Master Degree Project

UNIVERSITY OF SKÖVDE

HUMAN-ROBOT COLLABORATION ON AN ASSEMBLY STATION WITH THE ABILITY TO WORK REVERSE

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Abstract

The automation level of today’s industries is categorized as high. Some specific areas cannot be fully automated, such as manual assembly operations. Manual assembly stations often require high flexibility due to variation in products and product types, and some operations also require human finesse for conducting the operations. A collaborative robot is produced to facilitate for the worker during operations and tasks, which can be categorized as non-ergonomically and repetitive. The technical specification for the collaborative robots is not yet fully developed, and therefore it might be hard to create a safe work environment.

Design and creation is the research strategy used for the project, much due to the aim of creating something physical. The project aims to establish a demonstrator, and introduce a collaborative robot, a UR5 for human-robot collaboration for a manual assembly operations with the ability to work reverse. The fictional workflows implemented in the demonstrator are established with influence from real manual assembly operations and parts included in an engine of a truck. The widgets identified and included in the workflows are created and 3D-printed. The main goal for the project is to establish a collaboration between the worker and the robot and create a baseline for a future safety evaluation conducted on the demonstrator. The project included identification of equipment and widgets necessary, the layout of the demonstrator, workflow establishment for both assembly and disassembly, together with the configuration of the equipment and programming of the collaborative robot.

Safety standards concerning robots and collaborative robots, together with the technical specification not yet fully developed, worked as a base during the establishment of the workflow, configuration of the equipment, and programming of the robot.

The established workflow can work both for assembly and disassembly. The workflow includes tasks that are performed separately, together, and simultaneous on the same workpiece. Experiments have been conducted on the established workflows, and observations conducted on the tasks performed. Aspects, such as time consumption for individual tasks, risk identification of quasi-static and transient contacts, and gripper position have been included during the observation.

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Skövde, July 2020

My Andersson

Certificate of Authenticity

Submitted by My Andersson to the University of Skövde as a Master Degree Thesis at the School of Engineering.

I certify that all material in this Master Thesis Project which is not my own work has been properly referenced.

Signature.

My Andersson

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1 Introduction

This section introduces the problem to be addressed during the project together, with the purpose and objectives. Delimitations set for the project are along with the key aspects and the contributions that the project regards introduced.

1.1 Problem description

The level of automation in today's manufacturing process is, in many areas, categorized to be very high. Those areas are preferably those whose work tasks require more strength and are monotonous to perform. Hazardous environments, according to Groover (2015), are also one area where fully automated processes are preferred due to safety for the workers and time-consuming aspects. There are some cases or areas according to Li et al. (2019) that are hard to automate fully, e.g., work tasks that require human abilities such as flexibility, hard to reach jobs, and finesse. Manual assembly and disassembly are one of these areas where the human skills are hard to replace with a traditional industry robot or an automated process. A struggle that the new era, industry 4.0, faces, according to Cohen, Naseraldin, Chaudhuri and Pilati (2019), is the requirement for flexibility in production. The flexibility can come in different shapes, all from a high amount of variants to variations in features in one product. Flexibility in manual assembly and disassembly operations is more than flexibility in a specific task. It is also a variation in products and features in one.

For many producing companies, the ability to create an environment where disassembly is possible in the production to rework or reuse parts can be a challenging task. According to Li et al. (2019), disassembly can often be performed either in a manual way isolated in a specific area or by a robot. They also conclude that these tasks can be un-ergonomic and repetitive for the worker, which can cause RSI, which can lead to sick leaves and permanent disorders. Human-robot collaboration is one of the most promising approaches in order to facilitate the work performed on these stations.

Collaborative robots are manufactured to work together with humans. By including a collaborative robot, Mateus et al. (2019), states that they can facilitate tasks that can be non-ergonomic and repetitive. Due to the hard safety regulations and the fact that these regulations are not fully developed, the difficulty lies in work to establish a safe environment. The robots are designed to work without causing harm to the worker. They are designed without sharp edges and possess abilities such as the stop function when the worker can push the robot in another direction. Due to the design and the different skills it possesses, the collaborative robots are hard to categorize as safe for implementation in the industry. This is supported in the literature where it is stated that the biggest challenges for large scale implementation of human-robot collaboration applications are safety, design methods, and intuitive interfaces (Villani, Pini, Leali and Secchi, 2018). To ensure a safe working environment standards exist that need to be met to be able to ensure the safety of every unique situation in the industry.

1.2 Key aspects and the contribution to the addressed field

The implementation of collaborative robots is today limited in the industry, according to Liu et al. (2019), especially for disassembly operation. Many collaborative robots work on shallower levels of collaboration, which can be categorized as a fenceless robot working more or less by themselves. By including human-robot collaboration for manual assembly and disassembly operations, the possibility to combine strengths from both the human and the robot can be beneficial.

The purpose of disassembly operations is to remanufacture products, reuse or change malfunctioning parts and recycle materials. Liu et al. (2019) state that an improvement of the current practice of product remanufacturing, the potential of reusing parts, and increased recycling level, ecological sustainability will improve.

The project utilizes a recent design method for human-robot collaboration application development by Land et al. (2020), which in this project will be evaluated in terms of suitability with regards to assembly- and disassembly of the same product.

The project creates the possibilities for both assembly- and disassembly mode to utilize the same equipment and location. The demonstrator created is part of a production line that is intended to work in both modes. By including the surrounding environment, instead of creating a demonstrator totally isolated, the flow of widgets is included, and the demonstrator ready for collaboration.

1.3 Purpose

The primary purpose of the project is to create a human-robot collaboration demonstrator which contains typical manual assembly elements. This means that the elements performed on the demonstrator is divided between the collaborative robot and the worker. The demonstrator created will work in two modes, assembly and disassembly.

1.4 Objectives

The main objective is to investigate and evaluate the possibilities of using human-robot collaboration for manual- assembly and disassembly performed on the same demonstrator. The project also includes creating a physical demonstrator where human-robot collaboration can be performed and evaluated. Sub objectives that are necessary for the project to achieve in order to establish the main goal are:

1. Identify common manual assembly tasks in the industry, subject to human-robot collaboration.
2. Define products with inspiration from the industry and Volvo GTO, subjected to human-robot collaboration. These products should be defined so that parallel operation and hand guiding can be beneficial.
3. For given products define:
    a. Layout and equipment suitable to produce given products
    b. Operations needed to produce given products.
4. Classify operations in accordance to human-robot collaboration and divide operation between worker and the collaborative robot.
5. Create a demonstrator that includes the possibility to work in two modes, assembly and disassembly.
6. Include general safety aspects while creating the demonstrator, to establish a baseline for a future safety evaluation. This includes aspects, such as the layout of the demonstrator, configuration of equipment, and programming of the collaborating robot.

1.5 Delimitation

The focus of the project is on human-robot collaboration for a specific operation on one demonstrator. The process performed on the demonstrator consists of both assembly and disassembly of the operation. Delimitations for the project are:

- The demonstrator created is seen as a stand-alone machine, which means that the safety aspects and security measures shall include the specific demonstrator. The UR5-robot, the work environment where the assembly takes place, the robot tool, and the widgets needed for the operation are included in the machine.
- The demonstrator created shall not include any type of camera or vision system for the identification of objects or positions of the widgets.
- The demonstrator created shall take into account requirements from two surrounding stations. The first station is connected via a conveyor, which transports the widgets to the demonstrator. The second station is the engine, which is the final location for the assembly. During the disassembly mode, these stations shall have the reversed function.

2 Sustainable development

Social sustainability, ecological sustainability, and economic sustainability are included in the overall term, sustainable development, see Figure 1. There is a well-known and expressed quote used to define sustainable development, "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Cassen, 1987, s 41). The definition aims to express, according to Gulliksson & Holmgren (2018), the connection between the three areas. Equality among humans and their rights, only use the surplus of the resources and not affect the equality among humans and the environment in order to increase the economic aspects.

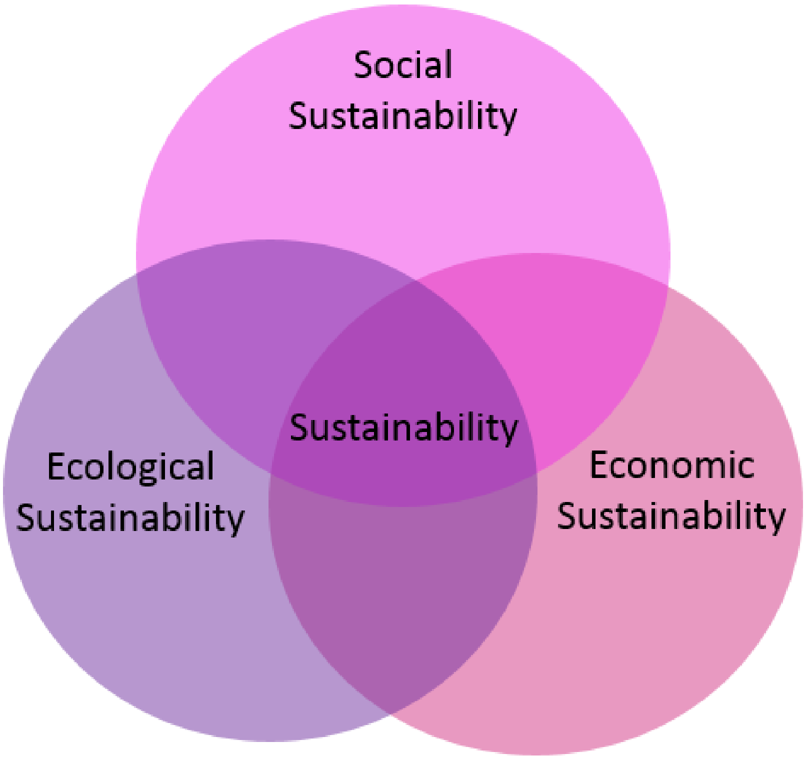

Figure 1: Connection between the three sustainability perspectives

According to Gulliksson & Holmgren (2018) are four main capitals described when it comes to sustainable development and the resources of society real, nature, human, and social. As their names may reveal, real capital is associated with creations made by humans, natural capital is associated with resources, human capital is associated with abilities, and social capital is associated with how people should act and interfere within a society.

2.1 Social sustainability

Both physical and psychological aspects are, according to Gulliksson & Holmgren (2018), included in the term social sustainability. The importance of equal rights and equality is in the main focus. Good working conditions are essential in order to strengthen social sustainability. This includes working to minimize or eliminate stress-related illness or non-ergonomically work tasks. Dahlin (2014) explains that in general terms, social sustainability is aspects such as freedom, education, work environment, and health.

2.2 Ecological sustainability

Nature and its different ecosystems are included in ecological sustainability, according to Gulliksson & Holmgren (2018). The authors also express the importance of avoiding overexploiting the environment and its resources.

2.3 Economic sustainability

In order to reach economic sustainability, according to Gulliksson & Holmgren (2018), finite resources should not be overexploited; the aim is to locate a balance between what is manufactured and what is consumed. The term economic sustainability should not increase if it affects the other two terms, social and ecological, negative.

2.4 General connections to the project

The different sustainability aspects are strongly connected to the project. The social sustainability aspect regards several factors, such as ergonomic and improper working conditions. The ergonomic factor needs to be taken into account while developing workplaces and working methods. If this is not done properly, the outcome can be devastating. Permanent disorders and RSI can be caused due to tasks, such as heavy lifting and repetitive work. Sick leaves can be a permanent factor if these aspects are not taken into account. Improper working conditions can be stress-related, which can cause accidents and also lead to unavoidable mistakes connected to machines and parts. The ecological sustainability aspect regards factors, such as the inability to rework and reuse parts and materials. In order to minimize the usage of environmental resources, the importance lies in avoiding defects and increasing the ability for rework and reuse of products and materials. Energy consumption and exploiting of resources can decrease if these aspects are taken into account. Economic sustainability should not increase on behalf of the other aspects. An incensement of the economic factor can preferably be by increase the productivity based on better working conditions together with avoidance of mistakes leading to defected parts.

The creation and implementation of the demonstrator can be performed with these aspects in mind. A collaborative robot is not developed to take jobs from workers. They are developed to facilitate workers. By reducing the load and repetitive tasks for the worker by including a collaborative robot, both stress-related aspects can be avoided, and the ergonomic factor can be increased. By working to avoid defects, the economic factor will increase. A disassembly mode will increase the opportunity for remanufacturing, reuse parts, and recycling of material. A reversed mode can also utilize the same equipment and tools, and the mode will increase the ecological aspect.

3 Frame of references

This section describes literature regarding LEAN, manual assembly, organizations related to standards, industrial robots, and human-robot collaboration. The LEAN concept is introduced together with standardizing work, which can be seen as a base to establish human-robot collaboration. Manual assembly is introduced to highlight the flexibility that might be required to perform certain operations. The organizations that develop the standards and standards in relation to collaborative robots are introduced, which are required to be followed to establish a safe work environment with a collaborative robot. Industrial robots, together with collaborative robots, are introduced to highlight their attributes and their differences. General information of collaborative robots, levels of collaboration, and the four collaborative safe-guard modes are introduced in the section.

3.1 The LEAN concept and standardize work

Toyota Production System (TPS) is a concept and a philosophy where the elimination of wastes lies in focus. LEAN is inspired and established based on the TPS concept. Stability and Robustness are the foundation in the LEAN concept, which are an essential part of achieving for a company in order to work to obtain a LEAN way of working. To obtain a LEAN way of working, every company needs to customize the concept to fit their organization or company, because they all vary. Quality is an important factor that focuses on ensuring quality in production in a way that makes it nearly impossible to perform a task incorrectly. Abnormalities can appear everywhere, and an important part is to make them visible in order to solve them.

The concept, standardize work, can be defined as the most optimal, self-explained, and stable way to perform work tasks, also referred to as work elements. In order to acknowledge and identify the most optimal way of performing the elements, thorough investigations and tests need to be performed before standards can be established or updated according to Bicheno et al. (2013). A change in work tasks needs to be categorized as an improvement before a standard should be updated or changed. Standardize work is not classified as statically can be applied to every level in a company, and the process to establish and identify them is iterative. As the name of the concept may reveal, to establish a standard, it is necessary to create instructions for the work elements. Bicheno et al. (2013) point out that an important aspect when it comes to standardizing work is to manage everyone who performs the elements to follow the instructions and work to identify improvements for the standards.

If a concept such as standardized work is not included in the workplace, can the lack of improvement work and the performance suffer. Working with collaborative robots requires that the tasks that are performed are specified, and information regarding the workflow and training are included.

