DEGREE PROJECT FOR MASTER OF SCIENCE WITH SPECIALIZATION IN ROBOTICS
DEPARTMENT OF ENGINEERING SCIENCE
UNIVERSITY WEST

Human-Centric Redeployable Robotic Manufacturing System for the Aeronautics Sector

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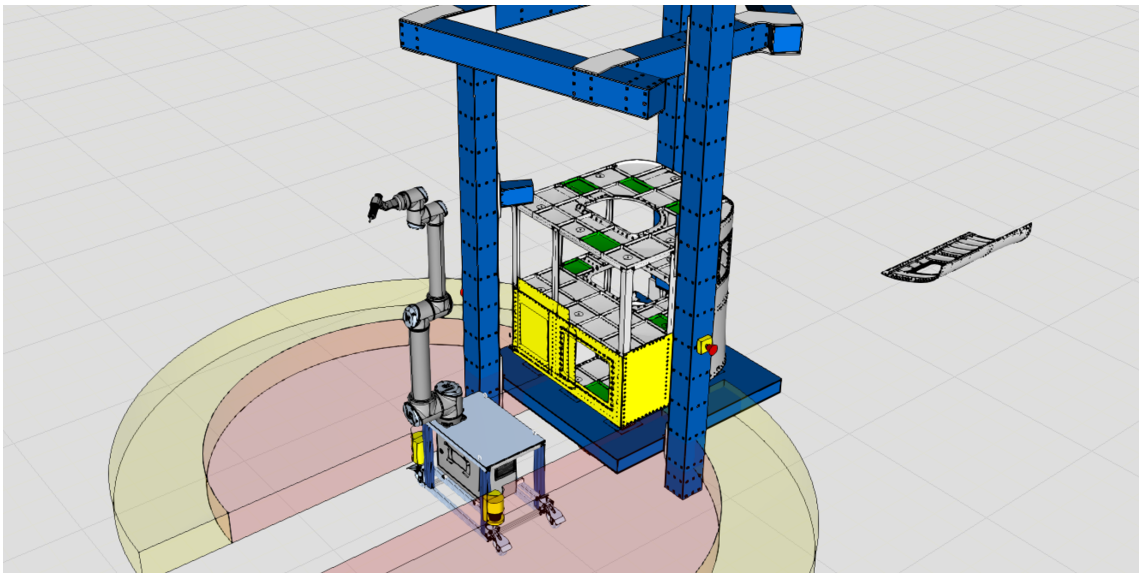

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Summary

Sponsored by SAAB Aeronautics, this study sets itself into the transition from the industry 4.0 to industry 5.0, putting operators at the core of the system development, with a focus on Human-Centric Design [1]. It aims to decrease the workload on operators and allow them to focus on other steps of the assembly process.
This study will explore how to implement a semi-mobile robot in a human-centric robot cell design for the manufacturing of aeronautic parts.
It investigates how to ensure safety in a human centric robot cell with a semi-mobile collaborative robot.
To answer these questions, the project follows an integrative, iterative, simulation-based research methodology. This combines an extensive literature review with iterative ideation, modeling and simulation. This approach allows the identification of relevant technologies, finding alternatives, and refining the concept with the objective to implement it in the SAAB assembly lines. Ultimately, this study aims to provide a practical and reconfigurable framework for a safe, flexible and human centric robotic manufacturing system. This work is intended to support the future choice of SAAB for their manufacturing systems, both for this use case, and for other assembly lines.

