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Faculteit Industriële Ingenieurswetenschappen  
master in de industriële wetenschappen: elektronica-ICT

## Masterthesis

Automated resupply management in existing production line with a  
cobot and an automated guided vehicle

PROMOTOR :

Prof. dr. ir. Eric DEMEESTER

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ing. Peter EVENS

COPROMOTOR :

ir. Danny JOOSTEN

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Dhr. Dario Batalha Par CLEMENTE

Wouter Van Rompaey

Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: elektronica-ICT

Gezamenlijke opleiding UHasselt en KU Leuven



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**KU LEUVEN**



## Acknowledgement

This master's thesis is conducted by Wouter Van Rompaey, student Engineering Technology in Electronics and ICT at the UHasselt and KU Leuven. It started from a challenge that was proposed by the T2-campus in Genk and consisted of four sub challenges, all in the field of Industry 4.0. The first two sub challenges were proposed for the thesis of two other engineering students, Charles Vancoppenolle and Eran Kaelen. Their thesis is called "Automated Recuperation and Stock Refilling in an Industry 4.0 Training Production Line". The third challenge has been tackled in this thesis. The period for the accomplishment was 6 months, from January 2021 until June 2021. This project was supervised by three external promotors are Peter Evens, Danny Joosten and Dirk Vrancken and by Prof. dr. ir. Eric Demeester as internal promotor. Besides these promotors, Dario Clemente Batalha Pardal was the mentor because he is responsible for the machines that were used and could help a lot with the research and the practical implementation. Also worth mentioning are the two fellow students that contributed to a successful cooperation to establish the communication between both projects. Besides that, they were also very supportive and helped to come up with different ideas to tackle a lot of the small problems along the way.



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## Glossary

Table 1 Glossary

<b>Word or abbreviation</b>	<b>Meaning</b>
<b>AGV</b>	Short for 'Automated Guided Vehicle'. It is a vehicle that can drive itself autonomously.
<b>Cobot</b>	Contraction from the words Collaborative and Robot. It is a robot that is made to work in collaboration with humans.
<b>PLC</b>	Short for 'Programmable Logic Controller'. This is a robust computer for industrial machinery.



## Abstract

In Industry 4.0 traditional factories transform into smart factories by integrating modern smart technology. The T2 campus in Genk features the Smart Innovative Factory (SIF) 400 developed by SMC International Training. This is a scaled model of a smart integrated factory created for training and showcasing purposes. It represents a nearly fully automated production line for the assembly, stocking, distribution, and recycling of goods. This is regulated by an educational MES system that can effectively handle highly customized orders.

This thesis's goal is to enhance the automation in this existing production line, in particular the stock refilling of the stacking module. The module's main function is that a collaborative robot stacks incoming containers together on a pack. The module is fully autonomous in its main functionalities, but the refilling of the packs currently must be done by an operator. Two other students make sure that a pile of packs arrives on an Automated Guided Vehicle and this thesis focusses on the unloading of the packs onto the module with the cobot.

To successfully automate the replenishing of the stock, two programs were created. The first one uses camera vision to determine the location of the packs on the AGV and then uses the cobot to move the packs into the buffer loader. The second program takes care of the stock management between the buffer loader and the main loader. By adding these programs, we can eliminate tasks for human operators and thus reduce costs significantly.



## Abstract (in Dutch)

In Industrie 4.0 veranderen traditionele fabrieken in slimme fabrieken door het integreren van nieuwe, slimme technologieën. Op de T2-campus in Genk staat de Smart Innovative Factory (SIF) 400, ontwikkeld door SMC International Training. Dit is een schaalmodel van een fabriekslijn die gemaakt is voor trainings- en presentatiedoeleinden. Het stelt een bijna volledig autonome productielijn voor, die zorgt voor de montage, stockage, distributie en recyclage van producten.

Het doel van deze masterproef is het verbeteren van de automatisering in deze bestaande productielijn. Meer specifiek het bijvullen van de voorraad van de stacking module. Het doel van deze module is dat een collaboratieve robot binnenkomende containers op een pakket stapelt. De module is volledig autonoom in zijn hoofdfunctionaliteiten, maar het bijvullen van de pakketten moet handmatig gebeuren. Twee andere studenten zorgen ervoor dat er een stapel pakketten op het automatisch gestuurd voertuig aankomt en deze thesis richt zich op het laden van de pakketten op de module met de hulp van een cobot.

Om het aanvullen van de voorraad succesvol te automatiseren, werden er twee programma's gemaakt. Het eerste gebruikt een camera om de locatie van de pakketten op de AGV te bepalen en gebruikt vervolgens de cobot om de pakketten naar de bufferlader te verplaatsen. Het tweede programma zorgt voor het voorraadbeheer tussen de bufferlader en de hoofdlader. Door deze programma's toe te voegen, kunnen we de behoefte aan extra personeel elimineren en zo de kosten drastisch verlagen.





# 1 Introduction

## 1.1 Context

Industry is rapidly evolving, and arguably we are in the middle of the transition towards “Industry 4.0”. [1] In this new industrial revolution, everything is connected to create a fully integrated smart factory. Different modules and machines can communicate with each other or with a central control service and we can capture and analyse data to further improve efficiency. This new industrial revolution is without doubt a very important step for the manufacturing industry.

The T2-campus in Genk has a scaled model of a smart factory called the Smart Innovative Factory (SIF-4o0) developed by SMC. It contains all the features of a smart factory and is especially made for training and demonstrating purposes. The SIF-4o0 contains 13 different modules (SIF-401 - 413) and an automated guided vehicle (AGV, SIF-414). As shown in the image below, 12 of these modules are lined up next to each other to form one production line.



Figure 1 SIF-4o0 [2]



Figure 2 Automated Guided Vehicle

The overall goal of the thesis is to enhance the automation to improve the productivity of the operator and the productivity of the SIF-4o0 smart factory. In the current setup, the stock level of all the stations separately is monitored, but an operator is still required to manually transport the final products and raw materials to the different stations and must manually refill these stations. The posted thesis assignments need to aim at providing more technological support for the operator by increasing automation to save time, reduce cost and thus improve productivity. This automation process comprises 4 different challenges.

- For the first assignment, the AGV will be used to transport finished goods from the shipping station (SIF-412) to the recycling station (SIF-413), which breaks down finished products back to raw materials.
- For the second assignment, the AGV will be employed to transport raw materials from the recycling station to the stations that are running out of stock.
- The third assignment is situated at station number 8 (SIF-408) which contains a collaborative robot (cobot). The objective of this third project is to automate the unloading of the AGV after it arrived with new materials for the out-of-stock module.

- The last assignment concerns the integration of an external cobot with the same functionalities as in assignment 3, but as an external module at the 4<sup>th</sup> station (SIF-404) which loads containers with customized products onto the conveyer belt

The first two challenges are tackled by two fellow students and this thesis is about the third challenge. The fourth challenge could not be tackled due to the limited time available for this thesis and will be considered as out of scope for this Master's thesis.

## 1.2 Research Objectives

There are 4 research questions that this thesis will cover.

1. What is the best way to add new functionalities to the existing integrated automated hardware system and its control software while guarding original separation of responsibilities and minimalizing changes to the current software?
2. How does the communication between the SIF and the cobot takes place and how can we implement new functionalities to the already integrated hardware?
3. How can we tackle all the physical limitations of the hardware involved in this project, e.g. the range of the AGV and the cobot, the accuracy of the machines, the physical appearance of the pack loader...?
4. How will the new functionalities of the integrated cobot developed within this project be combined with the new functionalities developed for the AGV within the other thesis.

## 1.3 Overview

Chapter 2 of this thesis is the literature review. This chapter starts with an in-depth explanation of the SIF-400, with an extra focus on the stacking module (SIF-408). Besides that, the communication protocols that are used in the SIF are described in detail. The last part of the literature review covers the physical limitations of the hardware involved in this project, including experiments, results, and possible solutions.

The following chapter, chapter 3, is about the materials and the method employed to obtain the expected outcomes for this thesis assignment. This part of the thesis first describes the SIF-408 in greater detail by covering all the different technologies that are combined on this module. After that, it describes the method that was used to complete the project. Finally, there is a part that covers the new communication between the SIF-408 and the AGV.

The fourth chapter contains the results and a discussion. The results are in depth explanation of the implementation. This will be explained based on a diagram. Furthermore, the updated Human Machine Interface is explained. The implementation is then evaluated and an overview of its value is covered in the discussion section.

Finally, this thesis will be wrapped up in chapter 5 with the conclusions. This chapter gives a conclusion about the results of this thesis and describes the importance of this thesis in the industry.

## 2 Literature Review

### 2.1 Smart Innovative Factory SF-400

SMC is a Japanese company founded in 1959 [3]. They started out with basic pneumatics for the manufacturing industry, but quickly grew into more sophisticated automation solutions. Nowadays, SMC has a global market share of 30% in automation solutions, which makes them an important player in the automation of manufacturing processes. SMC also has an educational division called SMC International Training [2]. This division developed a scaled model of an automated production line for training and showcasing purposes. This scaled model is called the Smart Innovative Factory 400 (SIF-400) and it simulates a highly automated smart factory in which a trainee can master all aspects of the factory's processes like production, storing, shipping, and recycling of products.

