.
  - SafetyEYE Configuration software v2.2.1 buildc28 (2011).
  - Indicator lamp.
- JOKAB PLUTO S46 (Safety PLC).
- Two worktables.

The robot cell is designed to support the usage of an automated guided vehicle (AGV) if needed. This equipment will not be part of the testing and analyse of HRI based on safety zones.

![Diagram of robot cell](image)

Figure 2 Layout of robot cell at PTC 1: KUKA KR 180R2500, 2: SafetyEYE system, 3: JOKAB PLUTO S46

4.3 Robot programming

The robot in the cell is a KUKA KR 180R2500 Extra C4 FLR and there by running on KUKA Robot Language (KRL), this language has many similarities in the basic programming and large differences for the advanced functions in comparison to ABB robots language RAPID that has been used as the main language during the master program.
To create a program that can reach the level of dynamic and flexibility described in the chapter “4.1 Concept declaration for HRI based on safety zones in a shared work environment”, and even the possibility to use automatic generated robot programs from Computed Aided Design (CAD) files.

The robot programming needs to be programmed, in that way that the dynamic and flexibility functions of the program is separated into two parts.

To create the dynamic part of the program, the usage of both basic and advanced functions such as sub programs, interrupts, system flags and logic functions is needed. The interrupts allow for pausing of on-going program to start a new program or function, and later continue with the paused program. The usage of flags together with logical function allows to control the behaviour of both programs and interrupts see Figure 3. The flexibility part of the program includes programme code handling changes to the robot motion and usage of automatic generated programs. This can be achieved by the using of sub programs containing only the robot motion and no other function or logic.

This results in a robot program that is easy to adapt to changes in the robot work task, and allows for a dynamic behaviour controlled by the in signals form the cell and especially from the virtual safety zones.

The robot program used to test the final solution is programmed with a low level of complexity to allow for easy changes and program traccability. A shorter and more structured program can be achieved with more time spent on programming, the usage of more advanced features and functions of the programming. Robot program see appendix 1.A “KUKA KR 180R2500 Extra programming”

Figure 3. Flowchart for main robot program and interrupts used during test.
4.4 Selection of Static or dynamic Safety Zones and SafetyEYE system configuration

The concept of static and dynamic safety zones was introduced in the literature study chapter 2.6.1 “Safety zones”. As mentioned then the technical level for equipment and programming is increased when creating a system using dynamic safety compared to a system using static safety.

The robot cell at PTC is setup to support the usage of static safety zones. The system allow for some level of dynamic, both in the programming of the SafetyEYE programmable safety and control system (SafetyEYE, PPS) that is used and by introducing an external safety PLC [19].

To allow for an increased HRI in the workstation, the usage of multiple safety zones combined into groups is needed and to be able to activate and deactivate the zone arrangements in a dynamic way. This to control the behaviour of the robot in a safe way based on both human and robot zone violations in the work station.

4.4.1 Two ways to configure the system to control the usage of zones

There are two possible solutions to program the robot cell system, communication and zone control. The first solution is to use the basic and the more advanced functionality for zone arrangement in the SafetyEYE PPS and use an external safety PLC (PLUTO) to control the usage of zones, safety decisions and the robot. The second solution is to use the basic functions in the SafetyEYE PPS and an external safety PLC (PLUTO) to control the zones, safety decisions and the robot. Both solutions have their individual advantages and disadvantages and should reach the same end result of the system behaviour for this work. This is based on the system is limited to the usage of two zone groups and taking the step from a static safety system to a low level of dynamic safety.

The principle of the system communication setup is when a zone violation is detected an out signal is sent from the SafetyEYE PPS to the external safety PLC. This is the point where the two solutions are separated.

The first solution is based on the usage of the advanced features in the SafetyEYE PPS, the zone arrangements allow for activation and deactivation of different zone arrangements from 1 up to 16 different groups. In a predefined order this makes the dynamic of this function limited to two zone arrangements, but it is well adapted if the system follows a predefined workflow.

To control witch zone arrangement that should be active the system sends out a signal for every zone violation and waits for an in signal to trigger a switch of the zone arrangements see Figure 4. This allows easier programming in the external safety PLC but limits the dynamic functionality of the system.