3.2 Manual assembly

Groover (2015) states that manual assembly can be defined as manual work tasks that one or more operators perform in order to create a product or a sub-product by combining parts. The author also concludes that in many cases, the tasks or elements that the workers perform requires skills that are hard and costly to automate. An example can be tasks related to cabling and access to areas that are categorized as hard to reach areas. Another essential aspect when it comes to manual assembly is the flexibility that the station work performed might require. When it comes to efficiency, flexibility by the workers to ensure problem-solving is an important part. To establish a station or line that is manually performed with high-quality output and with low time consumption, standardized work is encouraged to be utilized, and variants shall be introduced according to Bicheno et al. (2013) as late as possible during production.

3.3 Organizations in relation to safety standards

Implementation of machinery in the industry, such as industrial robots and collaborative robots, according to Land (2018), have the possibility to pose risks for workers and humans that come in contact with them. A machine directive, (2006/42/EC), is established with the purpose to enable designing of safe working environments. Different levels of standards have been developed to ensure safety while working with these kinds of machinery. Standards included in the directive, in relation to robotics, are ISO 12100, ISO 13849, and ISO 10218-1/-2. ISO 12100 regards the safety of machinery and the risk assessment process. ISO 13849 regards safety in relation to the construction of the control system. ISO 10218-1/-2 regards the elimination of risks that can occur while implementing and working with industrial robot safety design. The technical specification SIS-ISO/TS 15066:2016 is included and is created to be a complement to ISO 10218-1/-2 in relation to the design of safe working environments for collaborative robots. SIS-ISO/TS 15066:2016 includes aspects such as collaborative workspace, application design, and classification of collisions together with the collaborative safe-guard modes.

3.4 Industrial robots

For a robot to be categorized as an industrial robot, the robot needs to possess at least three axes or joints. The ISO standard, ISO 8372:2012, defines an industrial robot with specific key features it needs to possess. They need to possess at least three-axis or joints that can be programmed and reprogrammed, the ability to be automatically controlled and adapted to new tasks and environments. Another important aspect regarding the mechanical system is that the standard and the definition explain if human contact, also referred to as physical contact needs to be included during the two features, adaptability for new applications and reprogramming. When it comes to adaptability for new applications and tasks, the interaction of the physical kind often needs to be performed. During reprogramming of the robot, no interaction of the physical kind needs to be adapted to perform the feature.

Industrial robots can vary in their design and configuration, and they are divided into different robot types depending on their mechanical structure according to the definition from the ISO standard. Some of the robot types are Linear, Articulated, Parallel, Cylindrical, and SCARA. The industrial robots do not need to be fixed at one specific location; they can be flexible in a way that means that they can move around during work tasks.

Groover (2015) explains that industrial robots are adaptable when it comes to environments and work tasks. Industrial robots can be adapted to work in environments that are not suitable for humans to work in, such as hazardous environments. They can also be applied to perform repetitive tasks that require high accuracy with high performance. Heavy lifting and tasks that require strength, which can be categorized as non-ergonomically, can be eliminated from workers and replaced by a robot. Tools and grippers, which are located on the end effector on the robot, can be standard tools or tailor-made for specific operations. Depending on the operation to be performed, the tool or gripper can vary to fit the specific operation. Pick and place operations and welding operations are typical for an industrial robot to perform and require different designed tools such as traditional gripper and welder.

3.5 Collaborative robots

Robots that are created to work in close contact with humans are, according to Pilat, Klimasara, Pachuta and Słowikowski (2020), designed in a different way in comparison to traditional industrial robots. They also point out that collaborative robots possess different features, where the aim is to create a robot that can work safely together with humans. The traditional industrial robots are in comparison to collaborative robots stronger. This means that industrial robots can work with higher payload than collaborative robots. Collaborative robots are designed with the purpose of having an even body without any intrusive edges; sharp edges are eliminated. Some of the unique features the collaborative robots possess, concerning safety, are collision detection and hand guiding possibilities.

A collaborative robot has the flexibility to be adapted to several applications and environments. Some of them are, according to Park et al. (2019), industrial, hospital- and service applications. The robot can perform high accurate tasks which can be repetitive together with humans. Various tools and equipment can be utilized depending on the application the collaborative robot should perform. Claw grippers, vacuum grippers, cameras, and even tailor-made grippers are some examples of tools that can be equipped on a collaborative robot.

Park et al. (2019) state that the area where the robot and the human work together is referred to as a shared workspace. Inside the workspace, the human and the robot perform tasks either at the same time, collaboration, or at different times, in parallel.

Whenever a collaborative robot is introduced in the industry, a risk assessment needs to be performed according to (SIS-ISO/TS 15066:2016). This is done to ensure that the robot can work in a safe manner for the specific application. The risk assessment controls all the tasks the robot perform and the environment where the robot is placed, to ensure safety. ISO standards and the technical specification needs to be utilized to ensure that the robot application can be performed reliably.

3.5.1 Levels of collaborations

There are four levels of collaboration when it comes to working with collaborative robots. These four levels are compared to the robot cell, where the robot performs the tasks in a closed environment in relation to safety requirements and collaboration level. They are Human-Robot Collaboration, Cooperation, Synchronization, and Coexisting; Bauer et al. (2016) defines the level and explains the differences between them, see Figure 2. The differences between the levels are based on shared workspace and tasks performed on the pieces to be created. Depending on the level of collaboration, the workspace and collaboration differ. The first level is categorized as the deepest level of collaboration is referred to as Human-Robot Collaboration. It can be defined as the level where the worker and the robot both share the workspace and the workpiece, which means that they perform work tasks on the same part. The second deepest level is referred to as Human-Robot Cooperation. It can be defined as the level where the worker and the robot share workspace but have their own workpieces; they do not perform work tasks on the same piece at the same time. The third deepest level is referred to as Human-Robot Synchronization. It can be defined as the level where the workspace is shared, but they have no shared work tasks. Lastly and the most shallow work level is Human-Robot Coexisting. It can be defined as the level where they do not share workspace but perform their tasks in near contact.

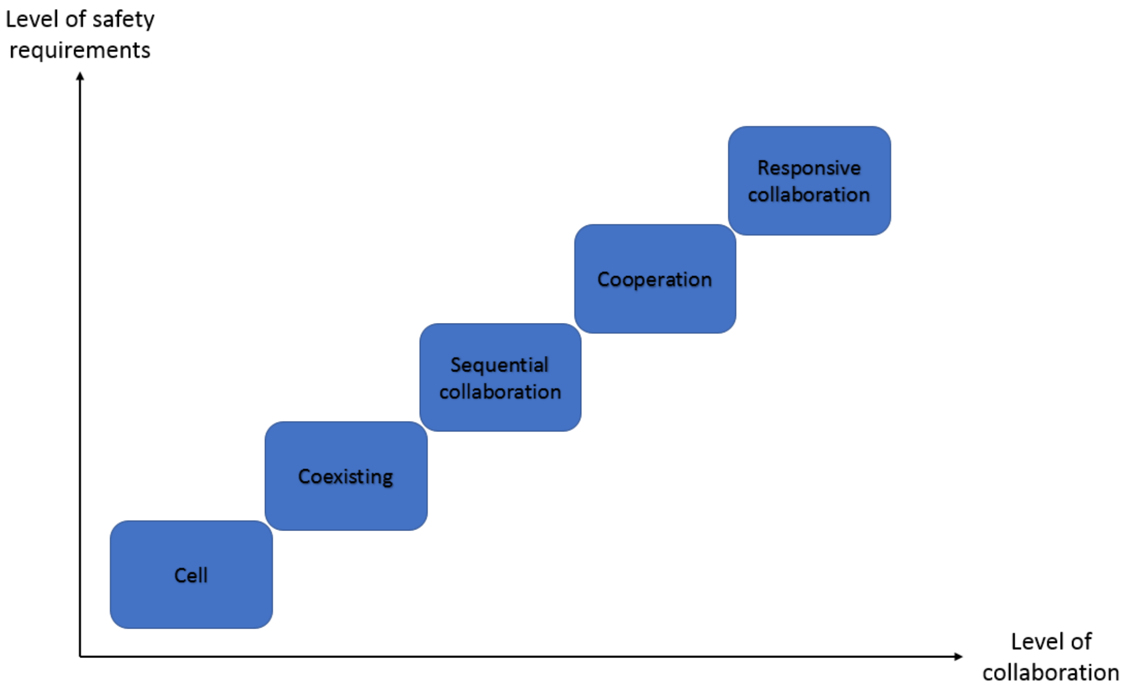

Figure 2: Types of collaboration with industrial robots inspired by WTWH Media LLC (2020)

3.5.2 Collaborative Workspace

Collaborative workspace can be defined as a shared workspace where both the human and the robot perform work at the same time. This means that the robot is activated while the human is inside the workspace. There are safety regulations, ISO standards that need to be investigated and followed to create and perform work in a collaborative workspace according to SIS-ISO/TS 15066:2016.

3.5.3 Design of the application

Some factors preferably need to be taken into account when the design of the application is being performed. By taking the factors into account while designing the application and designing the layout avoidance of unnecessary risks can be eliminated according to SIS-ISO/TS 15066:2016. The first factor regards the sphere of the robot; if the robot can reach a position that is not requested or even dangerous, it needs to be delimited. The second factor regards the collaborative workspace, which means the space and material that needs to be included in the application and workspace. Here limitations need to be thoroughly investigated in order to create a workspace that is not hazardous to work inside. The third factor regards the interaction and exposure that the worker can be exposed to in the workspace. Ergonomic aspects are also included in the third factor. The fourth factor can be referred to as the required user experience and restrictions of the workspace. The fifth factor can be referred to as the understanding of initiations and completion of tasks. Tasks are performed together with the robot, collaboration between humans and robots.

3.5.4 Definition of collisions

Collisions between human and the robot can occur in different ways according to the technical specification SIS-ISO/TS 15066:2016. They are quasi-static contact and transient contact. Quasi-static contact can be defined as a pinch risk where a human body part can during work be pinched. This means that the human body part can get stuck and cause harm to the human between the robot or between an object. Transient contact can be defined as the opposite of quasi-static contact, contact occurs; however, without a pinch risk.

3.5.5 UR robots

Universal robots manufacture collaborative robots in different sizes and are suitable to use for a considerable amount of applications, according to UR (2020). They can be bought in four different sizes UR3, UR5, UR16, and UR10. Two different variants of the models can be obtained, the e-series and the first launched variant, the CB-series. The difference between the e-series and the CB-series is that e-series have the built-in force and torque sensors. The UR5, see Figure 3, can lift up to 5 kilos in total payload, and UR16 can lift 16 kilos in the total payload. The robots are six-axis robots that are flexible and created to work together with humans. Applications such as pick and place, quality control, and industrial assemble can be performed with UR robots. The robot interface enables easy programming of their software, and the programming is performed as an online application, online programming.

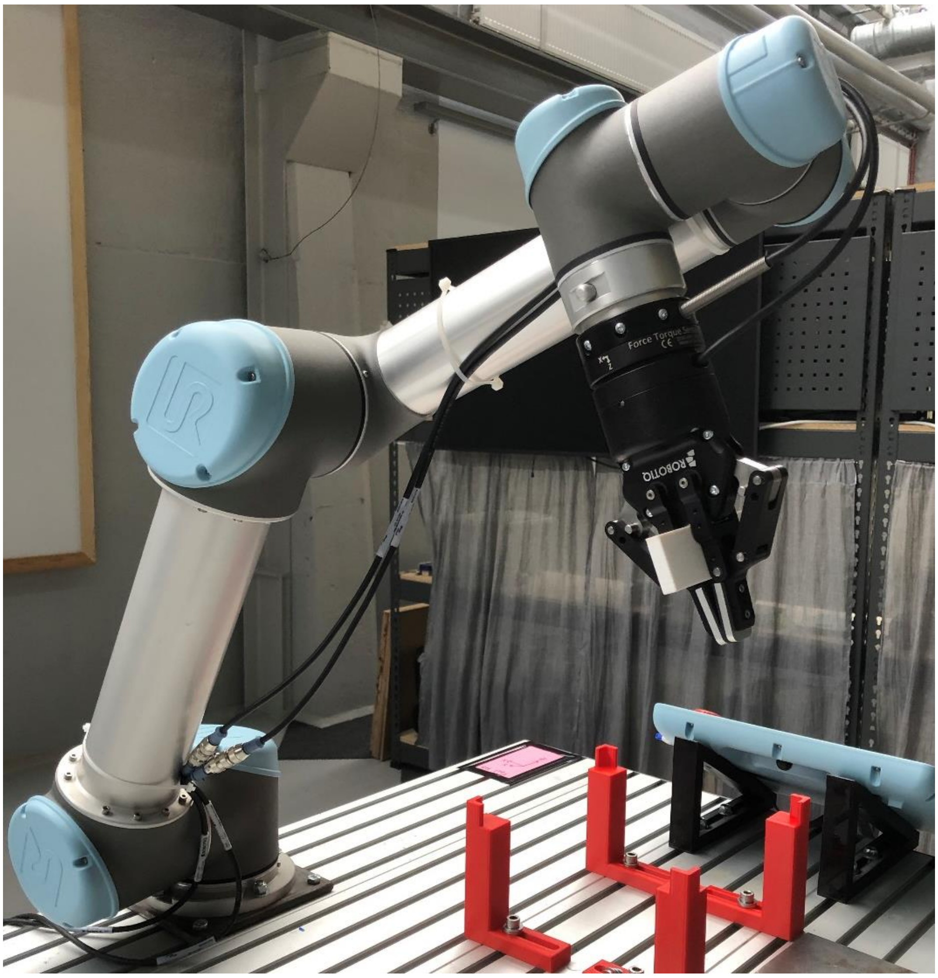

Figure 3: UR5 CB-series robot located at Assar innovation arena

3.6 Collaborative safe-guard modes

Working with collaborative robots can be performed on different levels and with different safe-guard modes. The ISO technical specification SIS-ISO/TS 15066:2016 describes four safe-guard modes for collaboration with a collaborative robot. They are Safety-rated monitoring stop, Hand guiding, Speed and separation monitoring, and Power and force limiting.

3.6.1 Safety rated monitoring stop

The method safety rated monitoring stop, according to SIS-ISO/TS 15066:2016, regards the deactivation of the robot movements when a human becomes present in the collaborative workspace. It is a function that stops the movement if a human becomes present and also limits the robot to the specific workspace. The definition can be referred to as a stop function of the robot movement. The stop function will become active if the workspace is excessed and a restriction for the robot workspace to prevent the robot from becoming present outside its workspace. The safety-rated monitoring stop shall protect humans but also prevent interference from a station located close to the workspace. For the robot system to be able to detect workspace intrusion, safety devices need to be installed.