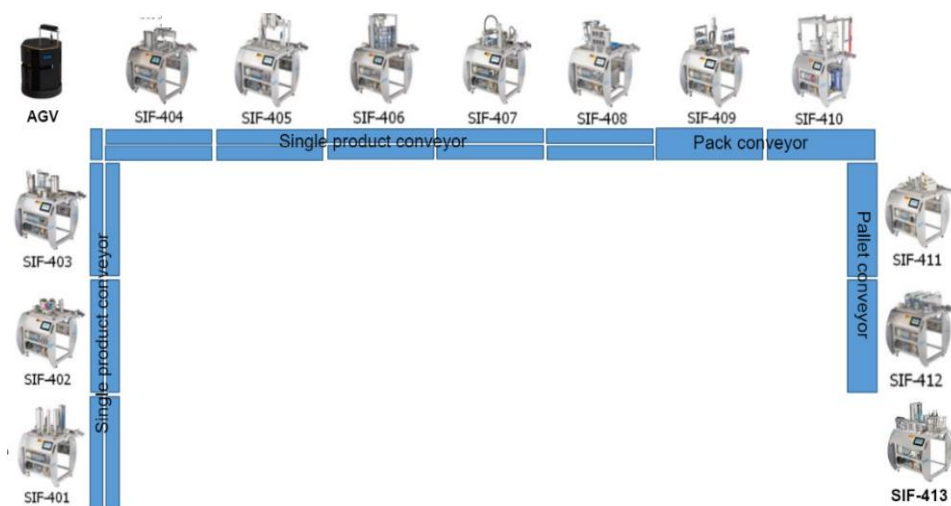


Figure 3 schematic overview SIF-400

The SIF-400 contains 13 different modules, and their names represent the chronological order in which they appear in the production line, going from SIF-401 to SIF-413.

The first 12 of these modules are aligned next to each other and connected via a conveyor belt as shown in the figure 3. They all have different functionalities that are combined to replicate a complete production process. Starting from composing the desired products to sealing containers, stacking them on packs, organizing in warehouses and packing finalized orders ready to ship to the customers.

The 13<sup>th</sup> station, SIF-413, is a recycling module that breaks down the finalized product back into its raw materials.

There is also an automated guided vehicle (AGV) that is called SIF-414, which will be used in the project of two fellow students. After the completion of the thesis of these students, the AGV will be capable of automating the transportation of raw materials and final products from and towards the recycling station. By doing so, it semi-automates part of the replenishment process of raw materials at the different stations and the collection of the finished goods for recuperation.

A central management system called the SIFMES is in place at the SIF-400. This is a web application that enables a supervisor to have a broad, yet detailed overview of what is happening in real time. The functionalities of the SIFMES are wide: it is possible to place orders, manage stock levels, monitor the energy consumption, get performance analytics and much more. This system is the core of what makes this production line part of Industry 4.0.

2.1.1 The stacking module SIF-408

This thesis focusses on the automatic replenishment of the raw materials at the SIF-408. This eighth module is shown in the figure 4. Its purpose is to stack the incoming containers onto black packs. The module starts when an RFID sensor notices incoming containers on their blue, RFID chip containing pallets. Then it takes this blue pallet with container off the conveyer belt and moves it into the module itself by means of the rotary transfer table to start the stacking process. At this moment, the collaborative robot (cobot) kicks in. The bays on the module are the places where packs are being stored while the containers are loaded onto them. The sensors behind these locations have a red and a green light indicator and keep track of whether there is a pack in the bay or not. Depending on this value, the robot either takes a new pack to place it on an empty bay or immediately start its native loading program. The first task in this native loading program is that the robot takes the container out of the blue pallet and puts it in the black packs on a designated position. Next, it removes the blue pallet into the blue bin on the side. Finally, when a pack is fully loaded with the correct containers, the robot takes the pack and puts it on the wide conveyer belt of the next module. Now, it can head over to the SIF-409, where it can be stored in the warehouse. A detailed description of all the different technological components of the SIF-408 will be covered in chapter 3.1.

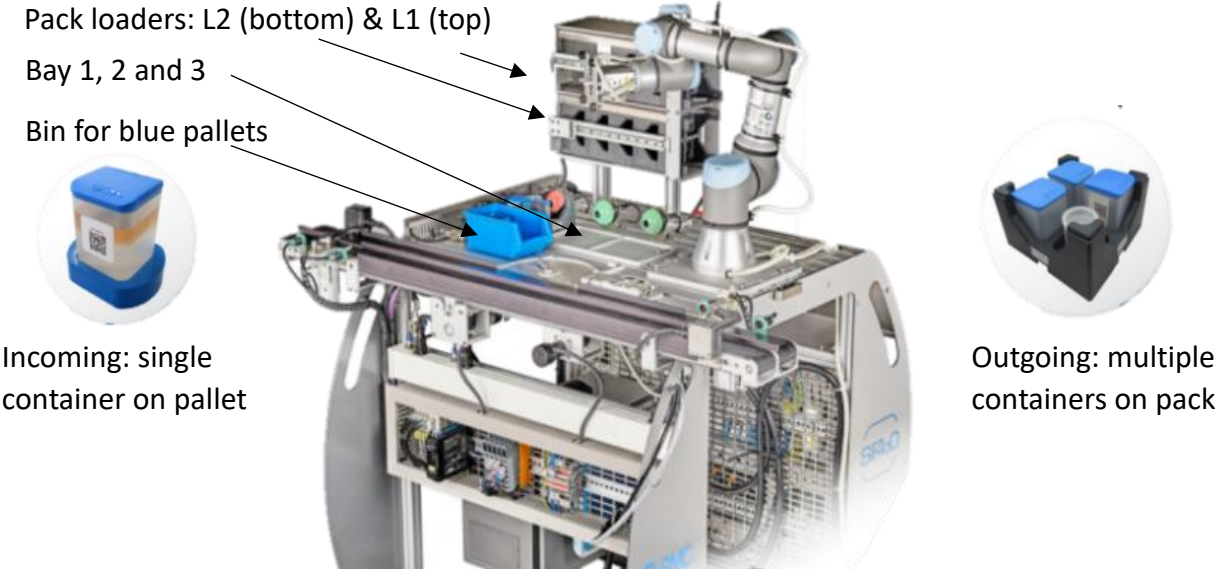


Figure 4 SIF-408 [2]

## 2.2 Communication

### 2.2.1 General

One of the main principles of Industry 4.0 is communication. In a fully automated and integrated production process, it is important that all the modules, machines, sensors, etc. talk to each other, whether it is directly from peer to peer or via a centralized unit. To determine the most efficient way of communicating, different aspects are to be considered. The speed of the communication is important, the quantity of data that must be transmitted every time, the physical distance between the peers, etc.

In the SIF-408 various communication protocols are used, which will be covered in this section. However, the research and implementation of possible new communication protocols is not in the scope of this project. Existing communication channels and protocols will be used to fulfil this project.

### 2.2.2 Transmission Control Protocol/Internet Protocol (TCP/IP)

The basic low level communication protocol is TCP/IP [4]. This pair of protocols is often used together because it was invented together.

The Transmission Control Protocol [5] is the most common protocol in the Transport layer. It provides a reliable stream of data between applications. A connection is established for every new packet of information with a three-way handshake. The protocol offers retransmission of lost packages and error-detection for a reliable communication. This protocol is used because it prioritizes reliability over latency, this is beneficial because a loss in communication between machines can lead to quality issues.

The Internet Protocol [6] is the most used protocol in the Internet layer. Its task is to deliver packets of information from source to destination, purely based on IP addresses. In the SIF-400, all the different machines, equipment, modules, etc. have their own unique IP address. These addresses are written in the headers of the communication packets.

These protocols are also used by the cobot to communicate directly with the camera and its internal control unit, but also to receive external commands from the PLC. The physical connection between the peers is made with an Ethernet cable with an 8P8C connector.

### 2.2.3 OPC Unified Architecture (OPC UA)

On top of the TCP/IP protocol, there is OPC UA [7]. This protocol is specifically developed for machine-to-machine communication in industrial applications such as manufacturing. It uses a client server structure to handle messages and is service oriented. Besides that, it is free to use and compatible with every operating system and programming language. This protocol is used to send data to the SIFMES and to the AGV control centre.

### 2.2.4 Communication between PLC and Cobot

To elaborate more on the second research question, the communication between the PLC and the integrated cobot has been studied thoroughly. Both machines transmit and receive two bytes, which means that there are two bytes from the PLC going to the cobot and two bytes in the opposite direction.

The first byte (Byte 0) that comes from the Cobot and is received at the PLC side, is split into bits that contain different states with Boolean values. The first bit is the 'READY' state, which indicates whether the robot's program has started or not. The second Boolean value is 'DONE', which indicates the progress of the cobots current sub-program. The next Boolean is 'TOOL', this is used to tell the PLC that the gripper can start a new movement. The fourth and last used bit is 'FullBin' and indicates whether the bin of pallets is full.