The second solution uses the basic function in the SafetyEYE PPS that can be seen as an advanced sensor that sends a unique signal or every zone violation to the external safety PLC. This makes that all zones are active at all time and will continue to send signals for all zone violations regardless if they are relevant or not.

This demands that the logic of which zones arrangements that should be read and affecting the signals to the robot needs to be programmed into the external safety PLC see Figure 5. This demands a more advanced PLC programming, and will require more I/O ports on the PLC to allow for unique signals to be transferred from the two PLC into the system.
The second approach was selected due to this solution allowed the work to focus on the usage of the more traditional approach of automation and PLC usage. This decision also demands less changes and configurations of the hardware in the current setup of the robot cell, which allows focusing on the programming issues and the system communication.

Figure 4 Flowchart of solution one, using the advanced features in the SafetyEYE PPS switch of zone arrangements is controlled by the external safety PLC.

Figure 5 Flowchart of solution two, using only the basic functions in the Safe-
4.5 Safety PLC programming

PLCs are a crucial part of the robot cell to have the cell working as one large unit. The current setup of hardware can be divided into three PLC systems. First we have the safety PLC system in the SafetyEYE PPS equipment, the second is the safety PLC system in the KUKA robot and finally the external Safety PLC from JOKAB PLUTO S46. Based on the decision to use the second solution presented in the previous sub chapter 4.4.1 “Two ways to configure the system to control the usage of zones”.

The main work is to configure the external Safety PLC to control the zone arrangements and the out signals to the robot. This work is done through the Pluto Manager software and is performed in leader and function block programming. The SafetyEYE PPS PLC is programmed through the system interfaces and consists of connecting the systems in- and out signals to the defined safety zones and how to handle the feedback from the other systems in the cell.
5 System evaluation

Concept testing and validation will be performed in a fictive process, designed to represent a robot mounted along the long side of a wall module, working with marking out points.

The robot program used for testing is written to consider the workspace of the robot and the size of the walls built at A-hus. The program performs a fictive work that can be compared to nailing, but with a smaller distance then would be used in the real industries, this to achieve a program that have more tasks and takes longer time, to allow for more time to test and evaluate at each simulation run.

The selection of how the zones are arranged for the test, is based on the idea that a robot is mounted on a rail to be able to work on the complete wall, that can vary in size up to 8 x 2.45 m see Figure 6.

The wall is divided into two or three parts along its length to allow for smaller robot programs and a more flexible usage of the safety zones. This will allow the work areas on the wall to be accessed better and increase the HRI further see Figure 7.

Figure 6 Illustration of possible work cell design whit robot mounted on a rail to be able to work on the complete wall.
5.1 Dimension and placing of safety zones

The SafetyEYE system comes with rules of how the safety zones should be dimensioned to meet the requirements from ISO regulations. The equation \( S = K \times (t_1 + t_2) + C + Z_g \) where \( S \) = Minimum distance of the warning and danger zones, \( K \) = to the speed of object requiring detection (1600 mm/s), \( t_1 \) = SafetyEYE reaction time connected to the usage of multiple evaluation, \( t_2 \) = machine overrun time (KR 180R2500 Extra = 939ms [20]), \( C \) = based on type and resolution of the camera (850mm), \( Z \) = compensation of SafetyEYE tolerance based on height of the mounting of the camera for the floor [19]. This rule can be used for designing the warning and danger zone at the edges of the wall, but will be insufficient to use for the zones on the wall, in this case a safety evaluation is needed to design the zone dimensions. Using the equation for zone calculation, gives the wide of 2.6m for the warning zone and 0.44m for the danger zone.

5.2 Zone arrangement used during test

The zone arrangement used during testing was selected to represent the edge of a wall module to both have the short and the long side of the wall. To have a representation of both sides of the wall allows for analyse of how to limit the access and control the behaviour of the robot based on the usage of two or more zone arrangement along the length of the wall module. During the system test 3 zone arrangements were used, two arrangements used to control the access to the wall based on the proposed solu-
tion and the final to limit access to the robot cell to increase safety during test see Figure 8.

- Zone arrangement 1
  - Danger zone (Red) – Stops the robot if triggered.
  - Warning zone (Yellow) – Starts interrupt 1 if triggered

- Zone arrangement 2
  - Danger zone (Red) – Stops the robot if triggered.
  - Warning zone (Yellow) – Starts interrupt 2 if triggered

- Zone arrangement 3
  - Danger zone (Red) – Used to limit access to the robot cell during test and will stop the robot if triggered.