3.6.2 Hand guiding

The method, hand guiding, can be explained, according to SIS-ISO/TS 15066:2016, as a human in command. It starts with an activation of the method, safety rated monitoring stop, which is deactivated during the hand guiding operation and then reactivated when the operation is performed. During the hand guiding operation, the human can control the robot and re-orientate it to the requested location.

3.6.3 Speed and separation monitoring

The method, Speed and Separation Monitoring, regards safety distance between robot and worker inside the collaborative workspace, according to SIS-ISO/TS 15066:2016. As long as the limit is not exceeded, the robot continues working. The safety distance is decided upon the current speed. In order to establish a collaboration between a human and a robot, requirements need to be met. Some of the requirements are Safety-rated monitoring speed function and a Safety-rated monitoring stop function.

3.6.4 Power and force limiting

As the name of the function may reveal, Power and force limiting regard the real force that the robot is limited to possess during collaborative work tasks. SIS-ISO/TS 15066:2016 explains that if contact appears between the human worker and the collaborative robot, the force that the robot can achieve and apply on the worker shall not constitute any harm.

4 Literature study

This section describes research regarding human-robot collaboration and safety aspects. The section also includes disassembly and the benefits gained by implementing the capability of remanufacturing. Methods proposed to achieve a safe way of conduction human-robot collaboration and task allocation are introduced together with aspects of how to increase awareness during operations.

4.1 Methodologies for human-robot collaboration

A Framework for Realizing Industrial Human-Robot Collaboration through Virtual Simulation (Land, Syberfeldt, Almgren and Vallhagen, 2020)

Land et al. (2020) have identified three major reasons why human-robot collaboration is not implemented on a large scale in the industry: the lack of design methods, issues regarding safety aspects, and intuitive interfaces. In the paper, a framework is presented regarding the implementation of collaborative robots.

Five steps are proposed by Land et al. (2020), and the first step is to define the scope. It includes to identify suitable areas for implementation and to identify tasks that can be suitable for facilitation or replaced by a collaborative due to several factors. These factors regard aspects, such as un-ergonomically conditions, environments that can be harmful to humans, high requirements of precision, and monotonous tasks. The current state description is the second step, and it regards the data that needs to be collected. The collected data regards information of relevant operations, layouts, components, and flows. Operations are the first sub-step, and it regards the different components and the operations required to create desired products. There are often different variants that flow through the identified area or areas. To identify possible operations performed by a robot together with a human, or independently, information is required to be collected. The information regard aspects, such as a previously required operation for the components, operation times for human, robot and together, unsuitability for the worker and location of execution. The component list is the second sub-step, information of the components and their characteristics is defined. Flows of products, people, material, support function, and equipment is the fourth sub-step, and it regards the identification of how an implementation can affect them. The last sub-step regards layouts of the area or areas of interest. All relevant information on the current state should be included together with measurements of the areas. The third step regards the objectives that an implementation needs to achieve. They list objectives and Key Performance Indicators, and some of them are, cost, ergonomics, quality with scrap and rework, flexibility with process flexibility, and resource utilization with space usage and energy consumption. The fourth step regards conceptual solutions and includes specifying requirements for the new solution. Operation lists, flow, and component lists are some of the aspects covered during the step. The last step regards the creation of the virtual simulation. They discuss the importance of not starting with a too detailed environment, the requirement of hardware and unnecessary work put on one solution that cannot meet the set objectives.

A structured methodology for the design of a human-robot collaborative assembly workplace (Mateus et al., 2019)

The paper presented by Mateus et al. (2019) states that including collaborative robots in production can contribute to higher flexibility and a more ergonomic workplace. They also discuss essential aspects when it comes to human workers, and what a collaborative robot can imply; the aspects are related to the relief of workload. The workload can be defined as such, e.g., reduction or elimination of heavy lifting and stress-related aspects. The methodology that is proposed consists of four main steps; all main steps include sub-steps. The first step includes an investigation of the products to be assembled, preferably the models created in CAD. Sub-steps includes identification of how the parts are connected and in what order they should be assembled. They also extract and generate information regarding the precedence for the assemblies. The second step includes the creation of the elements and instructions on all levels Operational-, Subassembly-, Task-, Function- and function stage level. Requirements for functionalities are also identified in step two. The third step takes both the ergonomic aspects and the robot capabilities into account, which includes both necessary peripheral and safety actions. Safety aspects of the robot are included and assessed for every function. The last and final step regards the operator support, and in this step, the elements requested for the robot to perform are investigated and assigned. Verification that the elements and operations can be performed reliably is also included in the fourth step.

Collaborative Assembly in Hybrid Manufacturing Cells: An Integrated Framework for Human–Robot Interaction (Sadrfaridpour and Wang, 2018)

The focus of the work, conducted by Sadrfaridpour and Wang (2018), regards two aspects of Human-robot interaction for assembly tasks while conduction the case study to establish a framework regarding human-robot interaction, physical and social. They created a model with the purpose of measuring how much trust the human feels while working with the robot. As a part of the framework, the case study included facial expressions of the robot, which were visualized on two screens. A feature that was included regarding the ability to track an active mark with the robot's eyes. An active mark could be placed depending on distance requested to be measured from the robot manipulator. Safety distance was in this case study measured, from the hand of the operator to the manipulator of the robot. The facial expressions that were visualized on the screen were a happy face, a worried face, and a bored face. As the facial expressions might reveal, a happy face symbolizes safe working conditions where the safety distance is reached between the manipulator and the active mark. Worried face symbolizes a too short safety distance between the active mark and the manipulator. Bored face symbolized that the robot was more or less waiting for the operator. They concluded that by using the created framework, they manage to reduce the workload, increase usability, and increased trust.

Complexity-based task allocation in human-robot collaborative assembly (Malik and Bilberg, 2019)

Malik and Bilberg (2019) conclude that manual assembly is not suited to be performed by traditional robots. Some of the reasons that they describe are the number of parts used and the number of variants that can be included in an assembly station. Difficulties they point out while introducing a collaborative robot for assembly operations regards aspects such as identification of elements that can facilitate for the operator and division of elements. To form and establish the proposed methodology regarding task allocation between human workers and robots, the authors are focusing on two aspects. The aspects regard the sub-parts and the finished part that is fully assembled, properties of sub-parts, and how the assembly should be performed. This information is used to divide the elements into sub-categories, which is used in order to score them. In their conclusion, they point out that new products are introduced more frequently, and their method for task allocation can facilitate the allocation when new products are introduced. They also conclude that tools and equipment are an essential aspect when it comes to the utilization and performance of the robots.

4.2 Disassembly and remanufacturing

Human-robot collaboration in disassembly for sustainable manufacturing (Liu et al., 2019)

Human-robot collaboration used for disassembly is referred by, Liu et al. (2019), as human-robot collaboration disassembly (HRCD). The authors concluded that some benefits could be gained by implementing the disassembly of products. The benefits regard aspects, such as the opportunity to recycle resources and materials. They discuss further that efficiency can be gained by implementing human-robot collaboration when it comes to the disassembling of products due to the complexity it can contain. One obstacle that they express is the requirement of intelligence. In the paper, a framework was introduced for introducing HRCD.

A demonstrator was created containing AI and other smart technologies to handle aspects such as decision making. An industrial robot was used in the demonstrator. To cope with one safety aspect, they controlled the distance between a human and the robot. The speed of the robot was based on the distance. In their conclusion, they expressed that disassemble together with human-robot collaboration, can increase the sustainability aspect.

Sequence Planning Considering Human Fatigue for Human-Robot Collaboration in Disassembly (Li et al., 2019)

By implementing the ability to remanufacture products, aspects regarding sustainability will be increased. Li et al. (2019) discusses the benefits and disadvantages of disassembly for both the human and the robot, performed separately. Finess and the ability to handle hard to reach tasks are referred to as benefits for humans. Disadvantages are referred to as work operations that can cause permanent injuries. The benefits for the robots are the accuracy and efficiency they contribute. Disadvantages include the inability to respond to changes and the complexity of the disassembly. By introducing human-robot collaboration for the disassembly processes, the ability to increase the benefits and decrease the disadvantages can be achieved.

Sequence planning for disassembly performed as a human-robot collaboration was the focus of the article. The division of tasks was performed much based on the part itself and tasks required for the disassembly operation. An algorithm was used for the optimization of the sequence created in the study. The main objective of the study was, according to Li et al. (2019), to decrease the appearance of fatigue for disassembly operations.

4.3 Techniques to achieve collaborative safe-guard modes

Collaborative Manufacturing with Physical Human-Robot Interaction (Cherubini, et al., 2016)

The contributions that the case study, Collaborative Manufacturing with Physical Human-Robot Interaction, performed by Cherubini et al. (2016), outlines are the ability to include contact between human and robot and its environment during assembly, usages of standard position during assembly and different behaviors of the robot. The created human-robot collaboration cell can, according to Cherubini et al. (2016), be certified. A certification means that all safety aspects have been taken into account; a risk analysis has been performed and approved. A homokinetic joint was assembled in the human-robot collaboration cell and included an improvement when it comes to the ergonomic factor. A specification list was developed, and the four criteria needed to be fulfilled. The first one involved the human workload in order to facilitate a better ergonomic standard. Second, involved the interaction part between humans and robots, the essential thing was that it could be performed safely. The third criterion involved avoidance of blockage. Last, regarded the accepted speed of the robot. Some of the tools and equipment used to create the cell and upheld the safety were admittance control and image processing. Experiments were conducted.

Implementing speed and separation monitoring in collaborative robot workcells (Marvel and Norcross, 2017)

The case study, Implementing speed and separation monitoring in collaborative robot work cells, focuses on one of the four collaborative safe-guard modes, which is guidance when it comes to collaboration between humans and robots, speed and separation monitoring. Marvel and Norcross (2017) discuss the proposed equation to calculate the protective distance at a specific time, which is required according to the technical specification ISO/TS 15066. An important aspect that they point out is that in order to consider the specific time as the current time, they consider the safety aspects at all times. In order to actively control the distance between robot and human, a device is used, which is external with an SSM algorithm. They concluded that Power and Force Limiting is a method that is included in most of the collaborative robots. An industrial robot is not forced to include the Power and Force Limiting functionality, which makes it more important to be strict when it comes to speed and separation monitoring if they become collaborative. As their conclusion, they are questioning the equation stated in the technical specification. They also state that to ensure safety while working collaboratively with industrial robots is an area that requires more investigation and research.

4.4 Aspects regarding safety for human-robot collaboration

Assessment of pressure pain thresholds in collisions with collaborative robots (Park et al., 2019)

A study with 90 male participants with different physical attributes was performed by Park et al. (2019), regarding the pain tolerance in the technical specification ISO/TS 15066. The technical specification introduced the pressure point, and 15 of them were investigated, from the forehead to the back of the lower leg. The study was performed to control collisions between robots and humans. In order to perform the experiments, a device was created, which consisted of different parts required to perform the investigation. The pressure applied was calculated with newton per square centimeter. During the experiment, when the participants were reaching pain tolerance, the applied pressure was calculated. The statistical calculation when all participants have gone through all the 15 points, showed that when it comes to the areas of the hand, palm had a mean of 97.8 and back had a mean of 196.2 newtons per square centimeter. When it came to the arm and the arm nerve, the mean value was calculated to be 64.9 newtons per square centimeter. As their conclusion, variations of the measurements are both affected by factors that can be about physical attributes and external factors. All tests were performed three times to record variation that occurred for the same participant. They could not identify any massive difference in the measured value between the three tries.

Understanding situational and mode awareness for safe human-robot collaboration: case studies on assembly applications (Gopinath and Johansen, 2018)

Gopinath and Johansen (2018) discuss and explains some of the essential aspects when it comes to humans, together with complex systems regarding safety. This includes machines that need human interaction in some way. Two case studies were conducted with safety in mind with industrial robots used for collaboration with humans and different setups.

An important factor is the training and knowledge an operator needs to possess while working with machines and systems that can be defined as complex. The authors describe that situation awareness is an essential aspect when it comes to collaboration and understanding between humans and machines. Three factors can lead to a decrease or loss of those aspects. The first one regards the role of monitoring and can occur if the attention of the task is in some way interrupted. The second regards the ability to take control over a task; if that does not happen, the loss might be a fact. The third one regards deduction in the ability of the system to give a response of the state. In the article, trust is expressed as an essential aspect when it comes to working with systems that are defined as complex. The authors give examples of factors that can help increase that aspect; some of them are Communication styles, Appearance, and Feedback. In their conclusion, they discussed the importance of situation awareness to decrease the risk factors.

4.5 Evaluation of the literature study

Essential aspects that have emerged through the literature study will form a basis for the implementation and result of the project. The first aspect regards the methodologies and framework that has been introduced in the first sub-chapter. Surrounding information and data regarding parts and their features, together with assembly operations, plays a significant role while introducing collaborative robots in the industry. The importance of establishing operation lists, predecessor lists, assembly instructions, are discussed. The project involves creating a demonstrator that is based on real cases from the industry, and therefore the widgets and operations included are based on real parts and common tasks. The division of tasks between the robot and worker is also one of the challenges and where more than one framework describes the essential aspects to control while performing the division. These aspects regard the relief of heavy and un-ergonomic tasks, high utilization, capabilities of the robot, and the parts and their attributes. Relief of workload, such as heavy lifting, is one of the benefits the collaborative safe-guard mode hand guiding can offer. These aspects will be taken into account during the project, together with the importance of controlling if the robot can perform all assigned tasks during experiments.

The proposed framework by Land et al. (2020), will be partly adapted for the project. The proposed framework will mainly be introduced from the third step, and then instead of creating a virtual environment, go directly to the implementation. The division of tasks between robots and humans, together with necessary data, will be in focus for the project.

Disassembly and remanufacturing of products are stated to be a beneficial combination between collaborative robots and humans, where all strengths from them both can be combined. Sustainable development will also increase if remanufacturing and disassembly increase together with including collaborative robots instead of performing it manually or automatically. This due much to the fact that it gives the opportunity to relieve the load from heavy tasks, chance to decrease the stress level, and recycle and reuse material. The project focuses on reversibility, assembly, and disassembly, and by combining the workflows with a collaborative robot, it can prove to be beneficial regarding many aspects.