Affirmation

This master degree report, Human-Centric Redeployable Robotic Manufacturing System for the Aeronautics Sector , was written as part of the master degree work needed to obtain a Master of Science with specialization in Robotics degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

BONABAU Guillaume

Signature by the author

September 14, 2026

Date

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Symbols and glossary

IOT	Internet Of Things
HMI	Human-Machine Interface
UI	User Interface
MoCap	Motion capture: "process of capturing the large scale body movements of a subject at some resolution."[2]
Plug And Produce	"A flexible manufacturing system, where new products and resources can be seamlessly incorporated into the existing system without significant downtime, complex setup, or changes to the logical configurations"[3].
Industrial Robot (ISO 8373:2012(en))	"[...] automatically controlled, reprogrammable (2.4), multipurpose (2.5) manipulator (2.1), programmable in three or more axes (4.3), which can be either fixed in place or mobile for use in industrial automation applications" Note 1 to entry: The industrial robot includes: — the manipulator, including actuators (3.1); — the controller, including teach pendant (5.8) and any communication interface (hardware and software). Note 2 to entry: This includes any integrated additional axes.
PLC	Programmable Logic Controller
E-Stop	Emergency Stop
PNP	Plug And Play

1. Introduction

1.1 Introduction

With the ever growing need of industrialization, we see a new trend of robotization, focusing on shared workspaces. Unlike traditional industrial robots fixed in cells with safety barriers, this approach uses collaborative robots directly implemented into human workstations, to assist the humans in prepping steps, or in the assembly process, working jointly with them. These new setups aim to make use of the unused flexibility of industrial robots, allowing them to perform different tasks, at different places in the assembly process [4]. In many assembly settings, a traditional, fixed robot cannot be installed along side an operator. This is mainly because they lack the mobility a human operator has, that the assembly line was designed around. These problems are particularly evident in dense workstations and assembly lines with large complex parts. These settings create double-edged constraints, where a large robot is required for reachability, but the size of such a robot increases the risk of collisions within a densely packed assembly cell. While collaborative robots and mobile robotics have been widely investigated, there is little guidance and research for deploying robots for human centric operation in space-constrained assembly lines where access is constrained, with large workpieces to work on, needing frequent repositioning of small robots for a full coverage/access. This gap is even greater for inspection tasks and welding/sealing operations, where high accuracy and precision are required.

1.2 SAAB Aeronautics

Founded in 1937, SAAB AB aims to 'keep people and society safe' [5] by developing, products, services and solutions for the military and defense market. Their motto follows the old Latin proverb "Si vis pacem, para bellum". SAAB Aeronautics is the sponsor of this thesis, proposing a specific problem to investigate and identify solutions for.

1.3 Problem Description

1.3.1 Assembly Lines

In Linköping, Sweden, SAAB Aeronautics assembles the frame of military fighter jets, made mostly of machined aluminum parts, riveted and screwed together. The assembly line is divided in several workshops, juxtaposed to each other. These workshops are currently not robotized and rely entirely on human labor as of today. Each workstation is responsible for assembling part of the airplane frame (divided in four quadrants) that is then assembled together over the next workstation. This

follows a convergent multi stage assembly system structure. The Assembly line footprint is very limited, adapted for human labor, with walking space of around one to two meters, this is why the overhead cranes are often used to move subassemblies from one station to another. Subassemblies are held tight into the workstation through the help of a rigid steel frame, assuring repeatable accurate positioning of the parts around a tenth of a millimeter.

1.3.2 Aircraft Frame

Such that the space inside the frame of the aircraft is not useless, SAAB is using them as fuel tanks to store fuel for the engines. By applying sealant to all fasteners and angles, the frame can be airtight and hold fuel. However this increases the complexity of quality inspections, because they need to be continuous along the process as new parts will prevent access to previously assembled areas. Due to the complexity of a military fighter jet, all parts have very tight tolerances, often around a tenth of a millimeter. This precision require accurate method to inspect defects that may not be visible to a human eye.

1.3.3 Robotization

To improve efficiency of their assembly lines, SAAB Aeronautics aims to robotize part of the process of sealing and inspection. This change is intended to increase the inspection reliability, which is as of today performed by two different teams, and free the operators from part of the repetitive and precise task of sealing. However, due to the tight spaces in the part, it is expected that the robot will not be able to reach for these operations, and may still require operators to perform these tasks manually. The robot should be plug and produce as it will be often repositioned around the workstation, or from workstation to another. This repositioning should be done preferably without the overhead crane, such that it can be left available for more critical assembly processes.