Figure 8 Illustration of safety zones setup during test. 1: Zone arrangement one, 2: Zone arrangement two

5.3 Concept test on different materials and surfaces.

The main function test was performed at the robot cell where a workbench represented the work area on a wall module, to allow a better visibility and access to the test equipment during the test. After the main testing was completed, supplementary testing started. These tests aimed to verify the systems functionality on a mix of materials used within the construction industry to determine how these materials affect the camera and the zone placement. The material used in the testing is fiberglass insulation, wood, and hand tools such as hammer, screwdrivers, pincers etc.
6 Results and discussion

The presented concept of a dynamic system that allows increased HRI based on safety zones in a shared work environment has been tested and verified in the robot cell.

By combining the information collected during the work with configuring and programming the robot cell, the information collected and the results from the concept testing and system validation. A number of problems and limitations with the equipment, programming and system safety were detected. These results will be discussed in the following sub chapters.

6.1 Equipment

Looking at the design and the component in the robot cell, there are some disadvantages that come from the mixing of products from different suppliers see chapter 4.2 “Equipment” for a complete list of equipment. The SafetyEYE, the Pluto safety PLC and the KUKA robot support the usage of safety fieldbus communication, but all of them support different versions preventing this communication method to be used. This limits the communication in the system to the physical number of I/O ports on the Safety PLCs. For the configuration that was used during the test this was not a large problem, but if the system would be built out to cover a full size wall module and an increased number of zone arrangements, this will be a problem.

The positioning of the SafetyEYE camera and the Robot was already fixed when this project was started. This have created some problems with the fitting of the safety zones within the area that can be monitored by the camera, this have not had any effect on the result of the testing. Only raised concerns of possible problems of applying this concept to a full size wall module with the required zones needed for creating a safe work environment.

6.2 PLC Signals

The programming of the Safety PLC used during tests, uses a mix of failsafe and not failsafe signal, it would be preferable to use only failsafe signals. It also contains the reuse of some signals from the robot to the external Safety PLC. In a system in production these signals should be separated, together with the usage of only failsafe signals to create a better traceability and safer control system.

The usage of a mix of failsafe and not failsafe signal is based on the testing of the suggested concept and to minimize the rewiring of the robot cell.

6.3 PLC Programming

The decision to use the SafetyEYE PPS as an advanced sensor and to program all logic in to the external safety PLC describe in chapter 4.4.1 “Two ways to configure the system to control the usage of zones”.

This approach was during the system configuration and the testing identified as a possible source of errors that could affect the safety of the system. The software for the
programing the PLC only allows for verification of the entered program code is correct, leaving the verification of the function of the program to the programmer. The function and the safety of the program need to be verified through system testing and verification of the code based on predefined workflows and physical testing with the equipment.

### 6.4 Limitation in the interrupt functionality

To create a dynamic and flexible system the robot program is separated into two parts, a dynamic and a flexible part, presented in chapter 4.3 “Robot”. This requires the usage of interrupts.

The design of the interrupts in KRL demands that the robot is at the exact position at the end of the interrupt where the robot was when the interrupt was started. Interrupts cannot be interrupted before the task is completed. This creates a safety problem to the system. An explanation of the problem can be described in the following steps.

1. The operator enters a zone and triggers an interrupt in the robot program.
2. The robot stores its current position and retracts to its waiting position.
3. The operator leaves the zone and allows the robot to leave its waiting position.
4. The robot moves back to the point where the interrupt was triggered.
5. During the time the robot is moving back to the point where the interrupt was triggered, the operator re-enters the zone.
6. In this case the robot will continue to move towards the operator and not stop to retract.
7. When the interrupt has been ended the system will trigger the interrupt again if the operator have remained in the zone.

This will allow the robot to re-enter an area where the operator is working and create a safety violation if not attended to. In the conducted test the robot is stopped because of a safety stop programmed in the safety PLC. The safety stop uses the triggering of the second safety zone at the middle of the work area, to stop the robot from re-entering the area where the operator is located. This is a problem connected to the usage of a KUKA robot. If the result would be the same for another brand of robots is at this point unknown.