The first byte (Byte 0) that travels from the PLC to the Cobot is also split into bits to indicate different states with Boolean values. The first bit is called 'Run' and indicates the state of the module, which can be running (1) or stopped (0). The next value is 'InPosition', which represents the position of the gripper. When a gripper movement has been executed, this value will become 1 for the PLC to tell the cobot that it can continue its sub-program. The third bit is used to indicate whether the SIF-408 is in integrated mode or stand-alone mode. The last bit is called 'Halt' and is used for safety.

The second byte (Byte 1) is used to transmit unsigned integers, which are real values from 0 to 255. The value of the integer that is sent from the Cobot to the PLC is called the 'Gripper program' and holds the number for the next program of the gripper. The other integer is called 'Operations' and holds the value of the next program for the cobot and is sent from the PLC to the cobot.

A structured overview of the bits and bytes can be seen in the table below. The extension for this thesis in terms of communication between the cobot and the PLC are described in chapter 4.1.4 'Communication between PLC and Cobot'.

Table 2 Communication between Cobot and PLC

	PLC IN / Cobot OUT		PLC OUT / Cobot IN	
<b>BITS AS BOOLEANS</b>	Byte 0 bit 0	READY	Byte 0 bit 0	Run
	Byte 0 bit 1	DONE	Byte 0 bit 1	InPosition
	Byte 0 bit 2	TOOL	Byte 0 bit 2	Auto-play & Init
	Byte 0 bit 3	FullBin	Byte 0 bit 3	Halt
<b>UNSIGNED INTEGER</b>	Byte 1	Gripper program	Byte 1	Operation

## 2.3 Physical limitations of the hardware

### 2.3.1 General

An important part of this thesis are the physical limitations of the hardware involved in this project. If the stock refill of the SIF-408 must be automated, it is important to first determine the feasibility in terms of physical limitations imposed by the current components and systems. First, this thesis will look at the range of the cobot and the positioning of the AGV. After that, there is an analysis of the tolerances for the picking procedure with its solutions and an analysis of the tolerances for the placing procedure with a corresponding solution.

### 2.3.2 Range of cobot and positioning of AGV

The first and most important part of the physical limitations is whether the robot can reach the AGV. Several measurements and tests were performed.

First, the position of the arriving AGV was determined. The recycling module (SIF-413) is located on the outside of the production line (labelled in figure 6), so the fastest route from the recycling station to the SIF-408 can be achieved when the AGV arrives at the front side of the SIF-408. The range of the cobot is 0.5 m according to the datasheet [8]. However, due its installation on the module, the cobot cannot reach 0.5 m in every direction. Placing the AGV in front of the module would cause additional problems when programming the cobot, because this location is close to its limits. The alternative is using the space between the SIF-408 and SIF-409, as pointed to on the figure 5. This space is 40 cm wide whereas the width of the AGV is 34 cm wide, so this solution is physically possible. Besides that, it is also beneficial to place the AGV between two stations as it will not cause any nuisance for passing operators.

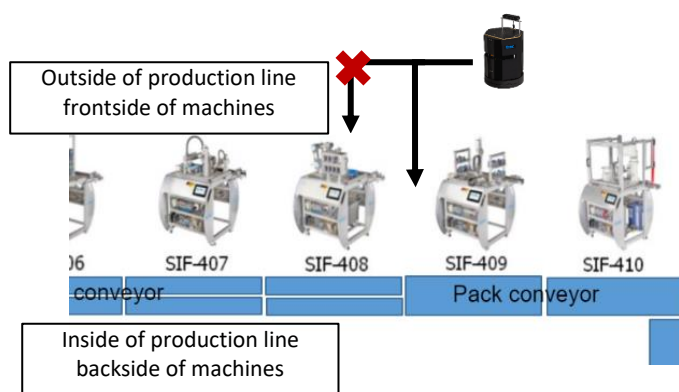


Figure 6 Floorplan of arriving AGV

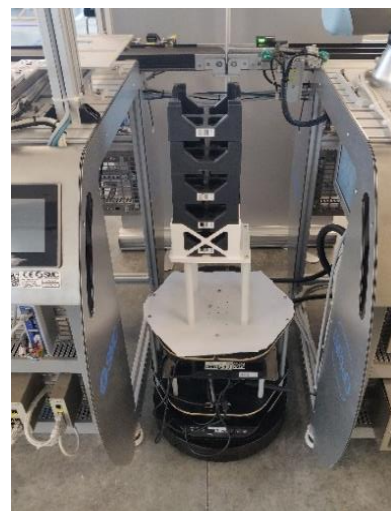


Figure 5 AGV in place between SIF409 and SIF408



To make sure that this position is feasible, it is also important to analyse the technical capabilities of the AGV to move into that position. The AGV has a camera and a sensor to determine whether it could move forward. The first problem was that the internal system of the AGV does not allow to move in between the two stations, because it is too tight for the navigation system of the AGV.

To tackle this problem, there were two possible solutions. The first one consisted of creating a QR-code and using the build in function to dock the AGV at the QR-code. The second option was to move the docking station of the AGV to the desired location between the SIF-409 and SIF-408. Tests showed that the docking function with the original docking station is much more reliable than the QR-docking. The conclusion was to use the docking station because it delivered the best repeatability and accuracy. On top of that, the AGV will also be charging while it is being unloaded. When the unloading has finished and there is no new task for the AGV, it will stay in the same position and keep on charging, which is a great benefit for the AGV.

The problem remains that with a height of 40 cm, the AGV is too low for the robot to reach. To tackle this problem, two solutions were tested.

- The first one was creating a slight hill with a platform to elevate the AGV into the range of the cobot. However, tests showed that the AGV was not capable of driving up a hill with the desired steepness.
- The second solution was the design of an add-on for the AGV to hold the pile of 5 packs. This add-on is designed and printed by the external promotor Peter Evens and successfully presents the pile of packs with a sufficient height.

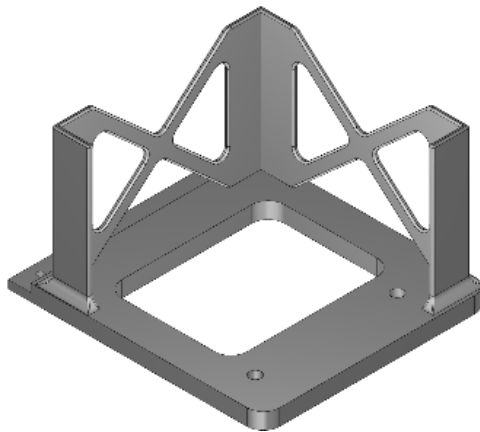


Figure 7 AGV add-on

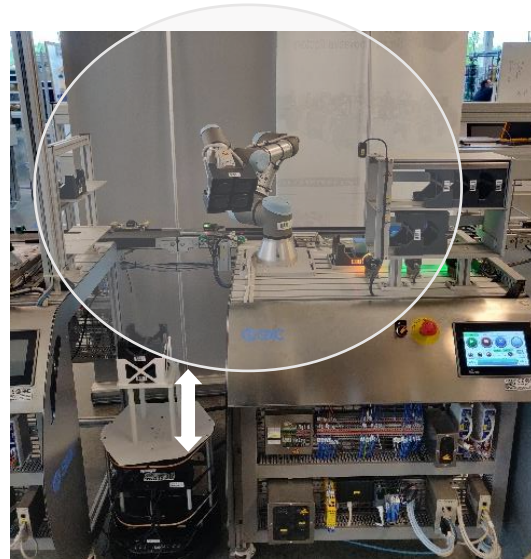


Figure 8 Range of cobot and height of add-on

### 2.3.3 Tolerance chain for the picking operation and its solutions

First, there is the positioning accuracy of the AGV. By using the docking station for the positioning of the AGV, we have an increased positioning accuracy compared to a manually added point on the map or a QR-docking. The AGV now arrives at the same location with a tolerance of about 1 centimetre in the X and Y direction. Above and beyond this deviation, there is also an orientation deviation of about  $-3^\circ$  to  $+3^\circ$ .

Besides the positioning accuracy of the AGV, the tolerances for the pile of packs need to be considered as a noise factor as well. In the process of the automated replenishment, the AGV must drive around while carrying the pile of 5 packs on top of itself. To reduce the deviation between the first pack and the last pack, high edges were added in the design of the previously mentioned add-on. Tests have shown that the solution in which the height of the edges is equal to one and a half pack ensures an accuracy improvement. More specifically, the highest possible deviation has been reduced from 2 cm to 1.5 cm, which is an improvement of 25 %. In addition to the improved accuracy, it also improved the stability of the packs while driving. Tests have shown that this pile of packs stays in position even when the AGV drives over obstacles, takes sharp turns, or rotates.