Different techniques have been introduced to handle safety aspects due to the lack of fully developed standards and methodologies. Many of the papers included in the chapter were introducing a technique to control the collaborative mode, speed and separation monitoring, or distance control. There are different frameworks proposed for achieving it to obtain active control of the distance to ensure safety regarding that aspect. The demonstrator created will not be equipped with a camera. Therefore the importance is to obtain as much distance as possible between the worker and the robot. This should be performed without compromising the reachability of the robot to perform its assigned tasks. Shortage distance is one aspect of documenting for future work to be performed.

One of the papers, Collaborative Manufacturing with Physical Human-Robot Interaction, manage to get their station certified. The station was controlled by cameras during the sub-assembly of a homokinetic joint, which both required finesse and were un-ergonomic to perform totally manual. The station included a sub-assembly of a part which highlighted the benefits of combining sub-assembly and assembly for the project. The benefits for the sub-assembly are the ability to perform parallel tasks in a controlled location, a pre-defined work area with fixtures. For assembly, the ability to, in a controlled situation, relocating parts from one location to another with the robot.

The paper, Assessment of pressure pain thresholds in collisions with collaborative robots, experimented on the pressure pain of different body parts in relation to the technical specification. The result showed that the lower arm was more sensitive than the hand when it was exposed to pressure. During assembly and disassembly with a collaborative robot that is working close to a worker, mistakes can be made. There is always a risk of getting exposed to quasi-static or transient contact by the robot or robot tool. The focus should lie on minimizing those risks, not only by increasing the distance but, to plan and work to identify them and eliminate their occurrence.

Operation training is essential while working with collaborative robots. Proper instructions, based on accurate data, and training can minimize risks of mistakes and unplanned contact with the robot. When it comes to awareness, control of the tasks, and feedback from the system can be aspects that can increase it. By giving control to the worker during the workflows, an incensement of awareness and trust can be gained. By allowing the worker to initiate the tasks, both awareness and safety can increase on the demonstrator.

5 Methodology

This section describes and presents the research methodology that has been chosen and applied during the project. Descriptions of methods included in the project, both regarding the research methodology and data collections, are presented.

5.1 Design and creation

The methodology Design and creation can be defined as a methodology with a focus on problems and how to resolve them, according to Oates (2006). The focus in the methodology lies much within the ability to identify and define the problem. The author explains that in order to identify and defining the problem, solutions need to be generated and evaluated. This will increases the knowledge that is requested to identify and solve the problem. Design and creation is a process that does not follow a linear approach; it is iterative. The process model for Design and creation, also referred to as the design science research process model is visualized in Figure 4. The methodology consists of five steps. They are Awareness, Suggestion, Development, Evaluation, and Conclusion.

- **Awareness** – The first step can be defined as the investigation and identification of a real-world problem. Literature reviews and new technologies can be a way to identify real-world problems. The problem itself should enable the opportunity for new research findings.
- **Suggestions –** The second step can be defined, as the name of the step might reveal the way from identifying the problem into suggestions on how to solve the problem, generated with the help of the ability to think outside the box, creativity.
- **Development –** The third step involves generating designs that can function as a way forward to identify and establish a solution to the problem that is addressed.
- **Evaluation** – The fourth step involves the evaluation of the established solution. The evaluation phase consists of a comparison against the expectations and requirements that the solution is expected to fulfill.
- **Conclusion** – The last step can be defined as an evaluation of the result together with, e.g., other researchers and the identification of further work to be done. The identification of the knowledge achieved is evaluated and noted. If the result achieved deviates from the requirements, expectations, or is unable to be understood, further investigation and research might be necessary to perform.

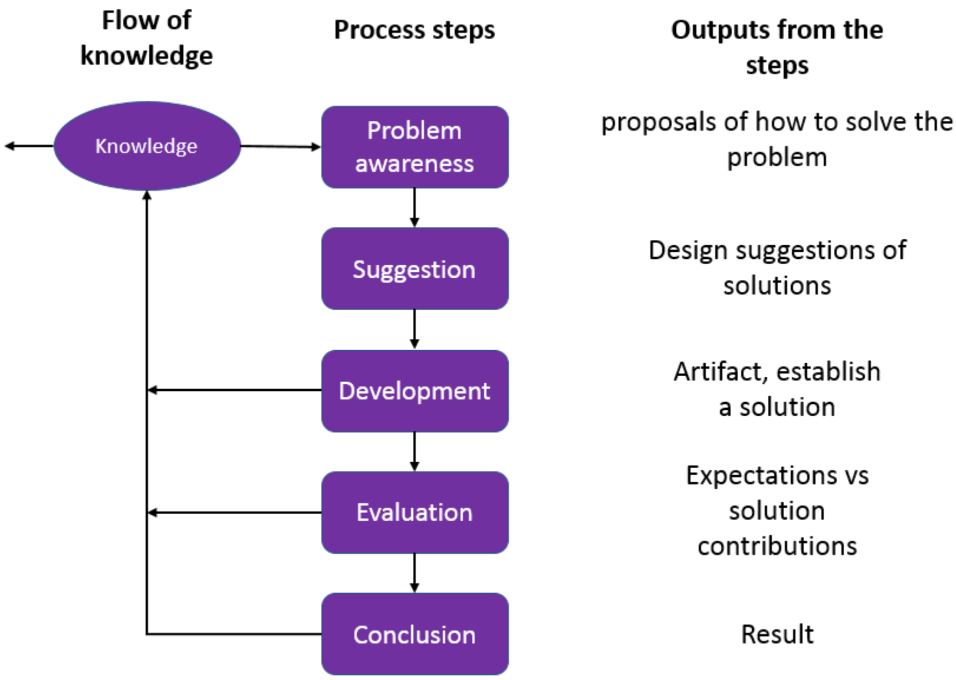

Figure 4: Design science research process model inspired by van der Merwe, Gerber and Smuts (2017)

The Design and creation methodology, according to Oates (2006), is a methodology that contributes to some appealing advantages. One of the advantages expressed is that the contribution of the research can consist of something that is created and thereby can be displayed. The effect that an establishment can contribute with is that the interest of people can increase; also, people who have a general interest in technical developments can be increased.

5.2 Documents

The data collection technique Documents, according to Oates (2006), consists of two subcategories. The first category is referred to as Found documents and includes existing documents that can be accessed. They can be, e.g., manuals and job descriptions. The second category, Researcher-generated documents, on the other hand, are not existing beforehand. They are composed during the research by combining materials such as photographs of specific material or events and essential records. The combined and established material is used for a specific purpose within the researchers' work. There is no restriction when it comes to who completes the documents that can consist of data collected over time.

Some data can be interesting to investigate, also depending on the type of research that is conducted that can be collected from organizations, individuals, and publications. Some of them are figures of sales, meeting reports, logs, emails, journals, and articles.

Evaluations of documents are an essential and necessary step of the research, purpose, and how accurate and authentic they are is important. If they are not evaluated, the research that is conducted might suffer from a loss in reliability. When it comes to analyzing collected documents, it can be performed according to Oates (2006), depending on how they are categorized. The two categories that the author explains are, as objects or as vessels. The first category, objects, can be defined as threatening them as just objects. The analyzing part is conducted around them instead of what they contain. The second category, vessels, can be defined as data stored inside the documents. The analyzing part is regarding the content that the documents consist of.

5.3 Observations

The data collection technique Observations can be defined as identifying and observe with different senses, what is actually happening. Observations can be performed, e.g., in order to investigate the production process or behaviors of people in different environments. Oates (2006) explains that there exist two research varieties when it comes to observations; they are fundamentally different, covert research and overt research. Covert research can be defined as an approach that includes observations that are performed in secret; they are performed without notifying the people that are observed. Overt research can be defined as the opposite of covert research, the observations are performed openly, and the people are notified. Many approaches can be used while performing observations. One approach can be to observe a specific event, and another can be to observe everything that occurs. The range of time when it comes to performing observation can vary between a few minutes up to a few years. An important aspect when it comes to performing observations regards the ethical part, consent given by people before conduct observations.

5.3.1 Systematic Observations

The approach, Systematic Observation, can be defined as predefined events that is investigated or, in other words, an event that is the subject for observation. Oates (2006) explains further that a systematic observation often leads to the collection of data, which is quantitative, due to the fact that the most common events that are investigated are the number of events and the time it took to perform them. Schedules are often used to store the collected data, which can facilitate the observation performed.

5.3.2 Participant Observations

The Participant Observation approach can be defined as the participation of the person who is conducting the observation. According to Oates (2006), the observation can be conducted in secret or the open. Participants are not aware that one of the people including in the observation, is the one who is conducting the experiment or the other way around; the participant is aware that the researcher is included, covert, or overt. The task while conducting a Participant Observation for the researcher is to observe the whole of the situation.

5.4 Choice of methodology

When the project consists of problem-solving and the creation of something physical, the Design and creation research strategy is a proper fit. First of all, engineers can be categorized as problem solvers; the project aims to create a system in which physical objects together shall cooperate both between them and together with humans. This project contributes to the design of a system that holds many problems that need to be addressed. Safety standards are one of the tasks that directly is connected with the type of work to be addressed. The five steps that are defined by Oates (2006) takes into account all necessary steps that need to be addressed to conduct such a project. The aim to create a demonstrator and create human-robot collaboration with a collaborative robot and tools and equipment that is already at hand creates a possibility for experimental evaluations on a physical demonstrator.

Observation and documents are together, according to Oates (2006), well fitted for a Research and Design approach. Observations conducted on real systems concerning safety aspects and solutions together can result in a broader knowledge base of approaches to handle and create a safe way of working with machines. Conduction of experiments in a physical environment can also lead to a broader knowledge base and the possibility to address problems in real-time for the specific work environment. Documents collected with both regards to manuals of equipment and journals and articles of human-robot collaboration can allow investigating different approaches regarding the establishment of a safe work environment. Collected documents regard both robots created to work with humans and the industrial robots modified for the same purpose. The safety standards can be investigated and analyzed to use them as a reference while designing the demonstrator, experiments conducted on it, and during the evaluation phases.

6 Strategy execution

This section describes the process for the project adapted from the research strategy, design and creation. The process flow is presented with a focus on the three steps, suggestion of strategy, development of the demonstrator, and evaluation of the demonstrator. Factors and aspects that influenced the design, the configuration of the demonstrator, and the evaluation are presented regarding the adapted process flow.

The process of the project was performed iteratively, and the process diagram is visualized in Figure 5. Steps included and discussed in the research strategy Design and Creation, laid the foundation of the procedure the project used. Literature review, safety standards, and input from real cases were together the starting point of the process, the problem area, and identification of it. A suggestion of a strategy was the next process step and included the identification of the strategy, how to manage the problem. The step included what necessary equipment together with the creation of widgets for the demonstrator inspired by real cases. The third step, development of the demonstrator, included the implementation of the strategy, more exact configuration of the equipment, the layout of the demonstrator, and establishment of the workflow for the two modes, assembly and disassembly. The fourth step included experiments and observations of the functionality and general safety aspects. The last step included the gained knowledge gathered together with further work to be performed.

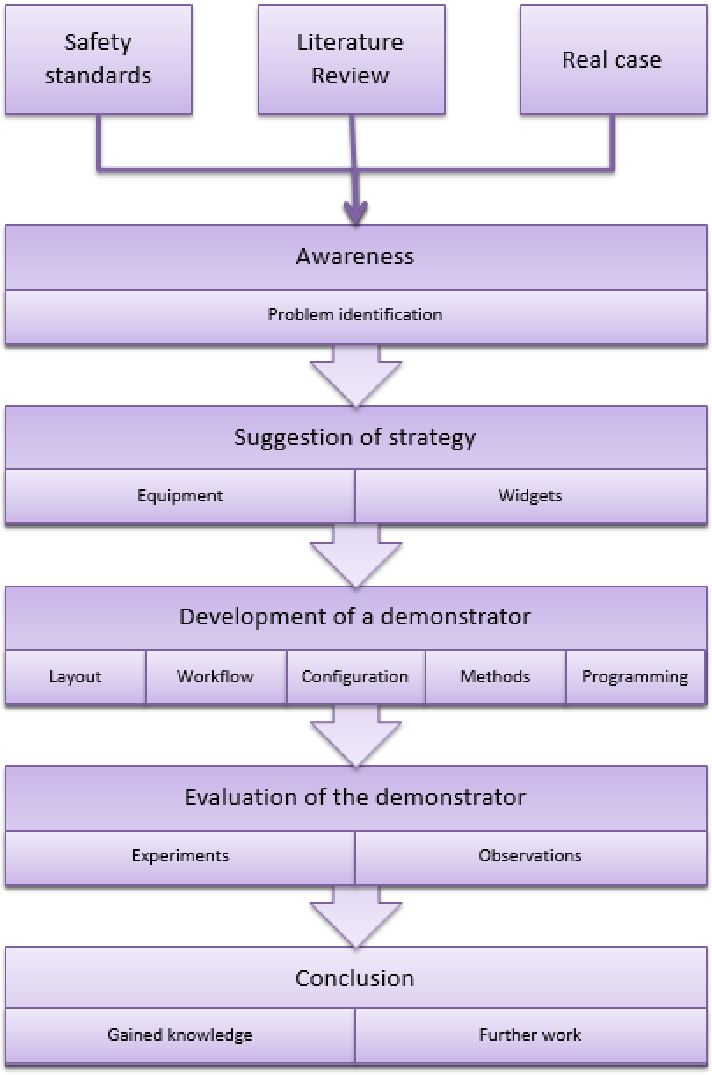

Figure 5: Process Diagram of the project, an iterative process.

6.1 Suggestion of strategy

To establish a suggestion, a strategy to address and identify a possible solution to the problem, the required equipment, and widgets were identified. The available robotic equipment consists of a UR5 for specification (Appendix A), a robot equipped with a grasping tool, and a force and torque sensor. Restrictions regarding the robotic equipment consist of a maximum payload of five kilos in total for the robot to carry, a reach of 850 millimeters, and a grasping width of the gripper of 85 millimeters. Equipment such as a conveyor and a work table with dimensions of 1000 times 700 millimeters are included for creating the demonstrator.

The available equipment, together with inspiration from real cases, laid the foundation for the creation and establishment of the required widgets used for assembly and disassembly. During the identification of widgets and tasks to include in the workflows, the focus was on the reversibility factor. The widgets were required to be able to be assembled and disassembled. One requirement was the ability to disassemble the parts to their original state. Models of the different widgets were created in CREO parametric and then produced in a 3D-printer. Widgets that had a geometrical shape that exceeded the limits of the printing area were divided into smaller parts and then glued and assembled.

6.2 Development of the demonstrator

The development of the demonstrator consists of five main parts; layout of the demonstrator, workflows, configuration of equipment, collaborative working modes, and programming of the robot. All parts are influenced by general safety aspects, requirements, and limitations from and to the surrounding stations, the literature review, and inspiration from real cases.

