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Industrial Electrical Engineering and Automation

# A Case Study of Emulate3D

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# A Case Study of Emulate3D

## Evaluating Distance Learning and Collaboration in Industrial Automation Through Safety Implementation Using a Virtually Commissioned Digital Twin

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# Abstract

A growing demand for specialized equipment training has led to the need for cost-effective and environmentally friendly alternatives to traditional training methods. In partnership with Rockwell Automation, this bachelor thesis investigated the development and potential of a digital twin application. The research aimed to evaluate the practicality of remote virtual commissioning by using Rockwell Automation's software Emulate3D, leveraging new design and testing possibilities within a collaborative environment while also gaining valuable experience in the realms of safety, simulation and emulation.

The result is a digital twin that successfully assembles and transports batteries along the production line with improved handling authenticity and adequate safety measures. The model incorporates Emulate3D-integrated Quick Logic for controlling robots, Magnemover Lite (MML) and Intelligent Track Systems (iTRAK). Programmable Logic Controllers (PLC) control conveyors and safety components like multifunctional access boxes (MAB), light curtains and emergency stop lines.

Throughout the thesis, the digital twin model was effectively developed remotely, with minimal in-person meetings. Screen sharing facilitated collaboration, reduced development times, and allowed seamless integration of components. Remote work provided some advantages such as worker comfort and safety, as well as reduced travel time but had some drawbacks like potential miscommunication.

This bachelor thesis contributes to the growing body of research on digital twin applications and the potential of remote work in specialized equipment training.

**Keywords:** Digital Twins, Virtual Commissioning, Remote work, Industry 4.0, Simulation, Emulation, Rockwell Automation, Emulate3D, Studio 5000, PLC, Virtual Reality

# Sammanfattning

Den ökande efterfrågan på specialutrustningsträning har lett till behovet av kostnadseffektiva och miljövänliga alternativ till traditionella träningsmetoder. I samarbete med Rockwell Automation undersökte detta examensarbete utvecklingen och potentialen för en digital tvilling-applikation. Arbetet syftade till att utvärdera användbarheten av virtuell idrifttagning genom att använda Rockwell Automations mjukvara Emulate3D, dra nytta av nya design- och testmöjligheter inom en samarbetsmiljö samt samtidigt få värdefull erfarenhet inom säkerhet, simulering och emulation.

Resultatet är en digital tvilling som framgångsrikt sammanställer och transporterar batterier längs produktionslinjen med förbättrad hanteringsautenticitet och lämpliga säkerhetsåtgärder. Modellen innefattar Emulate3D-integrerad Quick Logic för att styra robotar, Magnemover Lite (MML) och Intelligent Track Systems (iTRAK). PLC styr transportband och säkerhetskomponenter som Multifunktionella Accessboxar (MAB), ljusgardiner och nödstoppslinjer.

Den digitala tvillingmodellen utvecklades effektivt på distans, med ett minimum av fysiska möten. Skärmdelning underlättade samarbete, minskade utvecklingstider och möjliggjorde sömlös integration av komponenter. Distansarbete gav vissa fördelar som bekvämlighet och minskad restid men hade vissa nackdelar som potentiella missförstånd i kommunikation.

Detta examensarbete bidrar till den växande forskningen om digitala tvillingar och potentialen för distansarbete inom specialutrustningsträning.

**Nyckelord:** Digitala tvillingar, Virtuell idrifttagning, Distansarbete, Industri 4.0, Simulering, Emulering, Rockwell Automation, Emulate3D, Studio 5000, PLC, Virtuell verklighet

## Acknowledgements

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Lastly we would like to thank Per Fløe Moesgaard and Håkan Kristiansen, the safety supervisors at Rockwell Automation, for their experienced input, ensuring our solutions are feasible from a practical safety perspective.

I, Andreas Tingström, would also like to give my personal thanks to my girlfriend Dominika, who supported and motivated me throughout the duration of the thesis. And for her willingness to listen to me explain my thoughts surrounding the thesis, as well as providing help editing.