Problems connected to interrupts and incremental movement in combinations with program looping also occurred, resulting in the robot losing count of its position. This is a very specific problem that can be avoided by defining every point that the robot needs to pass by with its full coordinates. But it did raise the important fact, that the system can’t work without a robot program that is well written and defined to be classified as safe.

### 6.5 Camera system sensitivity/limitations

The camera used in the SafetyEYE system is very sensitive for changes in the light conditions and pollution in the air, this have resulted in the detection of problems with the camera.
6.5.1 Changes to light conditions

During testing the cameras sensitivity to light changes have been verified and resulted in the need to reset the camera to be calibrated to the new light conditions that occurred. This is not a safety issue since the system stops and triggers an error message referring to a problem with the light. This is more of a problem connected to the stability of the system solution, level of automation and system up-time.

6.5.2 Zone violations true disturbance

Another problem that occurred during the testing was that the camera registered violations to the safety zones without there being any actual physical violations of the zone. This is because of disturbances from reflections of light on equipment, things on the floor and the floor itself. The problem with reflections to the camera can be reduced with the help of "multiple evaluation", this is a function that can be used to change the number of violations detected before the system triggers. The disadvantage of this function is that it increases the reaction time of the system for a zone violation and thereby increasing the size of the danger zone.

The safety zones need to be placed at max 300mm from the floor to follow ISO regulations. This has been shown to be a problem in some areas, due to the problems with the reflections of equipment and floors that created false zone violations.

6.5.3 Different materials and surfaces

As mentioned in the paragraph above, disturbance through reflection was a problem, when placing the safety zones during the testing. The level of this problem is strongly connected to what material and what surface is located below the safety zone.

If the material is light absorbing or a matte colour, the level of disturbance will be lower compared to material of more reflecting nature. This result in the safety zones can be placed closer to a surface without triggering safety zone violation.

During testing the distance between the floor and the safety zone needed to be placed at maximum allowed level of 300 mm to minimize disturbance due to the surface of the floor. And the distance between the safety zone and the wall module of wood and fiberglass insulation could be set to 100-150 0m without triggering any violations.

The different materials also affected how tools that were left on the surface did triggering the safety zone through disturbance. Testing showed that the light absorbing or matte colour materials such as fiberglass insulation allowed for a shorter distance compared to the floor without triggering the safety zones.

6.6 Safety

Looking at the safety in the tested concept, the safety can be divided into two parts the first the safety around the wall module and the robot, the second the shared work space on the wall modules.

Looking at the safety for approaching the wall module the SafetyEYE system can be used as it was designed for, controlling the access to the robots workspace. This makes the safety setup and the zone design at this point very easy if the guidelines from the manufacturer are followed, see chapter 5.1 "Dimension and placing of safety zones".
The main concern at this step is that the system is not completely used as it was attended. The robot is stopped but only to start immediate afterwards, but in this case to move away from the operator.

At this point there are two approaches possible with some differences in the safety. The first approach allows the robot to retract at the triggering of the warning zone and after the retraction is finalised the operator is allowed to enter to the work area. If not meet the system is stopped. The second approach allows the operator to enter the workspace at the same time as the robot moves away after the triggering of the warning zone without a stopping the system.

The first solution is the most secure and allows the full usage of the SafetyEYE safety setup. The different safety zones can then be used to block an errors in the robot heavier.

The second solution allows the operator to approach the robot and even touch it during the retraction motion. This allows the operator to start to work without waiting for the robot to finish the retraction. This would not be a problem if the robot runs on a low speed and guaranteed that the robot not breaks the programmed behaviour. The solution used during tests was the second approach and used control signals from both the robot and the SafetyEYE to stop the robot if the retractions are interrupted in any way or an error would occur.

Looking at the second part of the safety arrangement on the wall, the safety gets more complex. The SafetyEYE system base design and guidelines for safety can no longer be applied, when the operator is within the work space of the robot and thereby can be reached by the robot. In this case the safety system needs to be designed to block the access between the robot and the operator. Here comes the aspect of the camera limitations described in chapter 6.5 “Camera system sensitivity/limitations” and especially the problem of distance from a surface to the bottom of a safety zone. In this case the system allows for a distance of 100-150 mm. This allows for the passing of a hand and an arm under the zone if it rests to the base surface. To reduce the safety risk the warning and the danger zone need to be design to be larger the length of an arm to guarantee the detection and triggering of the safety system.