1.3.4 Degree Project

This degree project primarily aims to answer how to implement a semi-mobile robot in a human-centric robot cell design for manufacturing of aeronautic parts. The secondary aim is to determine how to ensure safety in said human centric robot cell with a semi-mobile collaborative robot.
To find an answer, this degree project will try to identify the key technologies relevant to a plug and produce robotic cell used for the sealing and inspection operations on the current assembly lines through a literature study and simulate it in an adequate software.
Finally, it is important that the robot should include the key features relevant for its operational functions such as camera and sensors for inspection of fasteners and sealing operations.

2. Related work

2.1 Safety and Human-Centric Design

Industry 4.0 describes the shift in the technological advancement from the automation of industries into more connected, more intelligent autonomous systems, transitioning from mass production to individual production[6]. This was mainly characterized by the use of machine to machine communication and the use of IOT (Internet Of Things). Industry 5.0 reuses these strong foundations and aims to improve the operator wellness, by shifting the designs into being Human-Centric [1]. These improvements in the safety of the human and robot during their collaboration are intended not only to improve the well-being of the operators, but are also done in the aim to improve the flexibility and productivity [1]. As of 2022, G. Boschetti et al.[1] point out a "gap in the literature regarding a multiobjective task allocation that considers both the principles of Industry 4.0 and 5.0", gap confirmed during this project research. However, it is not uncommon to find literature related to one of these topics.
As of Industry 4.0, the IOT allowed for the development of remote safety element, such as wireless emergency stops. It is very important that at all times control can "be taken over these machines and also these machines, at any given time must be halted or stopped" [7] [8]. The paper published in 2014 by D. Garcia et al.[7] demonstrate how a wireless emergency stop works and its performance under standard conditions. This proves that an emergency stop can be triggered by anyone having access to one of those devices within a range of 25 meters of the receiver without a line of sight. In the eventuality that a robot is not in a fixed robotic cell, these wireless emergency stops could be moved along with the robot and placed to a safe distance, allowing anyone to stop the current process without getting too close, reducing the risk of an injury. Moreover, the paper proves that the framework will trigger an emergency stop in case of failure of the device. This is also how a wired emergency stop work, as a failure in the system will open the circuit, triggering the emergency stop. Finally the paper demonstrate that their device had a battery life of around 17h which is more than twice an eight-hour shift over a day.
Finally, we see research being done for the implementation of AI in HMI (Human-Machine Interface). This greatly simplifies the UI (User Interface), allowing any operator with any technical background to operate the robot for different operations. [9]. MoCap, also known as Motion Capture, is the "process of capturing the large scale body movements of a subject at some resolution."[2] Even though T. Moeslund et al. do not mention the use of MoCap as a safety element in a robotic system, it defines the "surveillance" use case as "one or more subjects are being tracked over time and possibly monitored for special actions"[2]. This implies the system could monitor operators with cameras around the robot and act based on the position of their body. For example, trigger an emergency stop if the operator is laying on the ground or slow the robot if the operator comes within the robot action range.

2.2 Plug and Produce Framework

ISO 8373:2012(en) defines an industrial robot as a "reprogrammable" "multipurpose" "manipulator". However in industrial applications, most of this "original flexibility is not utilized"[4]. Plug and produce systems are defined as "flexible manufacturing system, where new products and resources can be seamlessly incorporated into the existing system without significant downtime, complex setup, or changes to the logical configurations"[3]. It aims to make use of this flexibility by making the "the hardware exchange [...] in a plug and produce manner"[4]. This means that "the exchange must be fast and efficient"[4].
Plug and produce frameworks follow the guidelines of Industry 5.0 and human centric design, by making the changes to a robotic system more accessible to an operator without technical robotic knowledge. In 2022, G. Boschetti et al. observe a market trend in the robotic systems, leaning towards plug and produce systems, with high customization, with flexible yet highly productive systems [1]. To design a plug and produce framework, it is important to make a modular architecture, where the hardware and/or software should be modular allowing operators to make changes without technical knowledge. It is important to generalize some function, allowing different tools to be used within the same programs.[3][1][4]