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# Abbreviations

| | |
|---|---|
| AI | Artificial Intelligence |
| CAD | Computer Aided Design |
| CEC | Customer Experience Center |
| DPH | Degree of Possible Harm |
| E3D | Emulate3D |
| FE | Frequency of Exposure |
| HRN | Hazard Rating Number |
| iTRAK | Intelligent Track System |
| LO | Likelihood of Occurrence |
| MAB | Multipurpose Access Box |
| MML | Magnemover Lite |
| NP | Number of People exposed/at risk |
| PE | PhotoEye |
| PLC | Programmable Logic Controller |
| SPLC | Safety Programmable Logic Controller |
| VFD | Variable Frequency Drive |
| VR | Virtual Reality |

# Terminology

| Term | Definition |
|---|---|
| Child (visual) | A visual considered a part of a larger object in E3D |
| Digital twin | A digital simulation of a process or system |
| Emulate3D | A software for creating, simulating, and optimizing virtual industrial systems |
| Flow Control | An E3D protocol able to manipulate loads in a scene |
| Framerate | How many frames per second a program has, a higher frame rate leads to a smoother visual experience |
| Logix Echo | Tool for emulating Logix-based control systems |
| Mixed reality | Combining digital and physical components for simulation and visualization |
| Parent (visual) | A visual containing smaller subparts in E3D |
| PhotoEye sensor | A photoelectric sensor that detects objects by emitting and measuring changes in returned light |
| Reparenting | Changing the hierarchy of visuals in E3D, making the visual the child of a different parent |
| Scene | An E3D workplace for modeling |
| Studio 5000 | An engineering and design environment for programming, configuration, and maintenance |
| Teachpoint | A preprogrammed location for a robot |
| Transfer state | An Emulate3D protocol with pre-written procedures to facilitate transportation of loads |
| Virtual commissioning | Usage of simulation to design and test a digital model before physical implementation |
| Visual | A visual representation of an object in Emulate3D |

# 1

# Introduction

This chapter of the report provides an overview of the challenges faced by companies in training personnel in the use of specialized equipment and the potential of digital twin technology to address these challenges. It also discusses the concepts of digital twins and Emulate3D, as well as the role of Rockwell Automation in this field. The chapter further outlines the purpose, objectives, problem statement, rationale, methodology, delimitations, and resources required for the thesis. Primarily, the thesis focuses on remote work and collaboration using digital twins in the context of safety implementation in a battery manufacturing application.

## 1.1 Background

At present, training personnel in the use of specialized equipment can be difficult or even impractical, especially when the equipment is not easily accessible. Large corporations with employees stationed worldwide often resort to flying out personnel or constructing similar equipment on location when remote webcam training is insufficient. These trips can be both time-consuming for the individuals involved and expensive for the companies. In light of the increasing emphasis on climate change and sustainability, companies face an urgent need to reduce their emissions in a cost-effective manner. To address these economic and environmental challenges, emerging technology such as digital twins can be employed. By creating a digital replica of the machinery, it can be effectively simulated for training purposes. Moreover, incorporating virtual reality with the digital twin can enhance the sense of realism and interaction during training.

To comprehend the description provided, it is vital to understand the concepts of digital twins and Emulate3D. While the definition of a digital twin may differ based on its implementation, the most widely accepted description is a digital simulation or replica of a process or piece of machinery. Emulate3D is the software that the project will utilize to generate the digital twin.

Rockwell Automation, an American corporation, is a provider of technology and solutions in the realm of automation and information management for industrial production. The company provides software, machinery, systems, motors, drive systems, sensors, safety devices, and communication.

## 1.2 Purpose

As more and more people work remotely for various reasons (illness, environmental requirements, economic viability, etc.), new challenges and efficiency issues arise. The purpose of this thesis is therefore to investigate and demonstrate the ability to work remotely with digital twins (Emulate3D) and utilize new design and testing opportunities in a collaborative environment. Development of a digital twin for in-house use at Rockwell Automation's Gothenburg office will serve as a basis for the investigation of remote working capabilities using virtual commissioning.

Utilizing safety components at Rockwell Automation's offices on the Customer Experience Center (CEC) wall, a demonstration of how these components work in a factory environment is to be developed. With a Programmable Logic Controller (PLC), the digital twin should also be able to read input from physical devices on the CEC wall. This digital twin is intended to have full virtual reality (VR) functionality integrated. The end user will have access to necessary VR equipment while visiting Rockwell Automation offices, where it will be displayed.