Layout

Surrounding stations, a conveyor, transportation of the engine, and next station in line, were involved during the establishment of the layout of the whole manufacturing line. The layout for the demonstrator was established depending on different factors. Connection points are visualized in Figure 6.

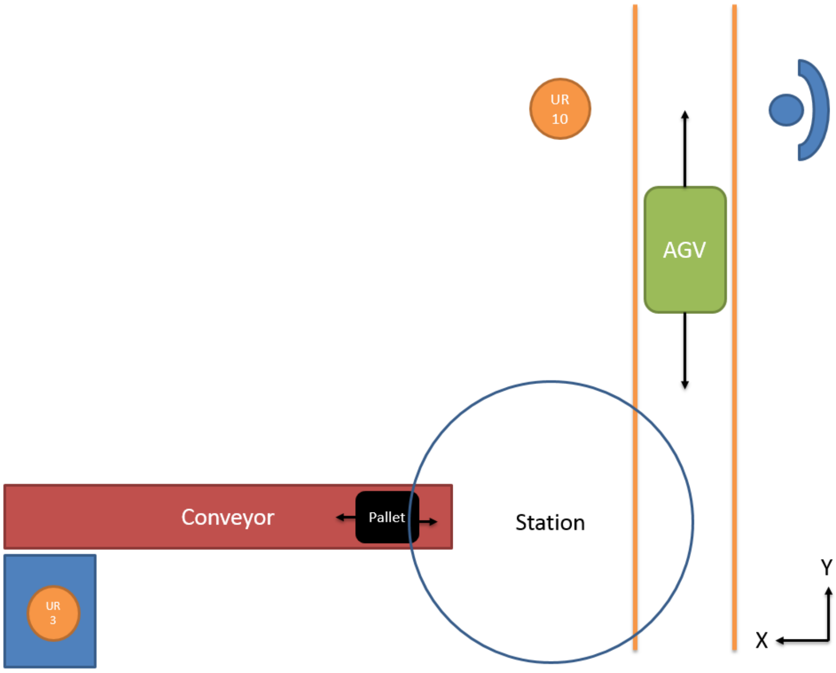

Figure 6: General layout of the manufacturing line, not to scale

The conveyor was the connection point between material delivery and the demonstrator. During the reversed mode, the conveyor had the reversed function. The widgets were placed back onto the pallet to their designated positions, however, in a different order. Transportation of the engine, an Automated Guided Vehicle (AGV), was the connection point with the next station in line and the final assembly position. During the reversed mode, the AGV had the reversed function, the starting point for disassembly.

Limitations of the robot and its reachability, together with requirements from the surrounding stations, were taken into account. Both the pallet and the AGV carrying the engine, had to be in reach for the robot in order for the workflow to be performed. The AGV was flexible in the Y direction when it comes to stopping at the demonstrator, and restricted in the X direction, 50 millimeters were required from the working table to the AGV. The conveyor was permanently attached to the floor. One requirement regarded the reachability of both the worker and robot to reach the pallet from different sides to prevent them from uncontrolled contact. The layout of the demonstrator could be established with all aspects in mind.

Workflow

The workflows regarded the tasks that the robot and the human were conducting together and separately. Tasks that were required to be performed on the demonstrator were a sub-assembly of an electrical cabinet, consisting of three flat and symmetrical parts, and mounting of sensor outlets with different shapes. The reversed mode required the sub-assembly to be reversed, disassembly of the electrical cabinet and the sensor outlets from the engine. Instructions regarding both assembly and disassembly were established together with the required predecessors of the tasks.

Aspects that influenced the distribution were requirements of human finesse for the two modes, robot capabilities, ergonomically aspects such as weight of the parts, location of tasks, and the geometrical shapes of the CAD models. The CAD models were investigated, and depending on their geometrical shapes, weight, and the requirement for finesse, the tasks could be divided.

Configurations

Configurations performed regarding the robot consisted mostly of safety features. Restrictions for the robot were created, safety planes which restricted the robot to exceed specific perimeters, speed and force limitations of the robot, robot path configuration, and work height of the robot tool. Safety planes were implemented to restrict the robot and the robot tool to come close to the human and the surrounding, in other words, to restrict the robot to enter the human work area. Speed and force restrictions were configured depending on the specific task that would be performed. The configurations were based on the distances to the worker during execution.

The Tool Center Point (TCP) was configured according to the gripper, together with the force and torque sensor. Both centers of gravity and payload of the tools were together with the TCP configured according to the manufacturer manual and initiated when no widgets were picked up. When the robot picked up different widgets, the center of gravity and the new and increased payload were reconfigured according to the new weight and center of mass.

Collaborative safe-guard mode

The collaborative safe-guard mode the project aimed to include in the workflow is referred to as hand guiding, between the human and the robot. The workflows established allowed, including hand guiding for both modes, assembly and disassembly. The initiation of the robot to perform both separate tasks and collaborative tasks were established to be initiated from the teach pendant. The main reasons were the inability of the robot to respond differently and to acknowledge and give control to the worker.

The weight of the widgets, ergonomic parameters, and the working location during tasks were the strongest reasons it was implemented as a collaborative safe-guard mode.

Programming

All programming of the robot were conducted in the Universal Robot programming interface polyscope. To increase the safety of the demonstrator, the programming of the robot had one specific aspect in mind, the initiation or acknowledgment of the robot for every new task. Due to the lack of cameras, the focus was to give the worker as much control as possible.

The Force mode, used for hand guiding, let the programmer or user choose in which direction and rotations the widget can be moved, it can be categorized as a lifting aid. The robot paths were carefully programmed to always keep distance between the robot and the worker to avoid any contact between them. When the robot tool worked closer to the worker, the robot speed and force were regulated, decreased. In order to avoid quasi and transient contact between the robot and the worker, especially fingers, the gripper was programmed to only fit the thickness of the widgets before picking them. The robot movements were programmed only to let the robot tool work in chest height, close to work table height, and avoid unnecessary rotations of the joints close to the worker.

6.3 Evaluation of the demonstrator

Experiments and observations were conducted iteratively. Changes were made to achieve the expected outcome, such as the robot program, speed, force, and paths, or positioning of widgets or the robot. All tasks were divided into two parts during the experiment. If something should be picked and placed, the picking operation was one and the placing operation the other. The aspects investigated during the experiments and observations regarded the robot movements, how close the robot tool could come to the worker, and what type of contact the worker could be exposed of. Two different locations were established for the worker pallet, and table. By controlling the minimum distance between the robot tool and the chest of the worker, the minimal distance could be identified, the robot tool, in contrast with the chest of the worker. Fingers and hands of the worker were different aspects that were controlled concerning contact. The established safety planes for the robot could also be tested and modified while conducting the experiments. Risk of contact the worker could be exposed to regarded the movement type of the robot together with the destination of it. Force and speed were regulated with inspiration from the standards during close contact with the worker. Before any picking or placing with the robot gripper, the position of it was regulated. No hands or fingers could fit between the widget and the gripper when the grasping of the widget was performed. Time was an aspect initially gathered from a real case scenario, which regarded the maximum time consumption of the workflows.

The technical specification, SIS-ISO/TS 15066:2016, includes tables of quasi-static and transient contact concerning maximum pressure and force limits for different body regions, and maximum speed concerning robot effective mass with different body regions. The limits stated in those tables, in combination with their body regions, influenced the limits used for the configuration of the demonstrator.

The experiment was conducted on separate tasks performed by the robot. Observations were conducted to investigate different aspects concerning safety and functionality. After an experiment and observation were conducted, the result was controlled. The distance between the TCP and the worker were noted to create a baseline for a future safety evaluation. Speed and force could be regulated and lowered due to the risk of contact in regard to the total weight of the robot, gripper, and widget together with the contact surface.

The proposed design method for human-robot collaboration proposed by Land et al. (2020) was evaluated based on aspects such as sustainability concerning reversibility, utilization of established data, and division of tasks. Due to the lack of an existing station for the project, only parts of the methodology were evaluated.

7 Result

This section presents the parts which the implemented demonstrator consists of. Widgets established, the layout of the demonstrator, division of tasks, established workflows, and the robot programs are presented together with an evaluation of its functionality according to investigated aspects.

7.1 Established widgets

Widgets included in the workflow consist of four sensor outlets, an electric cabinet consisted of two parts, a bottom plate, and a top plate, ten regular screws, M6, together with washers. A fixture too attach the electric cabinet on the engine and stands to hold the electrical cabinet in place are created and 3D-printed as peripherals. All widgets are included in Table 1. The created 3D-printed widgets included in the workflows are based on components that are assembled on truck engines. Picking and placing parts, anthra screws, and screw in screws are common tasks performed on manual assembly lines.

Table 1: Part list of the widgets included in the workflow

Part name	Widget type	Quantity	Material	3D-printed
Fixture engine				
	Plate	1	Plastic	X
	Screw	3	Metal	
Fixture sub-assembly	Stand	4	Plastic	X
	Screw	4	Metal	
Electric cabinet				
	Bottom plate	1	Plastic	X
	Top plate	1	Plastic	X
	Screw assemble	4	Metal	
	Screw mounting	4	Metal	
	Inner part	1	Metal	
Electric adapter				
	Adapter outlet	1	Plastic	X
	Washer	1	Metal	
	Screw	1	Metal	
Electric adapter				
	Adapter outlet	1	Plastic	X
	Holder	1	Plastic	
	Washer	1	Metal	
Electric adapter				
	Adapter outlet	1	Plastic	

	Washer	1	Metal	
Electric adapter				
	Adapter outlet	1	Plastic	X
	Washer	1	Metal	
	Screw	1	Metal	

7.1.1 Electrical cabinet

Components that are 3D-printed and included in the sub-assembly are the top plate and the bottom plate, see Figure 7. They together form a shell of a component, which is a box located on truck engines. Cables are connected to the box, and these cables are branched and connected to, for example, sensors. The shape and design of the box can vary between different engine models. The 3D-printed electrical cabinet allows operations on the work table, a sub-assembly, and to work directly on the engine. This allows the robot and worker to work in parallel. It also allows performing hand guiding together with the robot, functioning as a lifting aid. Without a collaborative robot, the task would require the worker to hold the electrical cabinet at the same time as attaching or detaching the screws.

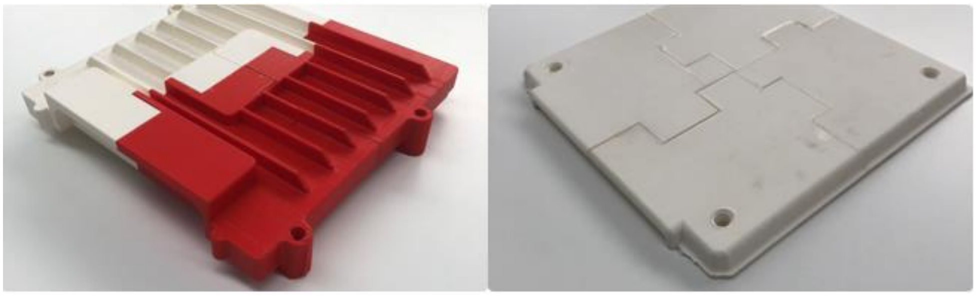

Figure 7: Top Plate (Left) and Bottom plate (Right)

7.1.2 Electrical adapters

The electrical adapters included in the workflows are outlets of sensors used on truck engines, see Figure 8. They simulate the connection of cablings, which are common tasks for manual assembly. The mounting and demounting of the sensor outlets requires finesse and are not heavy tasks to perform. This allows separating the worker from the collaborative robot during the parallel tasks in the workflows.

Figure 8: Electrical adapters

7.1.3 Fixtures

Fixtures are created for the demonstrator, four for the work table, and one on the engine. Four fixtures located on the work table holds the electrical cabinet in a stable position during the sub-assembly. This creates a fixed and accurate position. The robot gripper can, due to the fixtures, pick and place the widgets during the workflows without collide into the work table. The electrical cabinet is mounted and demounted on the fixture located on the engine during the workflows.

7.2 Layout

The final layout of the demonstrator is visualized in Figure 9. Included in the figure are conveyor, work table, the robot, the four fixtures on the work table, and fixture on the engine. Widgets are transported on the conveyor located at a pallet. The pallet is transported in both directions on the conveyor, back and forth to the kitting station. During assembly, the workflow goes from pallet to work table to fixture on the engine, and from pallet directly to engine. During the reversed mode, disassembly, the workflow goes from the fixture on the engine to the work table to pallet, and engine directly to pallet. Widgets located at the pallet are visualized in Figure 10.