2.3 Sensors and World Calibration

Explored as a strong possible solution for this project problems, calibration of the robot world position using sensors was investigated. These research identified to two separate key technologies allowing for accurate positioning of the robot, for drilling and welding tasks.
On one hand, B. Mei et al. describe a system used to calibrate a heavy duty industrial robot, mobile with three degree of freedom (both horizontal axis translation and rotation around vertical axis). This system uses a 2D camera vision system that calibrates the robot jig relative to the part using a reference hole in the part holder. By exploiting the camera depth with the focus features, they are able to calibrate the robot within all of its degree of freedom. Furthermore, as the camera is mounted parallel to the end effector, the robot is easily able to be calibrated up to 0.6mm. [10]
M. Rajaraman et al., on the other hand, use a laser sensor to calibrate a part to weld relative to the robot. This technology relies on using a 1D laser distance sensor and from a profile map generated with the robot movement, find the edges of the known part, then used to calculate its position in space.[11]
While both these papers provide relevant content about calibration, the SAAB assembly line has a few limitation that reduce greatly the use of such systems. First of all, the workstations are elevated compared to the building concrete floor, resting over a metallic structure with wooden flooring, a meter or so above the ground. This is done such that workers can go underneath the assembly for some operations. However the wooden flooring does not provide a structure rigid enough for the weight and inertia of the robot not to introduce inaccuracies while moving. Sec-

ondly, the frame onto which the assembly is connected is highly rigid, and can be used to assemble the robot onto it, leading to a far more accurate anchor point.

3. Method

3.1 Research Method

The research method selected for this degree project is an integrative, iterative, simulation-based research method. This method was selected as a means of addressing a practical problem identified by SAAB Aeronautics. The integration approach was selected as a way to explore different means of solving the problem. Research was performed to find papers related, or that might be adapted for the uses in this project. Finally, this project aims to simulate the found technologies to validate their relevance in this use case. The goal of the integrative approach was to reuse methods proposed by different studies, as none referred to this topic specifically. This allowed to combine relevant methods in one simulation. The iterative approach was used to refine the simulation after the integration of each component and method. This was very helpful to improve the simulation as it was getting more complex.

3.2 Simulation Environment

The simulation was carried on in Visual Component OLP Premium 4.9 and 5.0, and Visual Component Premium 5.1. Visual Components was selected because SAAB is proficient in the software and has used it previously, giving a starting basis for this project. When the need of new custom parts came in, OnShape was selected, as the author of this thesis has experience using it. Redaction of this degree project report was done locally in LaTex in a Visual Studio Code Environment as a text editor, using the LaTex Workshop extension, providing a graphical user interface for TinyTex, a LaTex compiler. All software has been used over a Dell Inspirion 16 7610 running the Windows 11 Operating System.

3.3 Project Schedule

The project followed an integrative methodology. The extensive literature review and the research were done prior to any development phase, such as the ideation, modeling and simulation. This decision was taken to be sure that the ideas developed and simulated would be the best choices for this application. Following this schedule allowed to investigate and eliminate technologies related to this study but not relevant for this specific use case. This waterfall progression established a strong theoretical baseline, limiting the risk of discovering major technical constraints during the simulation phase that would have required to start over. This was highly critical to be able to follow the academic calendar.
The ideation phase was also a crucial part of this thesis, where brainstorming and ideas were iterated and refined as new information/objectives from the company were specified, leading to more specific and precise aims.