The final consideration is about the allowable position tolerances on the gripper in combination with the geometrical tolerances on the packs. As visible in figure 9 and 10, the gripper takes the packs in their corners from the inside by expanding in one direction only. Because the expansion only occurs at one axis, the other axis is already in its maximum position. The deviation on this maximum position is determined by the width of the pack's corners, which allow for a tolerance of only 2 millimetres at each side. Possible misorientations of the gripper relative to the pack reduce this tolerance even more.



Figure 10 Pack

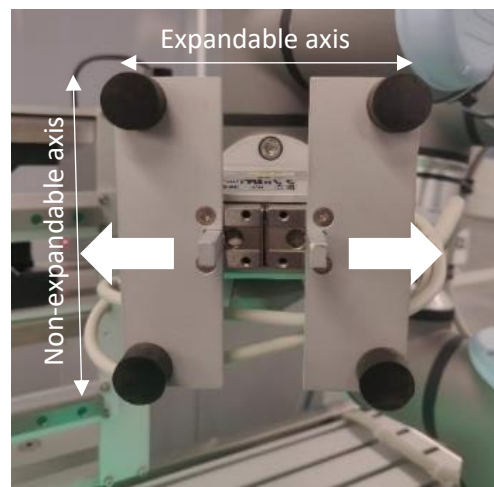


Figure 9 Gripper

To overcome these tight allowable tolerances of the gripper, extra modifications were needed. Research has shown that there are many solutions that can be implemented, all having their own benefits and drawbacks.

The first option is to hard code the position of the packs into the code of the cobot. This method is easy and quick to implement, but it lacks flexibility and robustness. To use this solution, the deviation on the positioning of the AGV and the deviation on the pile of packs should be eliminated.

To remove the tolerance on the positioning of the AGV it is necessary that the AGV arrives on the exact same spot every time. To ensure this, it is possible to add a cone-shaped structure above the docking station to physically assist the AGV with the docking procedure. However, experiments showed that due to the grip of the wheels, the AGV is unable to move into a cone-shaped structure with this guidance. A video for reference can be seen via the QR code in figure 11.



*Figure 11 AGV in cone-shaped structure video*

The elimination of the deviation on the pile of packs can be done by designing a new gripper that expands in both axis and has cone-shaped gripping tips. These modifications could allow for higher allowable tolerances. Unfortunately, the above-mentioned solution is not possible due to the restrictions about guarding the main functionalities as much as possible.

The other possibility is to use an extra sensor to measure the exact position of the packs. This device can be a proximity sensor, which can be placed in a strategic place on the gripper to determine the presence of a pack underneath. This method allows the robot to 'seek' for a pack before it would pick it up. This 'seeking' method [9] can also be performed with the force sensor that is built into the wrist on the robot. The problem of this method is the precision of the force detection. Unfortunately, the cobot in the SIF-408 is an old version with a lower precision than the newer e-series [8]. Tests showed that due to this lack of precision, the detection of the packs cannot be performed with a sufficient accuracy. Besides that, the sensing movement pushes down the packs, which causes some packs to fasten into the next pack. This results in the cobot taking two packs instead of one, which causes problems when entering the loader. This could also overload the AGV and damage the wheels.

Another possibility could be the addition of a camera to determine the exact location and orientation of the pack to be gripped. There are a lot of different types of cameras that are applicable for the detection of the pile of the exact position and orientation of a pack. Some of these cameras will be discussed in greater detail below.

- The first type that will be discussed is a 3D camera. An example is the Microsoft Kinect camera [10], which has a lot of open-source interface options [11]. It can create a virtual view with a sense of depth to determine the exact location and orientation of the packs on the AGV. The downside of this solution is the complexity. This implementation would require many additional components, such as extra software, an extra computer, and a reliable way of communicating with the cobot. To avoid these problems, it is possible to choose a camera that is compatible with the UR robot such as the SICK Ranger3 [12]. This camera can be mounted onto the wrist of the robot or on a fixed position on the station. Sick cameras have specific drivers, called URcaps [13], as an interface between the software of the camera and the software of the cobot. The downside of this camera, however, is the high price. These cameras can cost up to tens of thousands of euros per piece.

- A cheaper, yet compatible alternative is a 2D camera. For the category of 2D cameras, there are the same two options. Either a cheap, ‘normal’ camera that requires extra hardware and software to implement or a more expensive camera that is more compatible and easier to get started with. Fortunately, the T2 campus has a SICK Inspector [14] in its inventory, which was available for this project. More information about this camera will follow in the chapter 3.1 “Materials” and the exact implementation will be explained in the 4<sup>th</sup> chapter with the results. A disadvantage of a 2D camera however is that it is not able to determine the height of the packs precisely. Fortunately, this can be solved by manually manipulating the Z-coordinates with hard coded values, because the height of the packs will always be the same.

Table 3 Comparison of cameras

	Price	Compatibility	Availability	View dimensions
<b>Microsoft Kinect</b>	\$	Via external computer	To be ordered	3D
<b>SICK 3D camera</b>	\$\$\$	URCaps	To be ordered	3D
<b>SICK 2D camera</b>	\$\$	URCaps	Directly available	2D
<b>‘Normal’ camera</b>	\$	Via external computer	To be ordered	2D



Figure 13 SICK Ranger



Figure 12 Xbox Kinect



Figure 14 SICK Inspector

### 2.3.4 Tolerances for the reloading operation and its solutions

The placing of the packs is performed in the loaders of the station that are displayed in figure 15. The tolerance for packs to enter these loaders is about 2 millimetres due to the presence of the iron inserts, which is visible in figure 15. The accuracy of the cobot itself is high enough to deal with this low tolerance, however, the packs are not always picked perfectly, which could cause errors when placing them in the loaders. To overcome this problem, Peter Evens will design an alternative for the inserts. This 3D printed piece will fit on the sides of the loaders. It will have the same functionalities as the previous inserts but does not lower the tolerance for the packs to enter. By removing the inserts and replacing them with these 3D prints, the tolerance of the loaders will be big enough for packs to enter. Unfortunately, this 3D printed structure has not been finished yet.

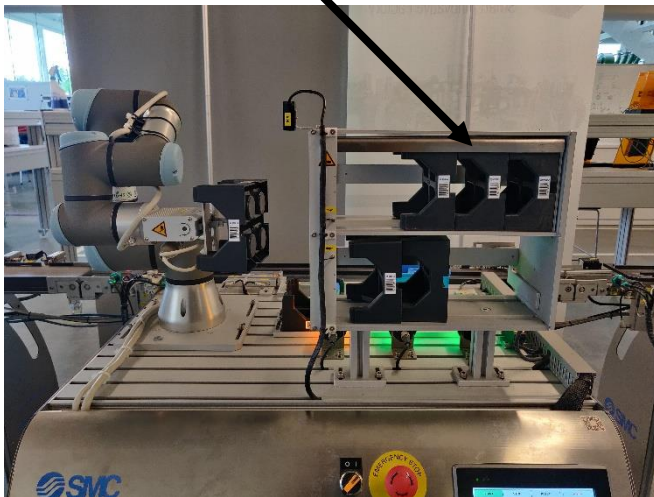


Figure 16 Loaders on the module

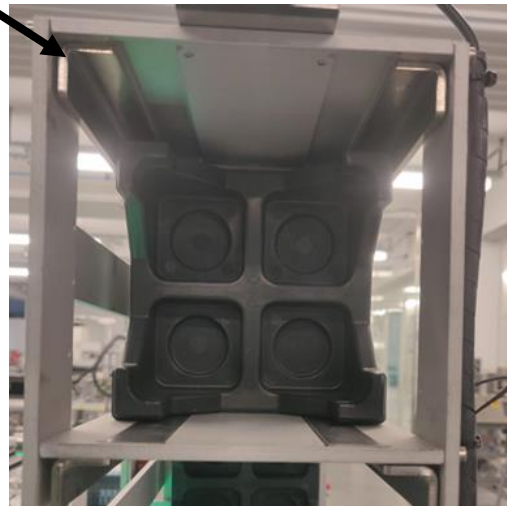


Figure 15 Loader with insert

## 3 Materials and method

### 3.1 Materials

#### 3.1.1 Overview

In the SIF-408, different technologies are combined to form one fully functional module. It is important to understand these technologies to pursue this project. Figure 18 shows the operator side of the SIF-408 with its modifications for this project and figure 17 displays the rear view with the working area.