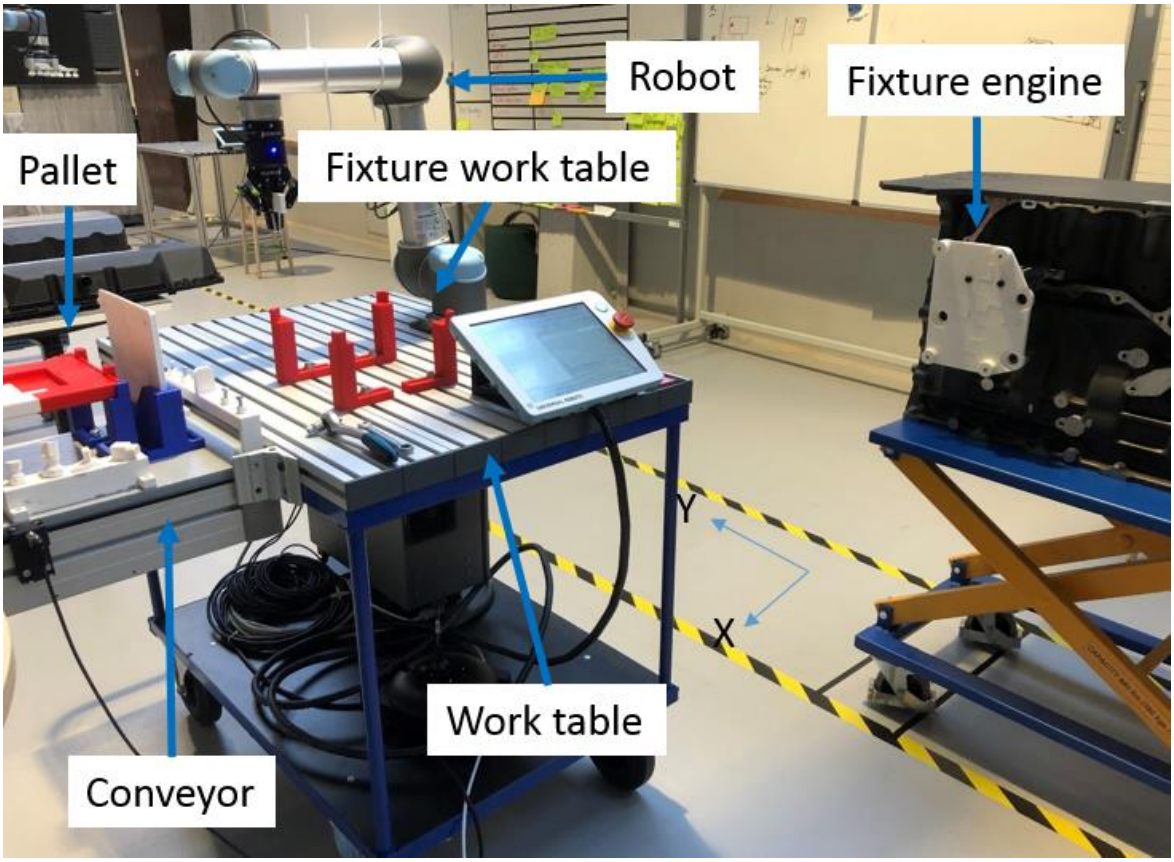

Figure 9: Final layout of the demonstrator

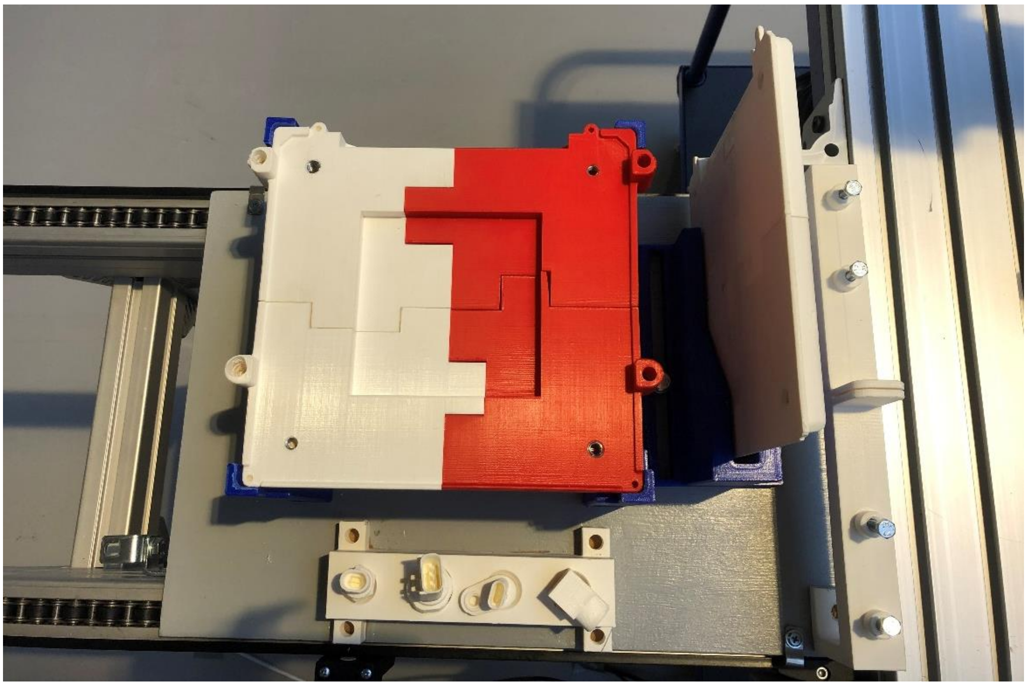

Figure 10: Widgets located at the pallet received from the kitting station

The electrical cabinet is assembled and disassembled on the work table and visualized in Figure 11. The robot performs the pick and place of the top plate and the bottom plate and locates them on the fixtures. The final assembly of the electrical cabinet is performed on the fixture attached to the engine. The final position of assembly is visualized in Figured 12.

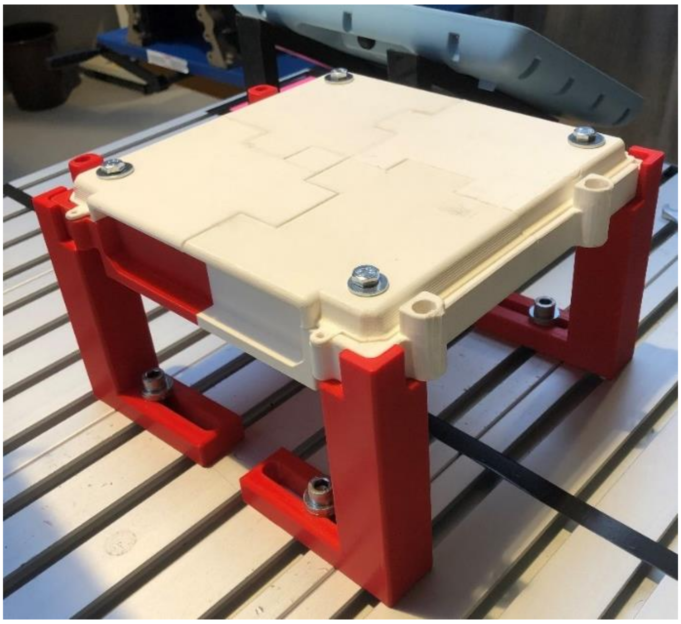

Figure 11: Assembled electrical cabinet located on the fixture

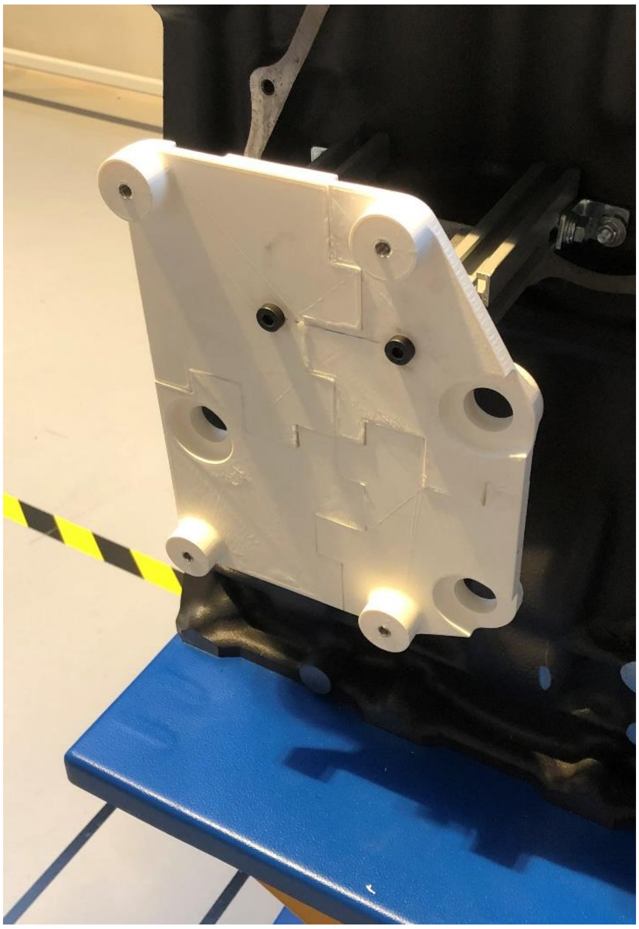

Figure 12: Fixture on engine

7.3 Division of tasks

The tasks are divided between the robot and the worker, depending on different aspects. Both top plate and bottom plate have the geometrical shape suitable for the gripper of the robot to pick and place. Assembling and disassembling these objects involves operations that are both repetitive and monotonous. Also, their positions are in a suitable range for the robot.

The inner part is added to the workflows to simulate tasks in between the ones performed by the robot. This to avoid separating the robot from the worker during these tasks. The inner part also adds weight to the electrical cabinet to simulate a heavier piece. These tasks are not classified in accordance to human-robot collaboration.

During the assembly workflow, two screws are assigned to the robot to be positioned, the two screws closes to the robot. The disassembly workflow does not include these tasks, and there are two main reasons for it. During assembly, the distance between the worker and the robot will decrease during the execution of the two screws located closes to the worker. The same reasons also apply to the disassembly workflow. Reason number two is that the requirement of accuracy for the pick and place of the two screws closes to the robot is too high due to variation in their locations. These tasks are classified as repetitive and monotonous, however, to assign the tasks to the collaborative robot, a tool change is required, camera for detecting the location of objects require to be included, and the layout should be rearranged.

Mounting and demounting the electrical cabinet is classified as poor ergonomics due to the weight, positioning, and the requirement for handling screws to attach and detach it at the same time as holding it in place.

Mounting and demounting sensor outlets are classified as requiring human finesse. The different positions on the engine for mounting and demounting and the low weight of them together with the simulation of cable connection are the main reasons for the classification.

7.4 Workflow

The tasks included in the workflow are divided into three categories, separately, hand guiding or working simultaneously on the same workpiece. The tasks are included in Table 2 for assembly and Table 3 for disassembly.

Table 2: Division of tasks between worker and robot, assembly

Division of tasks assembly

Operation	Task	Human	Robot	Hand guiding
Assemble Electric cabinet				
	Position top plate		X	
	Place inner part	X		
	Position bottom plate on top plate		X	
	Position screws	X	X	
	Anthra screws	X		
	Attach screws	X		
Mount Electric cabinet				X
Mount Electric adapter 1		X		
Mount Electric adapter 2		X		
Mount Electric adapter 3		X		
Mount Electric adapter 4		X		

Table 3: Division of tasks between worker and robot, disassembly

Division of tasks disassembly

Operation	Task	Human	Robot	Hand guiding
Demount Electric cabinet				X
Disassemble Electric cabinet				
	Unscrew screws	X		
	Remove screws	X		
	Remove bottom plate		X	
	Remove inner part	X		
	Remove top plate		X	
Demount Electric adapter 1		X		
Demount Electric adapter 2		X		
Demount Electric adapter 3		X		
Demount Electric adapter 4		X		

The hand guiding tasks consist of the assembled electrical cabinet, and widgets included are described in Table 4. The final positions of the electrical cabinet, together with the weight of the total part, are the reasons for including the hand guiding mode.

Table 4: Widgets assigned to the robot to handle

Electric cabinet		
Part name	Material	Weight (g)
Bottom plate	Plastic	226
Top plate	Plastic	362
Screw assemble	Metal	6
Inner part	Metal	923

Figure 13 described the work instructions for assembly established for the worker and the robot. The two tasks are the ones where both the worker and the robot are included. The task that is categorized as a sub-assembly has the final location at the work table.

Work instructions UR5								
Task	Nr	Element description	Require Initiation	Tool	Quantity	Human	Robot	Final Location
Assemble Electric part	1							Table
	1.1	Position top plate	X				X	
	1.2	Place inner part on top plate				X		
	1.3	Position bottom plate on the top plate	X				X	
	1.4	Position screws	X		2		X	
	1.5	Position + anthra screws			2	X		
	1.6	Attach screws		Socket wrench		X		
Mount Electric part	2							Engine
	2.1	Pick up Electric part + locate it to pre determined position	X				X	
	2.2	Start Hand-guiding	X			X		
	2.3	Position electric part for assemble against fixture				X	X	
	2.4	Position + anthra screws	X		4		X	
	2.5	Stop Hand-guiding				X		
	2.6	Attach screws		Socket wrench		X		
	2.7	Return to start position					X	

Figure 13: Work instructions for assembly shared between the worker and the robot

The work instructions established for the worker, which is separately performed and have no interaction with the robot are described in Figure 14. The final location for the tasks is located on the engine. This increases the distance between the worker and the robot during the operation.

Work instructions UR5					
Task	**Nr**	**Element description**	**Tool**	**Quantity**	**FinalLocation**
Mount Electric adapter 1	**3**				Engine
	3.1	Mount washers on screw			
	3.2	Mount adapter			
	3.3	Position + anthra screw		1	
	3.4	Attach screw	Socket wrench		
Mount Electric adapter 2	**4**				Engine
	4.1	Place washer on adapter			
	4.2	Assemble adapter + holder			
	4.3	Mount adapter			
Mount Electric adapter 3	**5**				Engine
	5.1	Place washer on adapter			
	5.2	Mount adapter			
Mount Electric adapter 4	**6**				Engine
	6.1	Mount washers on screw			
	6.2	Mount adapter			
	6.3	Position + anthra screw		1	
	6.4	Attach screw	Socket wrench		

Figure 14: Work instruction for assembly assigned to the worker

The order and predecessors of tasks for the assembly operation are visualized in Figure 15. Arrows symbolize the connection the tasks have between each other. Tasks one and two are divided between the worker and the robot, and therefore predecessors are required. Initiations of robot tasks are excluded from the figure except for the start and stop of the hand guiding.

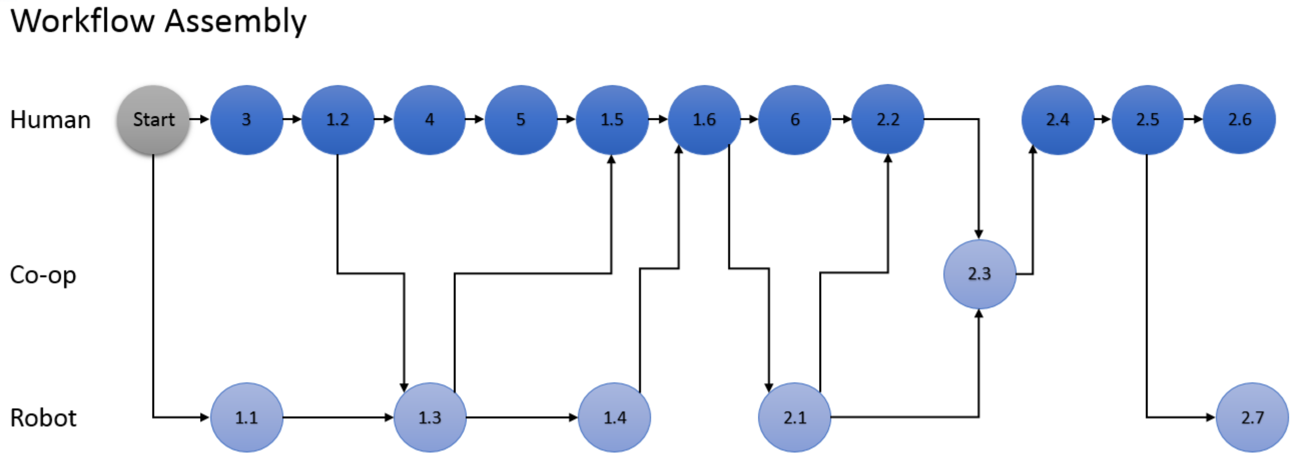

Figure 15: Workflow during assembly operation

Instructions for the disassembly operation, shared between the worker and the robot, of the workflow are visualized in Figure 16. The instructions for the workers separate tasks are visualized in Figure 17. The order and predecessors of tasks for the disassembly operation are visualized in Figure 18.