Additional to this the design of the danger zone can be reused in length based on the reduction of K in the equation for designing zones see chapter 5.1 “Dimension and placing of safety zones”. K represents the speed a human can enter a zone walking on the floor. In this case the human cannot move directly into the zone, when the wall module is at a level of 800-900 mm from the floor based on the wall cladding and insulation is added to the wall or not. This makes the requirement of the safety zones to be both larger and smaller depending which aspects are concerned. Looking at the wall the possibility of reaching in under the safety zone is the largest problem, and therefore is the aspect of the reduction of the zone based on a smaller K is not relevant. If the work height would change the outcome of the zones design might have to be change. This explains why a new safety analyses is required every time the cell setup is changed.

At close HRI the need of redundancy to the safety system is very important, due to the fact that a failure in the programming or the system, won’t allow the operator to move away from the robot in time if something happens due to the position of the operator when triggering this inner safety zones.

It can also be possible to implement additional sensors or safety stops to the system to complement the SafetyEYE system zone monitoring, in the shared work space on the wall module and to add an additional level of safety.
7 Conclusion

With the main focus on the following aims.

- Find a solution to increase automation and production without impact on the quality of the product.
- Find a safe solution for HRI in a shared environment,
- Usage of existing equipment on the market
- Find a solution that can be applied to the industry today

A literature study was performed to determine what safety solutions existed for robots, on the market and in what direction the research was heading. The literature study showed that a dynamic and flexible solution based on the usage of virtual zones was the way to go. The usage of 3D camera system with some modifications seemed to be the preferred solution to use to create the virtual zones.

With his information and the aims a concept solution was designed to focus on HRI based on safety zones in a shared work environment. Through testing and validation the presented concepts have proved to work.

The concept includes a robot to allow for increased automation and to improve the quality of work. Additional equipment used was a safety system based on a 3D camera called SafetyEYE designed to allow the removal of physical obstacles such as fences [11]. This system was configured to allow a dynamic HRI in a shared work environment, where the robot responds to the interaction of the operator based on the safety requirements and the triggering of safety zones, to ensure a safe work environment.

The presented safety solution is slightly more costly than the usage of fences or other traditional safety solution, but allows the system to operate without changing the current layout of the production line and to limit access to the work area.

7.1 Future Work and Research

The concept tested is focusing on the interaction along one part of a wall module declared in the introduction to chapter 5 “System evaluation”. A continuation of this project could be to investigate how to allow the robot to move along the fare side of the wall modules to allow interaction not only over the wall, but also along the wall. There is also an interest to investigate if the camera sensitivity towards light changes can be reduced in any way.

7.2 Critical Discussion

Based on the thesis work and how it initially was planned and how the work has proceeded, there are some changes that could be made. The changes are minor compared to the entire work. That the work has proceeded in the way it has, is connected to that the initial literature study was performed before the main thesis work was started. This gave a clear idea from the start of the project on what needed to be done, and allowed to set the time schedule with room for some delays if needed.
The two largest changes that could have been made to the work are the following.

- How to approach the KRL and the robot. It would have been better to approach the program based on how the program design learned during work with the ABB robots. Instead of trying to understand how the KRL was using predefined motion code and folder functions at the teach pendant. This could have saved both time and frustration.

- How the testing was planned. The concept testing and validation was initially preformed with the goal to verify the elimination of problems, detected during the work and mapping of the equipment. A better way might have been to start with the testing of the function of the concept and then trying to eliminate problems detected during this testing. This could allow for the elimination of more problems faster and save preparation time for the testing in the robot cell.

Apart from these two things there are other changes that could have been done to the work based on the knowledge acquired during the work. This is harder to list since it more connected to level of knowledge of the equipment and technology acquired during the work then to planning and implementation.

### 7.3 Generalization of the result

The presented solution aimed to be a general solution that could be used within the construction industry and not only for A-hus which was the original owner of the problem.

The presented solution of a HRI based on safety zones in a shared work environment can be used not only in the construction industry, but in all industries with manufacturing alongside production lines with large components. Two limitations to this solution are that the system needs a relatively dust free environment, good and constant lighting to reach a high up-time.