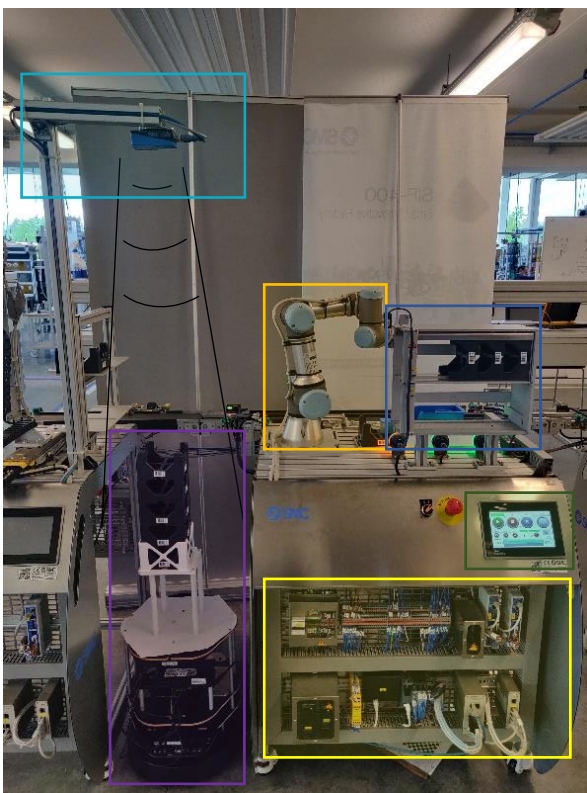


Figure 17 Final setup of modified SIF-408 with AGV

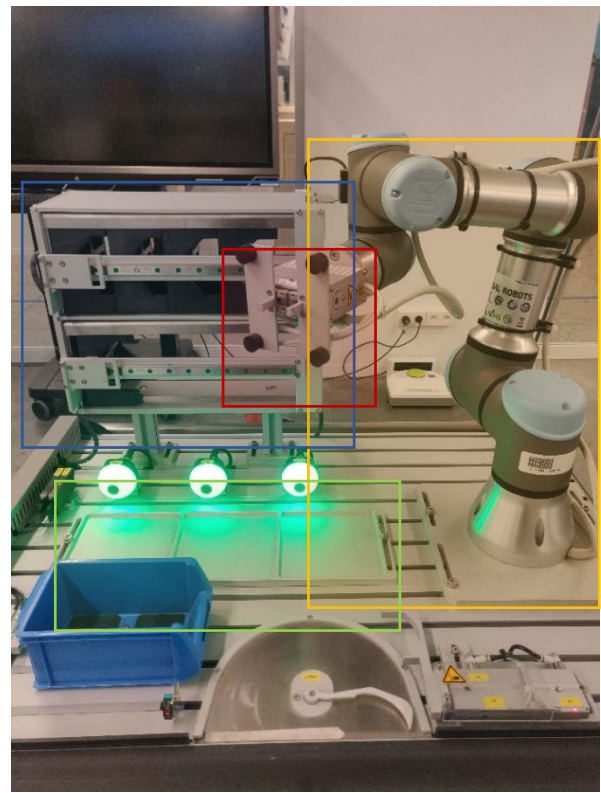


Figure 18 Rear view of SIF-408

In figure 17 in the top left corner in the light blue rectangle, there is the newly added 2D camera called the SICK inspector. This camera is looking downwards and sees the top of the pile on the Automated Guided Vehicle, which is marked in a purple rectangle. The AGV is now in its docking station between the SIF-409 and SIF-408. When taking a closer look at the robot arm, which is marked with an orange rectangle, we notice that its base is mounted on the SIF-408 and it has a custom-build gripper attached to its wrist. This gripper can be seen in figure 18 in the red rectangle. The robot also has a base station which controls the motors in the robot according to the commands in the script, this station is mounted inside module and is not visible on these figures. The pack loaders are located on top of the module and marked in a dark blue rectangle in both figures.

When moving closer to the module itself, the first thing that attracts the attention is the Human Machine Interface (HMI), marked by a dark green rectangle. This is the touch screen mounted on the operator side of the SIF-408. Beneath this touch panel, there is the hearth of the unit, coloured in yellow. In this lower area, all electrical wires are connected to the power and to the ground, and all the communication cables are connected to each other and to the Programmable Logic Controller (PLC). Besides these large electrical components, this module also has a lot of different smaller components on top of the module, which are visible from the rear side. The pack loader in the blue rectangle and the bays in the light green rectangle.

A more detailed description of these components will follow in the next paragraphs.

### 3.1.2 PLC

A Programmable Logic Controller (PLC) is an electronic device that is used in industry to control industrial processes. It is rugged, reliable, and easy to program. A standard PLC receives inputs from sensors that measure things like the pressure, the presence of a product, the weight of something, the colour of the product and many more. The PLC then sends specific output signals according to the needs of the production cycle. These outputs can vary based on the type of manufacturing. They range from moving the conveyor belt in another direction to telling a robot to pick up the product. In the SIF-400, every module is equipped with its own PLC to make them all operational in standalone mode. The PLCs used for these modules are the X20CP1301's by B&R. These PLCs contain a 32bit intel CPU, have 1 GB of onboard flash memory and 128 MB of DDR3 SDRAM. The programming of the logic in this PLC is accomplished using the PLC programming language "Structured Text" (ST) in the development environment Automation Studio by B&R.



Figure 19 PLC

### 3.1.3 UR cobot

A collaborative robot, or in short, a cobot, is a kind of robot that is developed to work in collaboration with humans. These cobots are safer than conventional robots because they are reduced in movement speed and force. So, the effect of an impact with a human body can be limited under normal operational circumstances.

In the SIF-408 there is an integrated cobot called UR3. This cobot is designed by Universal Robots. It is the smallest of the line-up, with a range of 500 mm and a maximum payload of 3 kg [8]. To control and program the movement of the robot, there is a controller and a touch panel. The computer is the brain of the robot. It calculates coordinates, executes commands, controls the motors, etc. The touch panel on the other hand is the interface for a human to communicate with the robot. It runs a software program called Polscope which creates a user-friendly User Interface. Through this program, the user can perform all desired tasks to control the robot. The first and most important thing is that it is possible to create scripts that contain specific movements for the robot to execute. Besides that, it is possible to interact with different inputs and outputs for communication with other machines such as the PLC in this case. The software also allows you to install different drivers called 'URCaps' to support third party accessories like an external camera. Apart from this intuitive user interface, the robot can also be programmed with a script on a computer that is connected via a socket to the computer of the Robot.



Figure 20 Teach pendant and UR3 cobot.

### 3.1.4 The gripper

The gripper is mounted on the wrist of the Cobot. It is a custom build gripper by SMC that is well designed so that it can grip the black packs, the blue pallets and both the round and squared containers. It has one expandable and one non-expandable axis. This linear expansion can be controlled by the PLC to grip the products. It has 4 rubber tips in the four corners that can grip the packs by expanding from the inside. It also has two small metal bars that can both take the containers by contracting or take the blue pallets from the inside by expanding. The gripper has 3 different positions, which are controlled by the PLC. Table 4 shows an overview.

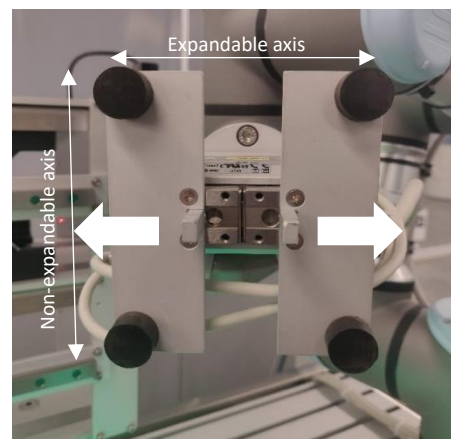


Figure 21 Custom build gripper



Table 4 Gripper programs

Program nr	Position	Goal
0	Closed	Start position / drop pack / drop pallet / take container
2	Open 75%	Drop container
5	Open 100%	Take pack / take pallet / before take container

In the first program, program 0, the gripper is closed as in figure 21. This is the start and rest position of the gripper. It is also used to release a pack or pallet or taking a container. The next program is number 2, which opens the gripper to 75%. Its goal is to drop a container by opening the gripper. The last program is program 5, which opens the gripper completely. This is used when taking a pack with the tips or a pallet with the metal bars. Besides that, program 5 moves the gripper this position before it will contract again to take a container.

### 3.1.5 SICK Camera

The company SICK develops different kind of sensors, among which also vision systems (cameras) that seamlessly work together with the cobots from UR. For this project, there is a SICK Inspector available for integration in the pick and place process. More specifically the SICK VSPM-6F2113 PIM60. This module takes 2D-images, recognizes objects, and can send the coordinates of these objects directly to the computer of a cobot. There are different ways that this camera can communicate with computer, but the most efficient and recommended method of communication with the cobot is with an Ethernet cable and the UTP/IP protocol. Via a URcap, which is a specific driver for the UR cobots, it is possible to connect this camera directly to the cobot. This driver allows the programmer to calibrate the camera via the cobot and use build-in functions to retrieve object coordinates. The calibration is needed to for the camera to share the same coordinates base as the cobot.

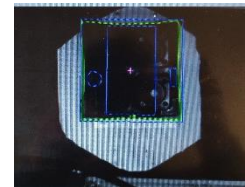


Figure 23 Pack detection of the SICK camera



Figure 22 SICK Inspector

### 3.1.6 Automated Guided Vehicle

The Automated Guided Vehicle is called the SIF-414 and it is a TurtleBot 2. This vehicle has a Kobuki base, which looks like an autonomous vacuum cleaner. On top of this base, there is a layered structure that holds an Orbbec Astra sensor and a Lidar sensor for the vehicle to 'see'. Both the base and the visual sensors are controlled by an intel NUC notebook. The controlling of these different parts is done with the Robot Operating System (ROS). This software is an open-source layer of software that runs in an operating system (in this case Linux, Ubuntu) and provides tools to control and program the robot. It is also equipped with a Wi-Fi router so that the AGV can be controlled over the Wireless Local Area Network (WLAN).