Work instructions UR5

Task	Nr	Element description	Require initiation	Tool	Quantity	Human	Robot	Final Location
Demount Electric part	1							Table
	1.1	Move to hand guiding pos	X				X	
	1.2	Start hand guiding	X			X		
	1.3	locate robot tool to determined position on electric part				X	X	
	1.4	Close gripper and lock robot so it holds Electric part	X			X	X	
	1.5	DeAttach screws		Socket wrench	4	X		
	1.6	Stop hand guiding	X					
	1.7	Place electric part on fixtur	X				X	
Disassemble Electric part	2							Pallet
	2.1	DeAttach screws		Socket wrench	4	X		
	2.2	Position bottom plate in kitting box	X				X	
	2.3	Remove inner part				X		
	2.4	Position top plate in kitting box	X				X	

Figure 16: Work instructions for disassemble shared between the worker and the robot

Work instructions UR5							
Task	**Nr**	**Element description**	**Tool**	**Quantity**	**Human**	**Robot**	**Final Location**
Demount Electric adapter 1	**3**						Pallet
	3.1	Deattach screw	Socket wrench	1	X		
	3.2	Demount adapter			X		
	3.3	Deattach washer					
					X		
Demount Electric adapter 2	**4**						Pallet
	4.1	Demount adapter			X		
	4.2	Disassemble adapter + holder			X		
	4.3	DeAttach washer			X		
Demount Electric adapter 3	**5**						Pallet
	5.1	Demount adapter			X		
	5.2	Deattach washer			X		
Demount Electric adapter 4	**6**						Pallet
	6.1	Deattach screw	Socket wrench	1	X		
	6.2	Demount adapter			X		
	6.3	Deattach washer					

Figure 17: Work instruction for disassemble assigned to the worker

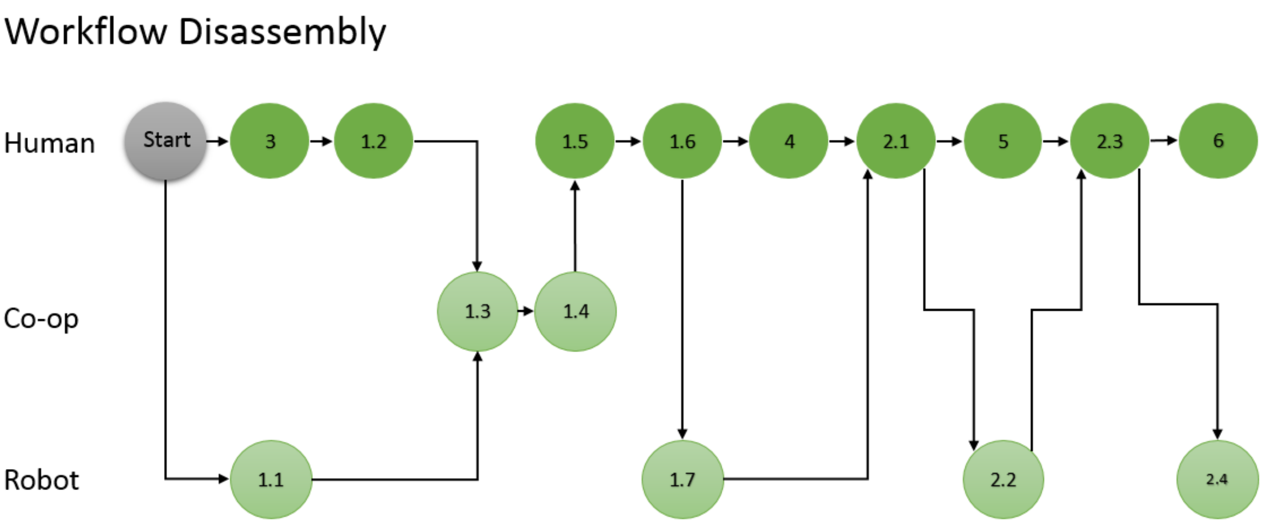

Figure 18: Workflow during disassembly operation

7.5 Configuration

A safety plane is created, which restricts the robot from moving the TCP below the base height of the work table. The robot is restricted regarding maximal force, speed, power, and momentum. In normal mode, which is the mode used for the demonstrator, the robot is limited to values according to Table 5. The weight of the gripper and the force and torque sensor, initial values without any widgets picked, is 1.22 kilograms, and the TCP has a minus 0.7 millimeters offset in X and 211.5 millimeters offset in the Z direction, the tip of the gripper. The center of gravity is put to 76.3 millimeters in the Z direction as the initial value of the gripper. The total payload and center of gravity applied for every widget included in the workflow for the robot are visualized in Table 6. The movement of the robot during execution is limited, according to Table 7. Hand guiding task, force mode, is limited to 150 mm/s in X, 100 mm/s in Y, and 100 mm/s in Z, together with 10 degrees/s for rotation around z.

Table 4: General limits assigned to normal mode on the robot

General limits

	Normal mode	Unit
Force	100	N
Power	150	W
Speed	300	mm/s
Momentum	10	kg m/s

Table 5: Settings of payload and Center of Gravity

Payload and Center of gravity

Widget	Weight of widget (kg)	Payload (kg)	Center of Gravity (CX,CY,CZ) (mm)
Bottom plate	0.226	1.446	(0, 0, 141)
Top plate	0.362	1.582	(0, 0, 141)
Electric cabinet	0.923	2.143	(0, 0, 141)

Table 6: Configurable max limits for robot movements applied

Configurable max limits for movement

Movement type	Tool speed (mm/s)	Tool acceleration (mm/s^2)	Limitation Joint speed (degree/s)	Limitation Joint acceleration (degree/s^2)
Move J			30	40
Move L	20	500		

7.6 Robot program

The tasks for the robot are divided into sub-programs, pick and place. The flowchart of the automatic assembled mode is shown in Figure 19. The program can be executed in two different modes, automatic or manual. The selection of the mode is performed at the beginning of the program. Automatic mode calls sub-programs, every task, picking a widget, and placing it, are two separate programs. Every new task has one home position in common. In between the tasks one local home position, for every pick and place operation, is in common, end of picking and start of placing, a confirmation is also necessary from the worker between them. In manual mode, the tasks can be freely chosen, and it also consists of calling sub-programs in the same way as in the automatic mode. The program for disassembling operations, both for automatic and manual mode, has the same functionality as the programs for assembly.

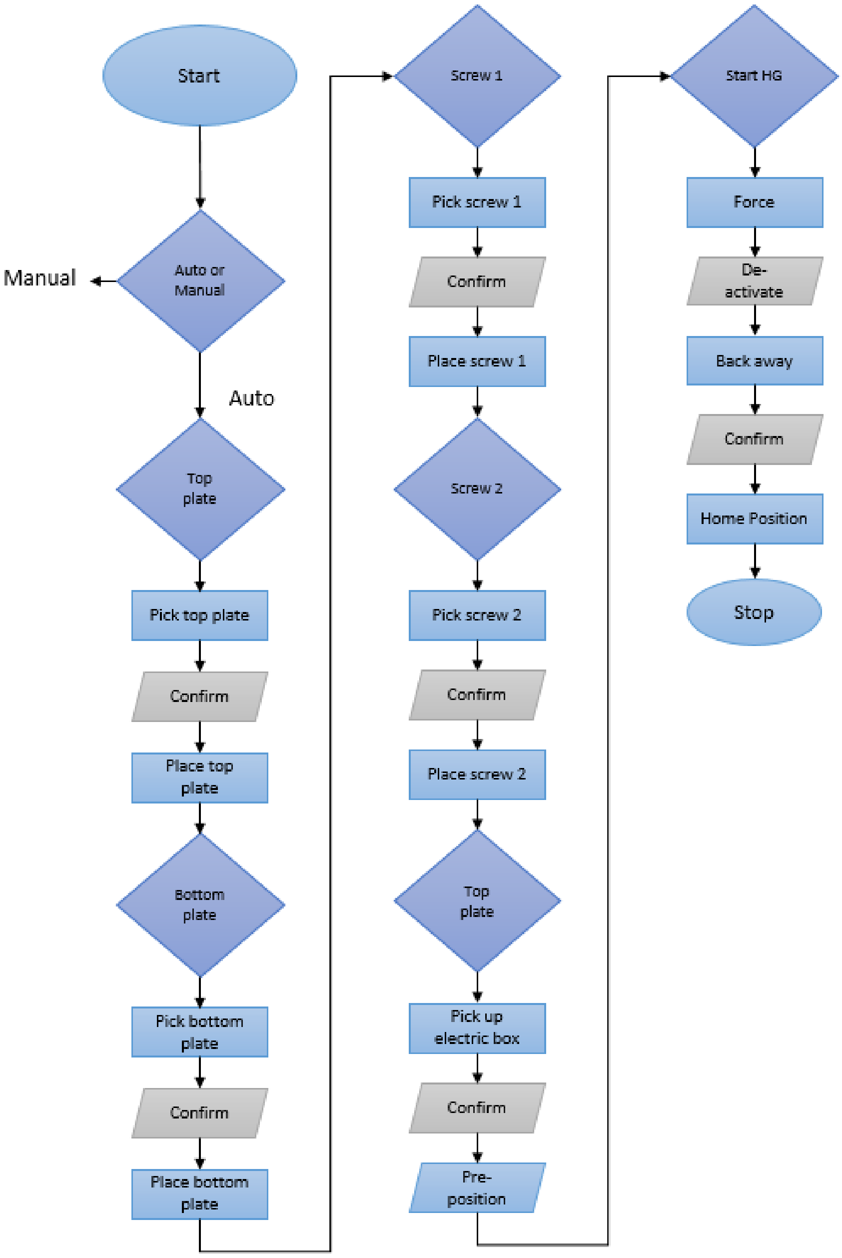

Figure 19: Flowchart of automatic mode

The hand guiding mode consists of a force mode, which is a function included in polyscope. The X, Y, and Z directions are configured to be free for the worker to move in. This due to the variation of the final assembly position, together with rotation around the Z-axis during hand guiding. The gripper is programmed only to fit the widget before it closes, to prevent any fingers from being clamped. The force used for the gripper is regulated depending on the type of widget it picks. When the hand guiding task is fulfilled, a movement that goes away from the worker is included. This is performed before the robot will continue to move home according to the programmed path.

7.7 Observations and experiments

The workflow of the demonstrator includes tasks performed by both the robot and the human, separate and together. Restrictions sat for the demonstrator are that the working height for the TCP is limited to the chest, and a maximum speed of 300 mm/s is configured. The experiments and observations are performed in four steps.

The first step is to ensure that the robot can perform its separate tasks back and forth. This consists of picking and placing the widgets from one position to another and then back again, reversed. Tasks that varied between the assembly- and disassembly mode is instead repeated with human interference to place the widgets back to their starting position. Figure 20 visualizes all tasks that are evaluated during the experiments. When the tasks can be performed ten times without any changes required, in positioning or movements, they are categorized as approved, and the next step is initiated.

Step 1					
Mode	Task	From	To	Repetitons (Nr)	Approved (Y/N)
Assembly					
	Pick top plate	Pallet	Home pos	10	Y
	Place top plate	Home pos	Work table	10	Y
	Pick bottom plate	Pallet	Home pos	10	Y
	Position bottom plate on top plate	Home pos	Work table	10	Y
	Pick screw 1	Pallet	Home pos	10	Y
	Place screw 1	Home pos	Work table	10	Y
	Pick screw 2	Pallet	Home pos	10	Y
	Place screw 2	Home pos	Work table	10	Y
Disassembly					
	Pick bottom plate	Work table	Home pos	10	Y
	Place Bottom plate	Home pos	Pallet	10	Y
	Pick top plate	Work table	Home pos	10	Y
	Place top plate	Home pos	Pallet	10	Y

Figure 20: First step of the experiments

The second step consists of separate tasks for the robot to be performed in the correct sequences. During this step, a human is participating so that the robot can perform its tasks in the correct sequences. Figure 21 visualizes all tasks that are evaluated during the experiments. For the robot to perform a new task, a human is required for initiation. The second step focus on maintaining the accuracy of the robot. Distances are controlled between the human and the robot. Changes in robot movements are made to increase the distances during the experiments and to ensure that the transition between tasks is performed correctly, according to their programmed home positions. When five runs of assembly and disassembly can be performed without any changes required, the step is categorized as approved, and the third step can be initiated.

Step 2				
Mode	Task	Order	Repetitons (Nr)	Approved (Y/N)
Assembly Sequence			5	Y
	Position top plate	1		
	Position bottom plate on top plate	2		
	Position screw 1	3		
	Position screw 2	4		
Disassembly Sequence			5	Y
	Position bottom plate	1		
	Position top plate	2		

Figure 21: Second step of the experiments

The third step consists of performing the hand guiding tasks as a sequence of mounting and demounting the electrical cabinet on the engine fixture. A human is participating during the experiments to perform the tasks together with the robot. Figure 22 visualizes all tasks that are evaluated during the experiments. The focus during this step is to increase the performance level of the hand guiding tasks, stability of the robot, and the flow during transportation. During this step, the configuration of the TCP is controlled and approved, payload and center of gravity play a major role in achieving stability during the performance. When five runs of mounting and demounting the electrical cabinet can be performed without any changes required, the step is categorized as approved, and the fourth and last step can be initiated.

Step 3								
Mode	Task	Order	Require initiation	Human	Robot	TCP config	Repetitons (Nr)	Approved (Y/N)
Assembly sequence							5	Y
	Pick up electric cabinet	1	X		X			
	Enter human workspace, hand guiding position	2	X		X	Electric cabinet		
	Hand guiding	3	X	X	X	Electric cabinet		
	Stop hand guiding	4		X				
	Mount electric cabinet	5		X				
	Move away from engine	6	X		X	Tool		
	Move to home pos	7			X	Tool		
Disassembly sequence							5	Y
	Move to hand guiding position	1	X		X	Tool		
	Enter human workspace, hand guiding position	2	X		X	Tool		
	Hand guiding	3	X	X	X	Tool		
	Stop hand guiding	4	X	X				
	Demount electric cabinet	5		X				
	Move away from engine	6	X		X	Electric cabinet		
	Place electric cabinet on fixtures at work table	7	X		X	Electric cabinet		

Figure 22: Third step of the experiments

The fourth step consists of performing the total workflows for both modes, assembly and disassembly. During the experiments, the focus is to identify any risks of transient and quasi-static contact. A human is participating during the experiments to conduct the workflows together with the robot. Other aspects documented are movement type of the robot, width and force used for the gripper, and the minimum distance between chest and TCP.