The usage of the solution in a production environment will require a safety analyse of the specific environment and the production it is planned to be used in. The safety cannot be generalised and needs to be a part of the installation and test process for new equipment.
8 References


A. KUKA KR 180R2500 Extra programming

Robot program used during test and validation of proposed concept.

```
DEF THESIS_WORK_SVANTE()
INI ;Folder

{ BASISTECH INI ; FOLDER
  GLOBAL INTERRUPT DECL 3 WHEN $STOPMESS==TRUE DO IR_STOPM( )
  INTERRUPT ON 3
  BAS (#INITMOV, 0 )
  USER INI ; FOLDER
  GLOBAL INTERRUPT DECL 1 WHEN $IN[4] == TRUE DO IR_2()
  GLOBAL INTERRUPT DECL 2 WHEN $IN[3] == TRUE DO IR_1()

$ADVANCE=0 ; Defines the number of steps the robot calculates the path ahead.
$VEL_CP=0.2 ; Defines the speed in m/s for LIN motion if nothing else is defined.
$APO_CDIS=5 ; Defines pass-through point for PTP and LIN motion in mm to call in programme C_DIS.
$TOOL=TOOL_DATA[1]
$FLAG[1]=FALSE ; Resets Flag1
$FLAG[2]=FALSE ; Resets Flag2

PTP HOME Vel=15 % DEFAULT ;FOLDER
  $BWDSTART=FALSE
  PDAT_ACT=$DEFAULT
  PDAT_ACT=$HOME
  BAS(#PTP_PARAMS,15)
  $H_POS=XHOME

PTP {X 1100,Y 0,Z 1200,A 75,B 0,C 180}
INTERRUPT ON 1
INTERRUPT ON 2

WALL_PART_1()
WALL_PART_2()
ENDIF
PTP {X 1100,Y 0,Z 1200,A 75,B 0,C 180}

PTP HOME Vel=15 % DEFAULT ;FOLDER
  $BWDSTART=FALSE
  PDAT_ACT=$DEFAULT
  PDAT_ACT=$HOME
  BAS(#PTP_PARAMS,15)
  $H_POS=XHOME

END
```

;------------------------------------------
DEF WALL_PART_1()
; Start point
Degree Project for Master of Science with specialization in Robotics

Short descriptive title of the work: KUKA KR 180R2500 Extra programming

LIN {X 2660, Y 250, Z 580, A 25, B 0, C 180}
; 1 ROW
LIN {X 2660, Y 250, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2660, Y 250, Z 570, A 25, B 0, C 180}
LIN {X 2660, Y 250, Z 580, A 25, B 0, C 180}
LIN {X 2660, Y 150, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2660, Y 150, Z 570, A 25, B 0, C 180}
LIN {X 2660, Y 150, Z 580, A 25, B 0, C 180}
LIN {X 2660, Y 50, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2660, Y 50, Z 570, A 25, B 0, C 180}
LIN {X 2660, Y 50, Z 580, A 25, B 0, C 180}
LIN {X 2660, Y -50, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2660, Y -50, Z 570, A 25, B 0, C 180}
LIN {X 2660, Y -50, Z 580, A 25, B 0, C 180}
LIN {X 2660, Y -150, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2660, Y -150, Z 570, A 25, B 0, C 180}
LIN {X 2660, Y -150, Z 580, A 25, B 0, C 180}
LIN {X 2660, Y -250, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2660, Y -250, Z 570, A 25, B 0, C 180}
LIN {X 2660, Y -250, Z 580, A 25, B 0, C 180}
; 2 ROW
LIN {X 2260, Y 250, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2260, Y 250, Z 570, A 25, B 0, C 180}
LIN {X 2260, Y 250, Z 580, A 25, B 0, C 180}
LIN {X 2260, Y 150, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2260, Y 150, Z 570, A 25, B 0, C 180}
LIN {X 2260, Y 150, Z 580, A 25, B 0, C 180}
LIN {X 2260, Y 50, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2260, Y 50, Z 570, A 25, B 0, C 180}
LIN {X 2260, Y 50, Z 580, A 25, B 0, C 180}
LIN {X 2260, Y -50, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2260, Y -50, Z 570, A 25, B 0, C 180}
LIN {X 2260, Y -50, Z 580, A 25, B 0, C 180}
LIN {X 2260, Y -150, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2260, Y -150, Z 570, A 25, B 0, C 180}
LIN {X 2260, Y -150, Z 580, A 25, B 0, C 180}
LIN {X 2260, Y -250, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 2260, Y -250, Z 570, A 25, B 0, C 180}
LIN {X 2260, Y -250, Z 580, A 25, B 0, C 180}