### 3.1.7 The Human Machine Interface

The SIF-400 can run in either autonomous mode or in stand-alone mode. In the former, the coordination is controlled by a control unit in the SIFMES. In the latter it is possible to control the module through its Human Machine Interface (HMI). This is a touch panel which the operator can use to interact with the machine. The HMI of the SIF-408 is displayed in figure 24.



Figure 24 Human Machine Interface of SIF408

## 3.2 Method

### 3.2.1 Two new programs: Unloading the AGV and Stock Management

An important aspect of this thesis was to separate the new programs from the standard workflow of the module as much as possible. This has been achieved in two distinct solutions.

The first solution is the usage of two different pack loaders. In the main functionalities of the SIF-408, the bottom loader is not in use. This created the opportunity to use this loader as a buffer loader to temporarily store packs. This choice allows the machine to be able to always stay functional, even though the buffer loader is empty and the AGV is on its way to get new packs. To complete the cycle, an extra program must be created to take packs out of the buffer loader and place them into the main loader.



Figure 25 Pack loaders (above = main loader, down= buffer loader)

The second solution is the PLC code architecture. As shown in the diagram in figure 25, all the different programs are separated from each other. The main tasks of the SIF-408 are marked in dark cyan. These are the placement of an incoming container onto a pack and the removal of a fully loaded pack onto the next conveyer belt. The programs marked in light cyan are newly added for this project, which will be explained in detail in the next chapter. In future work, it is possible to create a hierarchy for the different programs in the idle state to set different priorities to the programs.

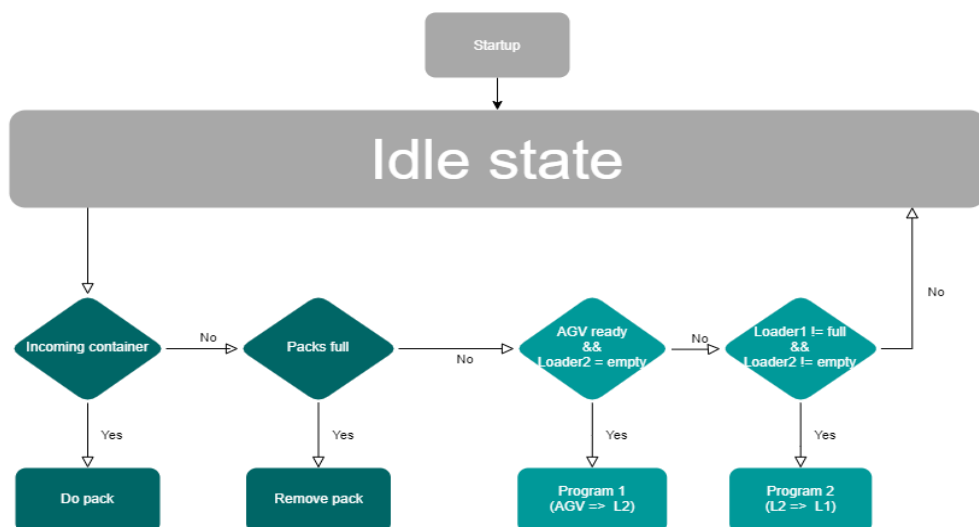


Figure 26 Program flow of SIF-408

### 3.2.2 Communication with the AGV control centre

To have a closed and fully automated cycle, it is important to have a reliable communication between different parts of the automating process. In this case, the automation consists of two parts: the movement of the AGV and the unloading of the AGV. The former is covered by another master's thesis and the latter is described in this thesis. The communication between both processes consists of three different signals.

First, there is the number of packs left in the buffer loader (= Loader 2). The SIF-408 internally keeps track of this value and publishes it via OPC UA to the SIFMES, which on its turn updates this value in the database. By doing so, it is also possible to view the current number of packs in the web application of the SIF. The AGV control centre reads this value via the API. Whenever there are no packs left in the buffer loader, this value has dropped to zero and the AGV will start a new task with the goal set to arrive at the station with a pile of five packs.

Secondly, upon arrival, there is a handshake between the AGV service and the PLC of the SIF-408 via OPC UA. A schematic overview of this handshake is displayed below. The AGV control centre makes the value of the Boolean 'AGVIsReady' true on which the PLC answers by making this value false again and starting its program to unload the AGV. When the unloading is finished, the PLC will change the value of 'UnloadingFinished' to true, the AGV control centre notices this value change and responds with putting the value back to false.

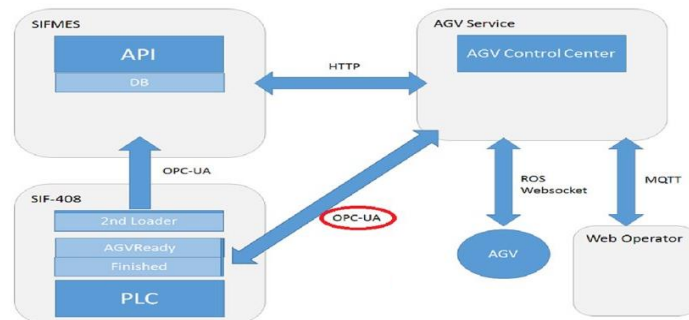


Figure 27 Communication protocol overview SIF408 – SIFMES and AGV

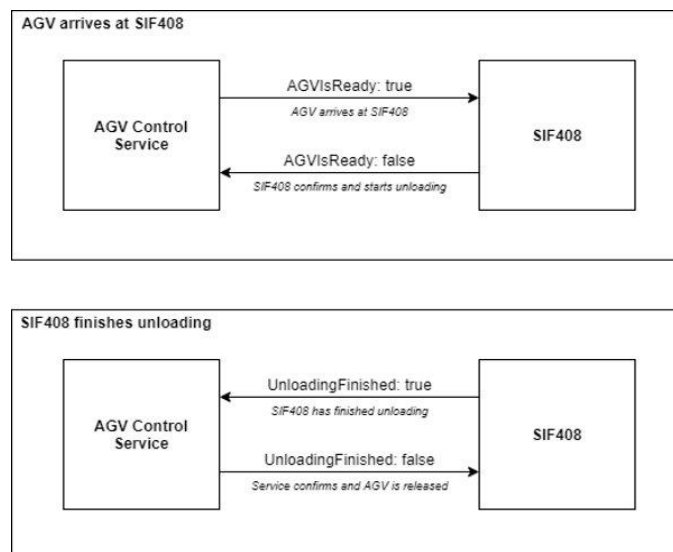


Figure 28 Handshaking between SIF408 and AGV

## 4 Results and discussion

### 4.1 Results

#### 4.1.1 Program 1: Unloading the AGV

The first and most important new program is the unloading of the packs from the AGV into the buffer loader of the SIF-408. The movement of the robot is visualized in the figure 29 with orange arrows and with a video via the QR code in figure 31. A structural overview of the flow of this program is visualized in figure 30. The green boxes resemble different stages in the PLC program and the blue boxes are the different parts of the cobot program. On the next page, the flow of the program is comprehensively explained.