4. Work

4.1 Robot Cell Setup

4.1.1 Robot Setup

This robot cell was designed around a Universal Robot UR10 collaborative robot. This choice was made to follow the current equipment owned by SAAB Aeronautics. This robot makes a solid choice for this system, thanks to its internal monitoring (allowing collision detection), and its easy integration to a system. Collaborative robots are also a standard choice for plug and produce robotic assistants [12].
This robot is controlled through the Universal Robot Standard Control box, which is a PLC (Programmable Logic Controller) with a safety controller, a power supply, and a teach pendant. This setup provides a strong plug and play basis for most of the robot functionality.
The controller is placed inside of a custom-made cart designed to be constructed with a modular aluminum frame. This cart aims to hold all of the necessary components of the cart, and internalize all the robot connections. The cart is semi mobile thanks to its retractable workbench caster, allowing an operator to easily move the robot when not in use. Furthermore, the cart has 4 eye bolts, allowing the full assembly to be quickly and safely attached to the workshop overhead crane if it cannot be moved to its next position on wheels. (Fig 4.1)
The robot is meant to be attached to a quick release base system designed by SAAB Aeronautics, allowing to be moved from the cart to other bases on the workstation frame. This system will allow operators to move the robot quite easily and ensure a very rigid assembly once mounted to the robot frame, minimizing errors at the end effector (Fig 4.2, 1). The robot will still be connected to the cart through cable to connect it to the PLC, and to compressed air. The cart can then be connected to the nearest power outlet and compressed air cable to receive the necessary power to operate.

4.1.2 Tool Setup

The cart on which the robot sets also includes storage for an automatic and manual tool changer. Suggested by Universal Robots, the TripleA Robotics Wingman Quick Changer allows for a fast and easy way to change the tool on the robot (Fig 4.2, 2). This tool changer can let compressed air and the sensor wirings through, making it suitable for all the applications of this use case. The tool changing operation can either be triggered automatically when the robot is standing on the cart, or done manually by the operator otherwise[13].
To perform all of its tasks the robot needs two different tool heads. One toolhead is solely dedicated to the sealing process, with a computer controlled caulk gun dispensing sealant over the fasteners. The second toolhead is mainly centered around the "Micro-Epsilon LLT3010-50/RT-BL" sensor. This sensor uses a laser to generate