$FLAG[1]=TRUE ;FLAG WALL_PART_1 IS COMPLETED
END

;-----------------------------------------------
DEF WALL_PART_2()
; Start point
LIN {X 1580, Y 250, Z 580, A 25, B 0, C 180}
; 1 row
LIN {X 1580, Y 250, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 1580, Y 250, Z 570, A 25, B 0, C 180}
LIN {X 1580, Y 250, Z 580, A 25, B 0, C 180}
LIN {X 1580, Y 150, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 1580, Y 150, Z 570, A 25, B 0, C 180}
LIN {X 1580, Y 150, Z 580, A 25, B 0, C 180}
LIN {X 1580, Y 50, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 1580, Y 50, Z 570, A 25, B 0, C 180}
LIN {X 1580, Y 50, Z 580, A 25, B 0, C 180}
LIN {X 1580, Y -50, Z 580, A 25, B 0, C 180} C_DIS
LIN {X 1580, Y -50, Z 570, A 25, B 0, C 180}
LIN {X 1580, Y -50, Z 580, A 25, B 0, C 180}
LIN {X 1580,Y -150,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1580,Y -150,Z 570,A 25,B 0,C 180}
LIN {X 1580,Y -150,Z 580,A 25,B 0,C 180}
LIN {X 1580,Y -250,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1580,Y -250,Z 570,A 25,B 0,C 180}
LIN {X 1580,Y -250,Z 580,A 25,B 0,C 180}
; 2 row
LIN {X 1180,Y 250,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1180,Y 250,Z 570,A 25,B 0,C 180}
LIN {X 1180,Y 250,Z 580,A 25,B 0,C 180}
LIN {X 1180,Y 150,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1180,Y 150,Z 570,A 25,B 0,C 180}
LIN {X 1180,Y 150,Z 580,A 25,B 0,C 180}
LIN {X 1180,Y 50,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1180,Y 50,Z 570,A 25,B 0,C 180}
LIN {X 1180,Y 50,Z 580,A 25,B 0,C 180}
LIN {X 1180,Y -50,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1180,Y -50,Z 570,A 25,B 0,C 180}
LIN {X 1180,Y -50,Z 580,A 25,B 0,C 180}
LIN {X 1180,Y -150,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1180,Y -150,Z 570,A 25,B 0,C 180}
LIN {X 1180,Y -150,Z 580,A 25,B 0,C 180}
LIN {X 1180,Y -250,Z 580,A 25,B 0,C 180} C_DIS
LIN {X 1180,Y -250,Z 570,A 25,B 0,C 180}
LIN {X 1180,Y -250,Z 580,A 25,B 0,C 180}

$FLAG[2]=TRUE ;FLAG WALL_PART_2 IS COMPLETED
END
;---------.-------------------.
DEF WAIT_POSE()
  PTP {X 1110,Y 0,Z 1200,A 75,B 0,C 180}
END
;---------.-------------------.
DEF IR_1() ;TRIGGERED BY I3 (SIGNAL FROM SAFETY PLC).
DECL POS IP1 ;DECLARATION OF STRUCT OF TYPE POS
  BRAKE
IP1=$POS_RET
SOUT[3]=TRUE
PTP {X 1536,Y 0,Z 700,A 25,B 0,C 180}; Robot retracts.
  WALL_PART_2()
SOUT[4]=TRUE
  WAIT_POSE()
  WAIT FOR ($IN[3]==FALSE)
ELSE
  SOUT[4]=TRUE
  WAIT_POSE()
  WAIT FOR ($IN[3]==FALSE)
ENDIF
LIN IP1; Return to breakpoint of Interrupt
RETURN
END
;---------.-------------------.
DEF IR_2() ;TRIGGERED BY I4 (SIGNAL FROM SAFETY PLC).
DECL POS IP2 ;DECLARATION OF STRUCT OF TYPE POS
  BRAKE
IP2=$POS_INT

Appendix A:3
$OUT[5]=TRUE
WAIT_POSF()
WAIT FOR ($IN[4]==FALSE)
LIN IP2 ; Return to breakpoint of Interrupt
RETURN
END
;-------------------------------------------------------------------------------