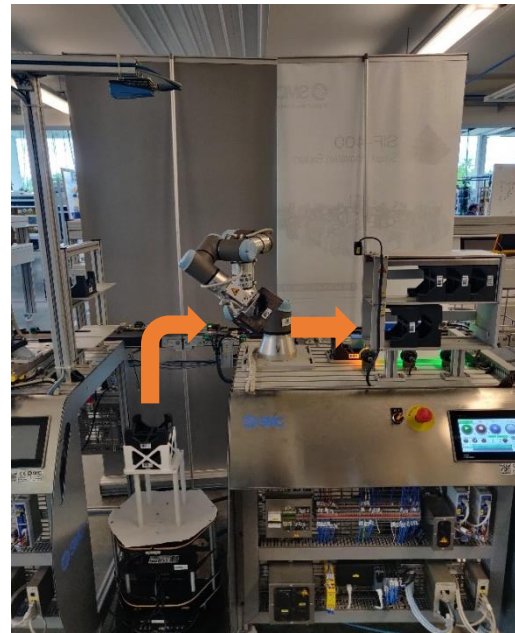


Figure 29 Program 1: Unloading the AGV



Figure 31 Video of program 1

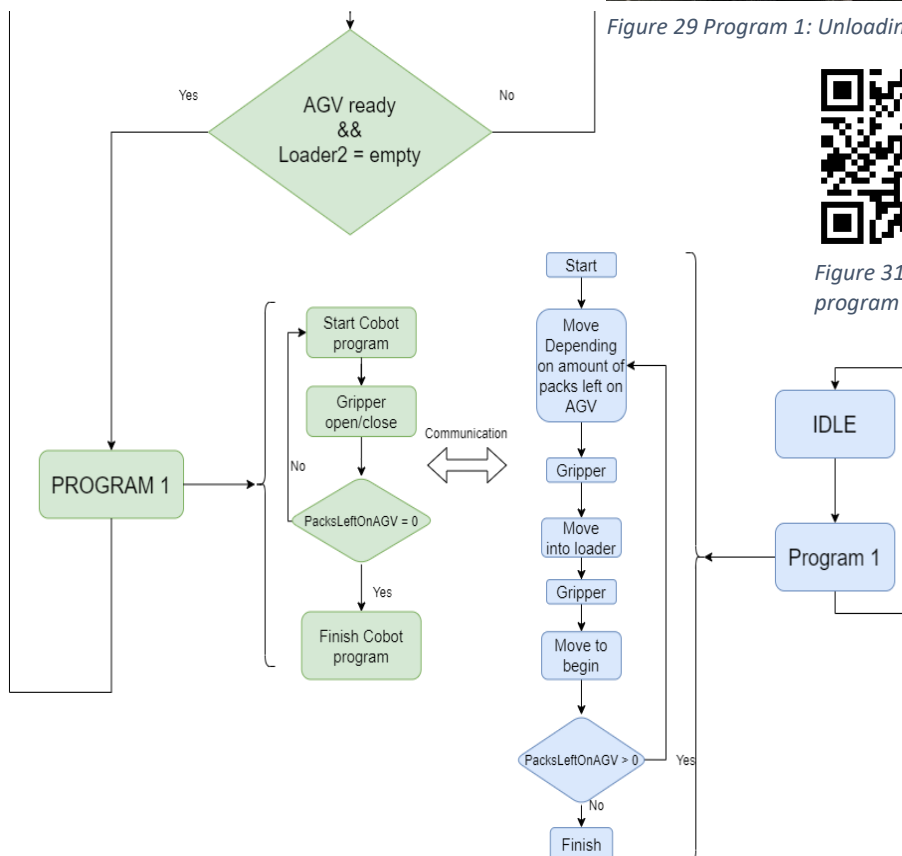


Figure 30 Program flow of program 1

When the buffer loader of the SIF-408 is empty, the AGV control centre will start a new task to bring a pile of five new packs to the module. After the completion of this task, the PLC receives a signal from the AGV control centre that the AGV has arrived, program 1 will then be initiated. The PLC will start communicating with the cobot to start the cobot program for unloading the AGV and placing the packs into the buffer loader.

The PLC then enters a loop that manages the opening and closing of the gripper depending on the commands of the cobot. This loop will be executed once for every pack. A counter keeps track of the number of packs that have been taken from the AGV and is synchronized with the counter of the cobot.

The cobot program as well consists of a loop that is executed five times. In every loop, the cobot first moves towards the pile of packs on the AGV. Then it reads the data from of the camera. This data contains the X, Y and Z coordinates as well as an alpha value. The detection of the X and Y coordinates is visualized in figure 32. These values are transformed from millimetres to metres and are used to create the next point for the cobot. However, because this is a 2D camera, the Z coordinate is not a correct value. Fortunately, the height of the AGV and the pile of packs will always be one specific value for every pack, therefore we can replace this incorrect Z value with a measured constant depending on the number of packs left on the AGV as shown in figure 31. The last variable in the data is the angle under which the pack is rotated. This value is not used to determine the location of the pack because the deviation on the angle of the arriving AGV is low enough. However, in future work this could be an extra upgrade for the reliability of the program.

When the cobot has calculated the next position, it quickly moves to a position right above the pack and slowly makes its way into the pack. When the gripper arrives inside the pack, the robot sends a signal to the PLC to open the gripper to take the pack. When the gripper is in position, the robot can continue its movements and moves towards the buffer loader. When it arrives, the same sequence as opening the gripper occurs, but with the command of closing the gripper.

Finally, after leaving the pack in the buffer loader, the robot returns to its begin position to either start a new cycle or finish the program.

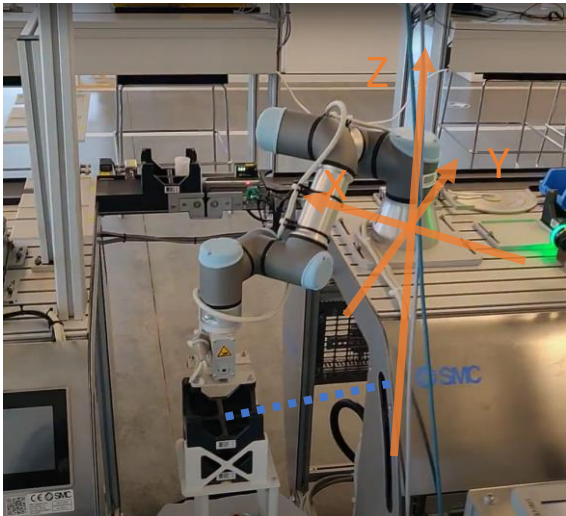


Figure 33 Z-coordinate of packs



Figure 32 X and Y coordinate detection of packs

#### 4.1.2 Program 2: Stock management between main loader and buffer loader

The goal of this program is to make sure that there are always enough packs in the main loader so that the standard task of the module can continue as smooth as possible. It achieves this by moving packs from the buffer loader into the main loader as shown with the orange arrow in figure 34. A video can be seen via the QR code in figure 34. A schematic overview of the process is shown in figure 36. The green boxes resemble different stages in the PLC program and the blue boxes resemble parts of the cobot program.

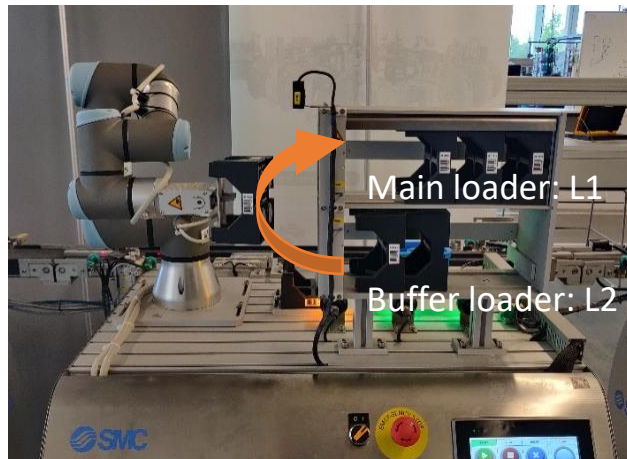


Figure 34 Program 2: Stock management between main loader and buffer loader

Program 2 will start when the main loader is not full and the buffer loader is not empty. The PLC will exit the idle state and jump into the program cycle. The first task of the PLC is communicating with the cobot about what program it has to start. In the cobot software, there are 5 different programs and depending on the amount of packs that are left in the buffer loader, the corresponding program is chosen. This happens because the gripper is not able to move into the loader and can only take a pack that is in front of the loader. To solve this problem, the cobot has a function to go to the backside of the loader and move a handle to the front so that the packs are aligned to the front of the loader. The robot has to know how far it should move the packs to the front and that depends on the amount of packs left in the loader.

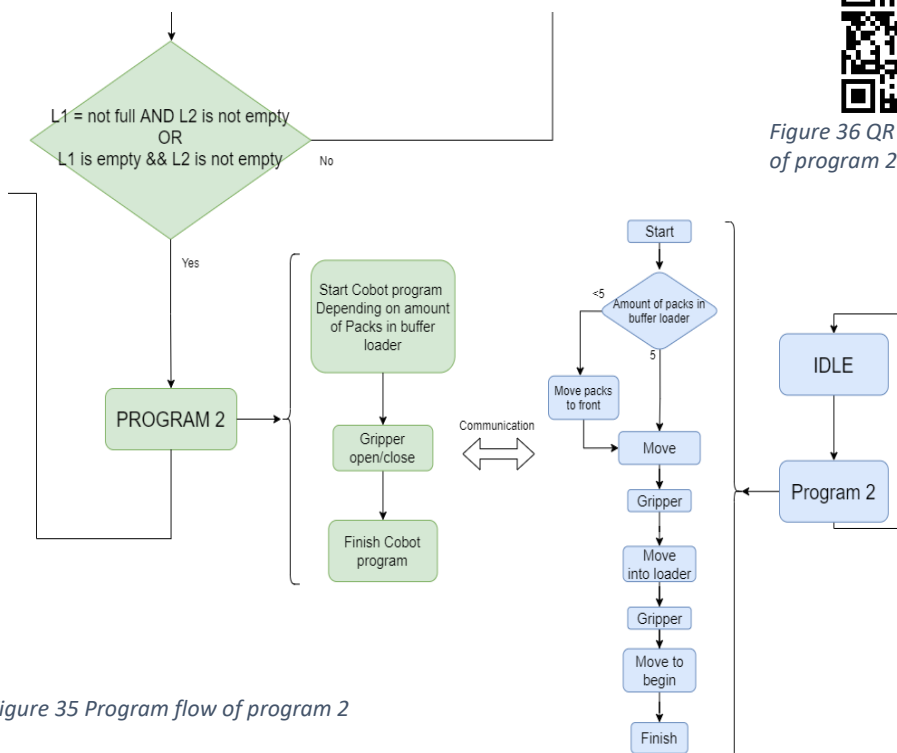


Figure 35 Program flow of program 2



Figure 36 QR code to video of program 2

When there is a pack in the front of the buffer loader, the relocation of the pack from the buffer loader to the main loader can begin. The gripper will be guided into the buffer loader and the PLC will be commanded to open the gripper in order to take the pack. When the PLC is ready and returns the cobot the confirmation that the gripper is in position, the cobot moves out of the buffer loader and into the main loader. After the arrival in the main loader, the closing of the gripper will occur in the same way as the opening. The cobot then leaves the main loader and finally returns to its begin position. The robot and the PLC return back to their idle state.