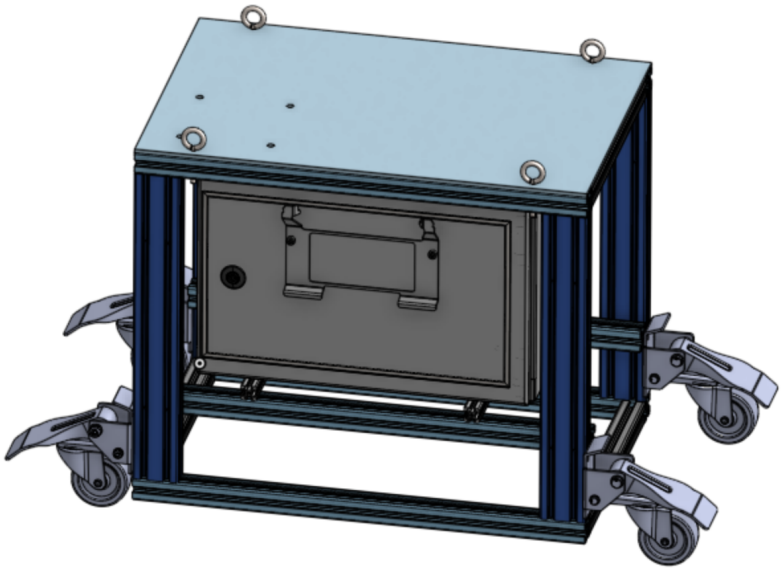

Figure 4.1: 3D Model of the robot cart in OnShape

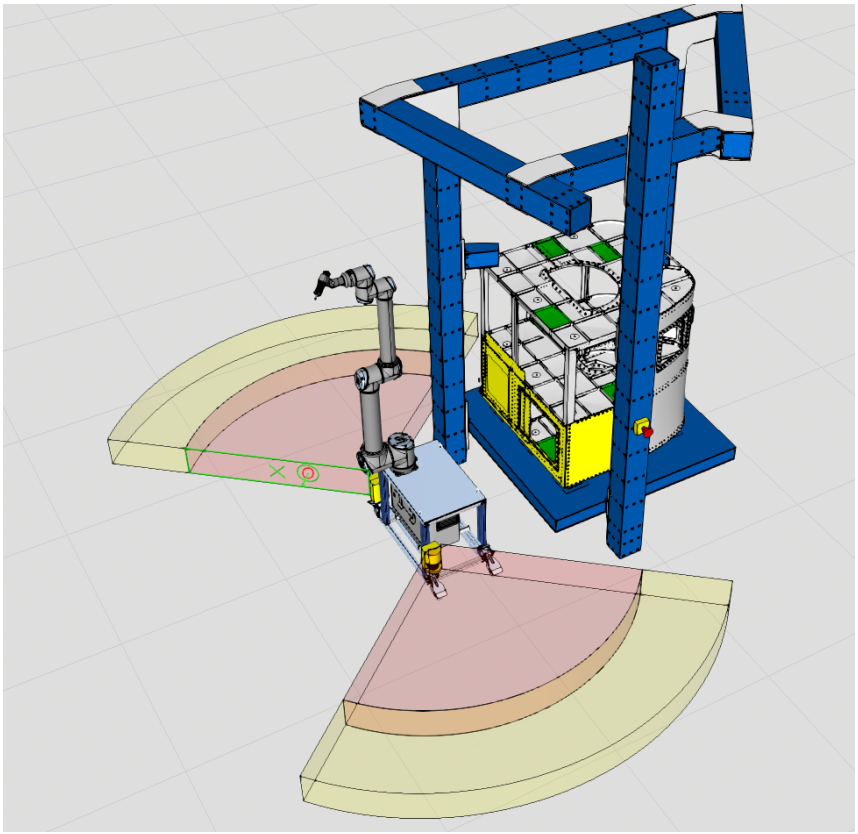

Figure 4.2: 3D Model of the robot cell in Visual Components

a linear profile of a surface, allowing to detect surface finish defects, scratches, and most importantly the offset between rivets and the surface[14][15].
This sensor can communicate to the robot using PROFINET, EtherCAT, EtherNet/IP which are all very common communication protocols. For this project it was chosen to use EtherCAT as it is the most used communication protocol with PLC in the automation industry[14][15].

4.1.3 Safety elements

Security is very important to ensure no one and nothing is hurt while operating the robot. To make the robot cell safe, preventive and reactive safety elements were implemented. To find operators within the cell and estimate a danger level, safety scanners and cameras were implemented to the robot cart (Fig 4.2, 3). The scanner detects the distance to the closest object, in the robot cell. Cameras, on the other hand, are able to precisely detect human operators and their limb positions relative to the robot thanks to MoCap. This allows the robot to calculate if the operator is within its next path.
As a last resort safety feature, several wireless emergency stop buttons have been placed around the workstation, allowing operators to quickly react to an emergency and stop the robot to avoid more damage. One more emergency stop can also be found on most teach pendants, allowing the operator, if they have it in their hands, to trigger an E-Stop. Lastly, the ur10 robot can detect a current surge in case of collision and trigger an emergency stop on this event, this technology is called internal monitoring. Even though this should not be used as a safety feature as damage will already be done by then, it can avoid further injuries or damage to the operator or the robot cell. [16]