The evaluation table from the fourth step is visualized for assembly in Appendix B and for disassembly in Appendix C. Results from the evaluation are, contact of hands and fingers can occur during positioning of the top and bottom plate. During the tasks, quasi-static contact can occur between the fixtures and top plate and top plate and bottom plate. Transient contact can occur during positioning before the hand guiding operations.

7.8 Evaluation of the adapted methodology

The objectives of the project were established based on the primary goal of the project. The collaborative robot was introduced to establish high flexibility in relation to aspects, such as reversibility, quality, and ergonomic. Established data, predecessors, sequences of the workflows, operation lists, and attributes of the widget have been utilized and included in the result. Division of tasks between the collaborative robot and the human has utilized the proposed areas where poor ergonomics, monotonous tasks, and positions of tasks, have been identified. The results from the project point out that the proposed methodology has been adaptable and applicable, even with the lack of a current state.

The sustainability factor has increased for the project. By including a collaborative robot for both flows, an incensement of the ergonomic factor has been achieved. The safe-guard mode, hand guiding, has made it possible to facilitate tasks that are categorized as physically demanding and includes poor ergonomic. The flexibility level has increased; the operator can control the robot and skip tasks together with the possibility of disassembly on the demonstrator. The quality aspect has increased; the workflows require the worker to be active and control the robot and the fact that a collaborative robot is implemented.

8 Discussion

Safety standards and the technical specification used as input to the project influenced the implemented demonstrator. Aspects, such as the layout of the demonstrator, configuration of equipment, and programming of the robot, were influenced to acknowledge aspects that could be harmful during the workflows. The separation distance between the robot and the worker was the first aspect. It influenced the layout, the goal to keep the distance between the worker and the robot as high as possible without restricting the performance. The fact that the distance to the final assembly location should be able to be reached with the robot, during hand guiding, without interfering with the restricted distance, between the demonstrator and the AGV of 500 millimeters. The pallet, located on the conveyor, was something that the positioning of the robot interfered with, the reachability. The restricted distance, between working table and engine, limited the engine to stop at the start of the working table to ensure that the possibility to clamp the worker against the engine or table during hand guiding was eliminated. The aim to reduce or eliminate the risks of transient and static-quasi contact influenced both the layout, configuration, and programming of the robot. During the configuration of equipment and programming of the robot, the aim was to eliminate risk factors. The gripper was programmed only to fit the widget picked to avoid that fingers could be clamped during the closing of the gripper. Dependent on what widgets were picked, the force and speed applied were regulated.

Many parameters and requirements were needed to be addressed during the project. Other projects included in the overall project were influenced by each other and their specific requirements. Widgets included in the project were required to be in reach during pick and place with the robot.

For a collaborative robot implemented without a camera, for monitoring or object localization, where the accuracy or variation of different aspects are included, most variation in positioning, the way to conduct the work might be restricted. Automatic tasks can always fail due to the lack of accuracy, not only for the robot. For this project, the variations in the positionings of the widgets included in the workflow received can restrict the performance of the workflow itself. The hand guide mode is not only preferably for relieving of heavy tasks, but also for tasks that can variate in both small positioning changes and to new locations.

The two workflows included in the project had some differences between each other. The pick and place of the two screws could not, in an accurate way, be performed during disassembly. The programming part for the disassembly workflow could reuse many of the waypoint used in the assembly workflow. This required the parts to be picked in the same position as when they were placed.

The positioning of the parts on the fixtures was essential for the reuse of waypoints. An important aspect when it comes to the created widget is that they were designed with the reversibility factor in mind. The workflows did not include any tasks that change the attributes of the widgets included. In the industry, parts used might be assembled in a way so that they are not easy or even impossible to disassemble. When it comes to sustainable development, one important aspect is as far as it is possible to design products that can be disassembled, or at least possible to separate different materials from each other.

Division of tasks between robot and human were based mainly on a proposed framework. The project focused on different aspects, and facilitation for workers was one of them. By decreasing the heavy and un-ergonomically tasks, the created workflows could focus more on awareness for the worker. During the workflows, the worker had control. The worker was required to initiate tasks performed by the robot. By including parallel workflows, the initiation of the tasks was included to establish a flow.

The project has contributed with essential aspects regarding human-robot collaboration, mainly concerning reversibility. Disassembly of products is mainly performed either by a robot or a worker. This project combines them to gain both their strengths to perform a disassembly operation. The result of the project can be seen as an eye-opener when it comes to combining them during this type of operation. All companies cannot perform the disassembly on the same station as this project aimed to do. Utilization of the same tools and location were also in focus during the project. Even so, the project can inspire companies and other interested parties to evaluate this type of solution in the future.

Benefits that the solution can contribute with are an increase of flexibility for assembly and disassembly, rework potential, and to increase the recyclability of products. The demonstrator created was not isolated during the creation. Inputs and requirements from other linked stations were taken into account to reach the goal of the project. When it comes to the creation of stations for evaluation purposes, they are often isolated from the surrounding. The technical specification has been utilized during the project to create a baseline for further safety evaluation. This is an important aspect when it comes to the establishment of human-robot collaboration. By including the aspects in an early stage, unnecessary rework can be decreased or eliminated. The project has utilized a new methodology for implementing human-robot collaboration where many steps and aspects have been taken into account during the project. The results from the project show that the framework provides clarity in the project design process and that the majority of the methodology applies to projects without a current state. However, the used method could also be improved to incorporate completely new workstations where no current solution exists. There is not always a current state, and new products can arrive that require new lines or stations where collaborative robots can be utilized.

9 Conclusion

This chapter evaluates the work performed against the purpose and objectives established for the project. Recommendations regarding future work are explained at the end of the chapter.

9.1 Evaluation of the purpose

The primary purpose of the project was to create a human-robot collaboration demonstrator which contains typical manual assembly elements. This means that the elements performed on the demonstrator is divided between the collaborative robot and the worker. The demonstrator created will work in two modes, assembly and disassembly.

The implemented demonstrator contains typical elements included in manual assembly. These elements are divided between the robot and the worker to obtain the strengths of both. The demonstrator can perform assembly and disassembly of the workflow.

9.2 Objectives

Main objective: *The main objective is to investigate and evaluate the possibilities of using human-robot collaboration for manual- assembly and disassembly, performed on the same demonstrator. The project also includes creating a physical demonstrator where human-robot collaboration can be performed and evaluated.*

The demonstrator created can perform both assembly and disassembly operations of the established workflow.

Sub-objective: *Identify common manual assembly tasks in the industry, subject to human-robot collaboration.*

Common manual assembly tasks performed are identified from the industry and implemented and divided between worker and robot.

Sub-objective: *Define products with inspiration from the industry and Volvo GTO, subjected to human-robot collaboration. These products should be defined so that parallel operation and hand guiding can be beneficial.*

Products identified are an electrical cabinet together with sensor outlets. Engines are equipped with a central part where cablings are connected to. The assembly of the electrical cabinet mimics the mounting of heavy parts on the engine at the same time as sub-assembly elements can be included. Sensor outlets are included to mimic tasks where workers connect cablings and stripes on the engine, common elements performed during manual assembly of an engine.

Sub-objective: *For given products define:*

- *Layout and equipment suitable to produce given products.*
- *Operations needed to produce given products*.

Layout and equipment required to perform the workflows with the identified parts are defined and established. All operations required are defined, and operation lists are created.

Sub-objective: *Classify operations in accordance to human-robot collaboration and divide operation between worker and the collaborative robot.*

The tasks required are both classified and divided between the robot and the worker for both assembly- and disassembly workflow.

Sub-objective: *Create a demonstrator that includes the possibility to work in two modes, assembly and disassembly.*

A demonstrator is created where human-robot collaboration can be performed for two modes, assembly and disassembly.

Sub-objective: *Include general safety aspects while creating the demonstrator, to establish a baseline for a future safety evaluation. This includes aspects, such as the layout of the demonstrator, configuration of equipment, and programming of the collaborating robot.*

General safety aspects have been in focus during the creation of the demonstrator. Distances, initiation of tasks, programming and configurations have been implemented with safety in focus.

9.3 Future work

Future work that is recommended to perform regards mostly safety aspects for the demonstrator. A safety evaluation needs to be performed concerning the current workflow. Safety equipment required to perform the workflow safely together with limitations of speed, force, power, and momentum should be investigated. Variation of maximum speed, depending on the actual location and distance to the worker of the tool, should be controlled to lower the time consumption of the tasks.

To increase the flexibility of the demonstrator, including other products and new tasks to perform, human-robot collaboration, the required safety measures performed should include possibilities for increasing other products and tasks. A more extensive investigation due to flexibility aspects should be performed.

One restriction regards the equipment, a camera for monitoring positions of objects is recommended to include to decrease the level of accuracy, regarding positioning of objects, required of incoming and outgoing widgets.

Another aspect regards the collaboration with surrounding stations. In order to establish a functioning manufacturing line located at Assar, the collaboration needs to be continued regarding the requirements and limitations identified during the continued work. Requirements that are essential for the manufacturing line to function requires to be investigated and adapted for further work. The recommended aspects regarding the surrounding stations are signals from and to the robot controller and the sensors located on the conveyor.

10 References

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Appendix A: Universal robot, UR5 specification

EN 09/2016

UNIVERSAL ROBOTS

UR5 Technical specifications

Item no. 110105

6-axis robot arm with a working radius of 850 mm / 33.5 in

Weight:	18.4 kg / 40.6 lbs
Payload:	5 kg / 11 lbs
Reach:	850 mm / 33.5 in
Joint ranges:	+/- 360°
Speed:	All joints: 180°/s. Tool: Typical 1 m/s. / 39.4 in/s.
Repeatability:	+/- 0.1 mm / +/- 0.0039 in (4 mils)
Footprint:	Ø149 mm / 5.9 in
Degrees of freedom:	6 rotating joints
Control box size (WxHxD):	475 mm x 423 mm x 268 mm / 18.7 x 16.7 x 10.6 in
I/O ports:	Controlbox / Tool conn. Digital in: 16 / 2 Digital out: 16 / 2 Analog in: 2 / 2 Analog out: 2 / -
I/O power supply:	24 V 2A in control box and 12 V/24 V 600 mA in tool
Communication:	TCP/IP 100 Mbit: IEEE 802.3u, 100BASE-TX Ethernet socket & Modbus TCP
Programming:	Polyscope graphical user interface on 12 inch touchscreen with mounting
Noise:	Comparatively noiseless
IP classification:	IP54
ISO Class Cleanroom robot arm:	5
ISO Class Cleanroom control box:	6
Power consumption:	Approx. 200 watts using a typical program
Collaboration operation:	15 Advanced Safety Functions Tested in accordance with: EN ISO 13849:2008 PL d EN ISO 10218-1:2011, Clause 5.4.3
Materials:	Aluminum, PP plastic
Temperature:	The robot can work in a temperature range of 0-50°C
Power supply:	100-240 VAC, 50-60 Hz
Cabling:	Cable between robot and control box (6 m / 236 in) Cable between touchscreen and control box (4.5 m / 177 in)

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Appendix B: Observation performed on the assembly workflow

Observation sheet for Workflow													
				20 to 150 mm/s	20 to 235 N			Risk for contact		Minimum chest distance from TCP (mm)			
Task	Movements	Performed task (pick or place)	Gripper pos (%)	Gripper speed (%)	Gripper force (%)	Max distance between the claws and widget (mm)	Home pos	Transient	Quasi-static	Table	Pallet	Engine	Time (s)
Pick top plate	Move J		45	10			X						20
	Move J												
	Move J	Pick	100	10	100	3			Fingers or hand	>500			
	Move J												
Place top plate	Move J												20
	Move J												
	Move L	Place	0	10	10				Fingers or hands		480		
	Move J						X						
Pick bottom plate	Move J		64	10									23
	Move J												
	Move L	Pick	100	10	100	2				>500			
	Move J												
Place bottom plate	Move J												15
	Move L	Place	54	10	10						>500		
	Move J						X						
Pick screw 1	Move J		65	10									11
	Move J												
	Move L	Pick	100	10	10	3			Fingers or hands	>500			
	Move J												
Place screw 1	Move J												5
	Move L	Place	65	10							>500		
	Move J												
Pick screw 2	Move J						X						9
	Move L	Pick	100	10	10				Fingers or hands	480			
	Move J												
Place screw 2	Move J												8
	Move L	Place	67	10					Fingers or hands		>500		
	Move J												
Pick electric cabinet	Move J		35	10									22
	Move J												
	Move L	Pick	100	10	100	2					>500		
	Move J												
Position electric cabinet for HG	Move J							Torso				Close to worker	11
Initiate HG	Move L							Torso				Close to worker	10
Hand Guiding	Free drive											Close to worker	
Move away	Move L		36	10	10							Close to worker	25
	Move J		45	10									
Total Time													179

Appendix C: Observation performed on the disassembly workflow

Observation sheet for Workflow disassembly													
				20 to 150 mm/s	20 to 235 N			Risk for contact		Minimum chest distance from TCP (mm)			
Task	Movements	Performed task (pick or place)	Gripper pos (%)	Gripper speed (%)	Gripper force (%)	Max distance between the claws and widget (mm)	Home pos	Transient	Quasi-static	Table	Pallet	Engine	Time (s)
Pre HG pos	Move J		36	10	10		X						8
Position gripper for HG	Move J												11
	Move J												
	Move J												
Initiate HG								Torso				Close to worker	10
HG	Free drive							Torso				Close to worker	
Close gripper			100	10	100			Torso				Close to worker	2
Move Away	Move J							Torso				Close to worker	5
Place Electric cabinet	Move J												33
	Move J												
	Move J												
	Move L	Place	65	10	10				Fingers or hands		>500		
	Move J						X						
Pick Bottom plate	Move J												15
	Move L	Pick	100	10	100	2			Fingers or hands	480			
	Move J												
Place bottom plate	Move J												23
	Move L	Place	54	10	10				Fingers or hands		>500		
	Move J						X						
Pick top plate	Move J		65	10	10								20
	Move J												
	Move L	Pick	100	10	100	3			Fingers or hand	480			
	Move J												
Place top plate	Move J												20
	Move J												
	Move J												
	Move L	Place	65	10	10				Fingers or hands		>500		
							X						
Total Time													147