4.1.3 HMI Update

By adding these two new programs, the second loader is also in use. This means that the operator should also be able to monitor and interact with this loader. In order to do so, the Human Machine Interface was updated. An extra square is added in order to monitor the current amount of packs left in the buffer loader. Besides that, it contains a button for manually resetting the value back to 5, a full loader. This allows the factory to be flexible. The module can be fully autonomous, but an operator can still take control and interact with the module.



Figure 37 New HMI with zero packs left in Loader 2



Figure 38 New HMI with 1 pack left in loader 2



Figure 39 New HMI with a full loader 2



#### 4.1.4 Communication between PLC and Cobot

The content of the communication between the PLC and the cobot has been extended for this thesis. The new data in the communication is marked in green in the table below.

First, there is the addition of a new byte (Byte 2) that holds an unsigned integer. This integer represents the number of packs that are left on the AGV while unloading. Besides that, another bit of the first byte is taken in use. This bit becomes 1 when the camera detects a pack and becomes 0 when the camera does not detect a pack. The expansion of the communication allows the new added programs to be more reliable and secure.

Table 5 Communication between PLC and cobot updated

	PLC IN / Cobot OUT		PLC OUT / Cobot IN	
<b>BITS AS BOOLEANS</b>	Byte 0 bit 0	READY	Byte 0 bit 0	Run
	Byte 0 bit 1	DONE	Byte 0 bit 1	InPosition
	Byte 0 bit 2	TOOL	Byte 0 bit 2	Auto-play & Init
	Byte 0 bit 3	FullBin	Byte 0 bit 3	Halt
	Byte 0 bit 4	PackAvailable		
<b>UNSIGNED INTEGER</b>	Byte 1	Gripper program	Byte 1	Operation
<b>UNSIGNED INTEGER</b>	Byte 2	PacksLeftOnAGV		

## 4.2 Discussion

The discussion first covers the validation of the new functionalities and then the value of this automation by observing the benefits and comparing them with the drawbacks.

### 4.2.1 Validation

In order to validate different parts of the new programs and technology, several different tests were performed. Each of these tests validated a specific element or situation. Due to the lack of time, the tests do not have exact data, but are solely based on observations.

The first test was conducted in collaboration with the two fellow students because it involved the communication between the two projects. Results showed that when the buffer loader became empty, the service of the AGV was successfully notified. This test has been performed manually via a computer and automatically while the SIF-400 was processing orders. The same test also successfully validated the handshake between the PLC and the AGV.

The second test validated the camera precision on the different packs in the pile. The focus of the camera lens has been set on the height of the top of the third pack. This height has also been used to create the mask to detect the packs. This has the result that packs closer to the lens will appear bigger and vice versa. In order to validate the precision of the camera on different heights, a visual analysis has been conducted. Results show that the highest precision was reached at the pack in the middle and more deviation occurred at the last pack than the first pack. However, this deviation did not cause any problems during the tests. Even though the result is positive, it is worth mentioning that with further improvements, the precision could be enhanced even more. This could be achieved by changing the focus of the camera depending on the number of packs left on the AGV and creating a detection mask for a pack at all the different heights.

The third test was also created in order to test the performance of the camera. In this test, the deviation of the packs had been tested. The AGV arrived several times with the pile of packs being bowed to one specific side. Two samples of this test are shown in figure 40 until 43. The results of these tests were not straightforward because in a few cases the camera had difficulties detecting the first pack, which has the highest deviation. We can conclude that it is still important for the operator to place the packs in a straight pile. In future work, there can be a redesigned add-on that makes sure the pile will always be within the maximum tolerances. This can be done without the need for any other modification such as the code of the robot.

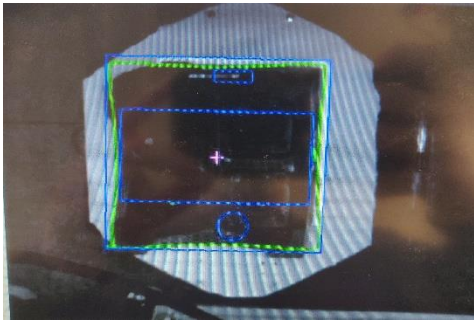


Figure 40 Top view of pile with no deviation



Figure 43 Side view of pile with no deviation

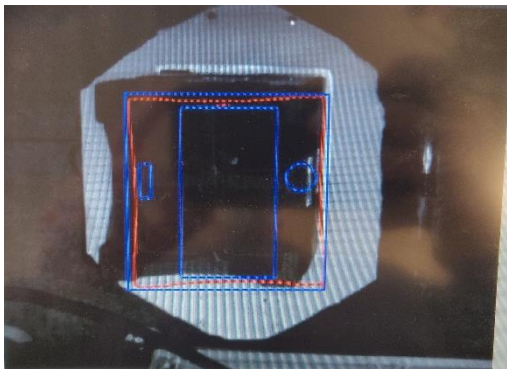


Figure 41 Top view of pile with maximum deviation



Figure 42 Side view of pile with maximum deviation

The last test validated the stock management between the main loader (loader 1) and the buffer loader (loader 2). This test consisted of executing this program for every pack in the buffer loader. The results were positive for every pack, resulting in a successful test. The only minor issue was that the 3D printed structures that replace the metal inserts were not implemented yet. This caused more deviation on the position of the packs in the loader. Fortunately, the deviation was still tolerable and didn't cause any problems.

#### 4.2.2 Value in Industry 4.0 context

First of all, this automation replaces a task of an operator, thus reducing his workload. This has the potential to be beneficial for the costs of manufacturing, because even though this extra automation is a costly investment, it will reduce the total labor costs. But to assure this, it needs to be sufficiently reliable. This means that no production hickups may appear and maintenance costs need to stay under control. It should also be confirmed by a financial payback analysis. Besides that, the challenge that rises with this, is that there will be a change in desired competences. The traditional worker that, for example, fills the stock manually has to be retrained to be able to work together with cobots.

Secondly, this extension improved the flexibility of the training module. By default, the station will call the AGV to bring new packs and unload the AGV by using the cobot. However, it is still possible for an operator to override this automation and refill the module manually. This results in a flexible solution.

Besides that, it increases the amount of training material for the classes in the T2 campus that use the SIF-408. For example in the course of 'Production operator', it is now possible to use the SIF-408 to analyse the time differences between manual refill and automated refill. Other extra training materials can be a comparison of the different cobot programs or a priority analysis of the PLC, and many more possibilities.

The next value proposition is the increase in uptime of the cobot. The uptime of a machine represents the percentage of time a specific machine is being used. By adding this functionality, the cobot will be busy more often, which increases the uptime of the cobot.

The last value is efficiency gain. To determine the gain in efficiency, precise comparisons have to be made. Unfortunately, these tests could not be carried out within the available timeframe.



## 5 Conclusion

This thesis enhances the automation in an already existing production line. It describes the addition of two new functionalities to an already integrated cobot to enable automatic replenishment of raw materials (packs) of the SIF-408. By doing this, it enabled the module to be completely autonomous, which is a great step forward in achieving a fully automated demonstrator of a Smart Factory.

This thesis showcased the possibility to add new technologies and automation to an already existing production line. The new software architecture allows to add new functionalities with only a limited amount of hardware investments and programming cost and minor interference to the original software. Thereby, the separated program structure of the new PLC code was designed so that it will not interrupt the main program of the module. Another example of the separation of tasks can be seen in the usage of the loaders, the second loader is selected to be a buffer loader so that the program can still be running with its spare packs while the AGV is on its way to bring a new pile of packs.

The result of this thesis can be the base for new improvements and additional automations for the SIF-400 as well. For instance, it could be a starting point for the challenges that were proposed by the fourth assignment. Much code and techniques can be copied over to perform the same automation at the SIF-404, but this time with an external cobot. Apart from this, the basic principles can also be applied for further automation of real scale production lines.

By extending these solutions to real scale production lines, this project was able to show a way to automate the machine tending task of an operator, which can have big advantages for a real factory. The most obvious advantage is that it can reduce the workload of the operators. Besides that, it also increases overall factory safety, because humans get tired and as their attention span lowers, they become sloppier, which may be the cause of many accidents. In contrary, the Automated Guided Vehicle and the cobot will almost make no mistakes whatsoever. Another advantage for a factory that adopts this technology is the increase in order and structure. Robots are programmed to perform specific, predefined tasks. This forces other operators to be much tidier and place objects in exact locations.



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