4.2 Robot cell Simulation

The cell was simulated in Visual Components OLP Premium 4.9, a path for the sealing operation was implemented. A new tool for the inspection sensor was used in Visual Components. Path for tool swapping was implemented, allowing the robot to choose which tool to use. To simulate the Wingman Quick Changer, the simulation uses an asset available by default in Visual Component. This asset is already prepared for the use in robot simulation with mounting positions and frames. Though the UR10 robot has a lot of reach, it was largely limited in the simulations due to the configurations. Each robot target and configuration had to be adjusted manually to ensure the robot would not collide with the part or itself during its process. Even if Visual Component provide a very easy plug and play approach for programming robots, its main limitation is the process required to reposition targets.

5. Results and Discussion

This degree project work has identified the key features required for the implementation of this robot cell. The simulation partially validated the reach of the robot, confirming the choice works for this use case. However, simulation proves that collision happens frequently during the programming phase due to the tightness of the space the robot operate within. It is essential to enable collision in the simulation software during the offline programming phase, to assess the risks of running the robot before applying it in a real world scenario. Every single path programmed without this feature proved to have collisions with the aircraft frame. To reduce the damage that a collision will provoke, all paths were designed with a robot speed of 20%. Even though the UR series robot has collisions sensors, those only trigger after or during a collision, when damage has already occurred. Following the $E_{\text{initial}} = \frac{1}{2}mv_{\text{max}}^2$ formula, reducing the speed to 20%:

$$
\begin{aligned}
v_{\text{new}} &= 0.20\, v_{\text{max}} \\
E_{\text{new}} &= \frac{1}{2}mv_{\text{new}}^2 = \frac{1}{2}m(0.20\, v_{\text{max}})^2 = 0.04\left(\frac{1}{2}mv_{\text{max}}^2\right) = 0.04\, E_{\text{initial}} \\
\Delta E &= E_{\text{initial}} - E_{\text{new}} = E_{\text{initial}} - 0.04\, E_{\text{initial}} = 0.96\, E_{\text{initial}}
\end{aligned}
$$

This reduces the energy of the impact effectively by

$$\text{Percentage Reduction} = \frac{\Delta E}{E_{\text{initial}}} \times 100\% = 96\%.$$

While this may sound like a lot, this does allow the robot to maintain quite high speeds. The robot is still able to change from one tool to another in 15 seconds, and to move from one screw to seal to another in a second.
Furthermore, a better robot for this specific use case would probably require more degrees of freedom, not to orient the end effector better, but to orient the last links better and increase reach in tight spaces.
The UR10 cobot was able to integrate both a scanner tool for inspection and a sealing gun tool to add sealant to screws and edges. This provides the robot with versatility in the tasks it can do. Tool changing is automatic, but can also be done manually by an operator as is common with most tool changers. Automatic tool changing is only possible when the robot sits on its carrier. It is in this position that the robot knows where the tool changer is, and can perform this routine. This is done within a very quick 15s swap time.
The newest generation of the UR10, the UR10e, has a higher payload and, more importantly, a torque sensor at the base. While both the UR10 and UR10e use internal monitoring of motor current to detect a collision, only the UR10e has a true torque sensor, providing a second layer of redundancy. The UR10 is a good choice for prototyping the robot cell, but switching to a UR10e for the production environment will increase the safety of the cell.
The safety scanner, works in the perfect simulation environment, but because it detects anything in its range it stops/ slow down. In a real world environment, it

may falsely detect objects such as a workshop trolley, an operator walking by, a tool falling from a table, or anything crossing its path. These events will trigger a slow down in production or even a complete stop. These sensors must therefore be tested in a production environment to assess their value as a safety element in the real world. It is expected that a camera might prove to be a more reliable way of detecting risk, danger, and act upon it. The camera, in contrast to the laser sensor, can identify the items within its field of view, and be programmed to assess whether they represent a threat for the safety of the equipment or a human, where a laser scanner only senses if something is within the range.
The redeployment of the robot is based on two key elements. First, the robot is placed on a detachable zero tolerance base, similar to a tool changer. This base developed by SAAB allows to attach the robot around the cell on the assembly frame and on its cart very easily with less than a tenth of a millimeter accuracy. This cart was developed to move the robot around a larger distance when that is needed. It encase the robot controller, the safety controller, and all the equipment required for the robot to function. This cart is to be connected only to a robot, a power outlet and a compressed air line (The compressed air lines are commonly available around the workshop in Linköping), limiting the cables around the workspace, and therefore reducing tripping hazards. This cart is mounted on workbench caster wheels, that are retractable, allowing the cart to rest rigidly on the floor. Yet the wheels can be easily engaged with the push of a foot to move the cart again. These wheels can hold from 75 to 300 kilograms, more than enough to hold the 30kg of the robot and the rest of the cart. As the assembly line in Linköping are elevated compared to the concrete floor, the cart has 4 mounting points for lifting straps, such that the whole assembly can be moved with the overhead crane if it needs to be moved from the aircraft frame assembly line to the wing assembly line (both are situated at different elevations). Once the robot operations are done, it folds itself into its "storing position", to reduce its footprint over the cart and facilitate handling. Though the robot can be lifted by two operators or more, it is recommended to use the overhead crane or an engine crane to lift it from the cart to its mounting points. Especially because some of the mounting points are above the waist.

6. Conclusion

This study has implemented a semi-mobile robot in a human-centric robot cell design for manufacturing of aeronautic parts. While the accuracy of the robot cannot be quantified in a simulation, the tolerance stackup from the positioning systems stays under 0.2mm and is expected not to compromise the overall accuracy. Furthermore, while they have very high repeatability of around 0.1mm, Cobots have a very low positioning accuracy above a millimeter. This means the targets taught during offline programming of the robot will have to be retaught in real world to account for this error and ensure maximal accuracy. Safety was also investigated to ensure a proper setup guaranteeing the safety of operators and workers around the robot. By respecting the guidelines for Human-Centric Design and developing a way for the robot to be semi mobile, this project successfully answered its main question.

6.1 Future Work and Research

Even though the question was addressed through simulation, this simulation is incomplete as it cannot reproduce a real world environment. It will be necessary to develop a prototype to challenge the results of this project to validate or revoke the results. Furthermore, on a very important note, the safety element of the robotic cell will never be enough if the operators have not received proper safety training with the robot, as inadequate training will lead to errors and increase the frequency of dangerous situations and accidents.

6.2 Critical Discussion

The results of this study indicate that the presented system can be integrated in a human centric assembly line. The simulated tolerance stackup stays under 0.2mm. However this result is based on assumptions in the simulation and needs to be verified experimentally. Visual Component also can not simulate the absolute accuracy of the robot, and it is believed to be the biggest component of the real world tolerance stackup. therefore the targets taught during offline programming may have to be repositioned once, when installing the robot. The main limitation of this project is the simulation only based approach. Though very good to indicate the feasibility of the concept, it cannot be considered as a complete validation. A model cannot recreate the mechanical deformation, environmental disturbance, calibration error and other real world factors. This project has been a great professional experience, it allowed me to strengthen my skills, such as automation, research and analytical, critical thinking, and other soft skills. Working under NDA was a big challenge for this thesis, as very few outside help for proof reading or Visual Components assistance was possible. Though challenging, this pushed me into deepening my research and strengthen my academic writing skills.

6.3 Generalization of the result

This degree project answers a very specific problem, however, most of the results and methods can be generalized and used in similar projects. This project synthesizes very clearly the aims and goals of industry 5.0, Human centric design, and Plug and Produce systems. Those principles can be applied in any robotic project, as trends show they are now more and more investigated to the point they might become industry standards. Furthermore, sensors and technologies for this robotic cell are useful for similar quality control or welding/sealing operations.

7. Acknowledgements

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