Furthermore, the objective is to provide the authors experience in using simulation and emulation as well as practical use of PLC, variable frequency drives, and safety equipment (sensors, scanners, light curtains, cable-pull safety ropes, etc.).

## 1.3 Objective

The primary aim of this thesis is to design and showcase a digital twin application for a robot cell that incorporates PLC, variable frequency drives, and safety equipment, all of which facilitate remote work and collaboration throughout the design and testing process. The ultimate objective is to document and demonstrate the capacity to work remotely, leveraging new design and testing possibilities within a collaborative environment while also gaining valuable experience in the realms of safety, simulation, and emulation.

## 1.4 Problems

Through this thesis, the following questions will be answered:

- How well can one work with digital twins remotely?
- What challenges and efficiency issues arise when working remotely with digital twins, and how can they be managed?
- Which problems can be detected with a virtually commissioned digital twin?
- How can digital twins be used to enable remote work and collaboration in the design and testing process of a robot cell?
- In what ways can simulation and emulation be used to develop and test a digital twin application for a robot cell?
- How can Emulate3D be evaluated and documented to demonstrate efficiency and the ability to work remotely and collaboratively?

The questions will be answered by developing and demonstrating a digital twin application for a robot cell using PLC, HMI, variable frequency drives, and safety equipment, and by conducting investigations and evaluations of remote work and collaboration with digital twins.

## 1.5 Rationale for the Thesis

The decision to pursue this thesis stems from a shared passion for the field of automation and its potential to optimize the efficiency and performance of various processes and products. Digital twins, as a novel and rapidly evolving technology, present a plethora of opportunities for developing more cost-effective, safer, and adaptable production systems.

This challenge is viewed as a thrilling prospect to actively participate in the technological advancements within digital twins, while also contributing to the exploration and demonstration of remote work capabilities in this domain.

Enthusiasm for digital twins was further ignited by a lecture hosted by Rockwell Automation at an educational institution. The presentation offered an insightful overview of the company and the possibilities inherent in this field of study.

In conclusion, undertaking this thesis is expected to grant an unparalleled chance to acquire in-depth knowledge and experience with digital twins and their potential applications. Additionally, it will enable a contribution to the growing understanding of how this technology can be harnessed to create more efficient and versatile production systems.

Rockwell Automation is equally keen to support this thesis in order to gain a more comprehensive understanding of the challenges associated with remote work involving digital twins, and to assess the extent to which simulations can effectively replace traditional in-person training sessions.

## 1.6 Methodology

The thesis will frequently utilize simulations as they form a significant basis of the project's purpose. In order to develop knowledge pertaining to safety, simulation, transport solutions, and robotics, several meetings will be held with relevant experts. Finally, training and studying documentation will constitute a significant part of the project, particularly in connection with training in the use of the Emulate3D software.

The work will mostly be conducted remotely, as remote work is a fundamental aspect of the thesis's nature. Physical visits to Rockwell Automation in Gothenburg will occur by agreement during the project, with an initial plan for a total of three real visits – one at the beginning, one in the middle, and one at the end of the project.

## 1.7 Delimitations

The scope of this thesis will not encompass the modeling of components from scratch, such as creating models using CAD software or other similar tools. Instead, the digital twin will be primarily pre-constructed with conveyor belts, robots, turntables, QuickStick, Magnemover Lite, and Intelligent Track System components with partial logic implemented at the beginning of the project.

What remains to be implemented during the project is improving the implementation of the robots, and transport solutions, as well as the incorporation of safety equipment, including light curtains, emergency stops, and guards. All of these safety components are designed to minimize injury risks in a real-world application of the system.

Not all existing programming will require replacing. As the scope of the project regards remote collaboration using digital twins and security, reprogramming these components will primarily serve to familiarize the authors with their functionality.

The safety components utilized in this project will be restricted to those available on Rockwell Automation's "Safety Wall," which includes the multifunctional access box, light curtains, scanner, grip safety switch, and GuardLink. The specific functions and operational details of these components will be elaborated upon in the chapter regarding safety components.

Finally, the finished digital twin is not intended to be designed for usage outside of Rockwell Automation’s office. Therefore the model will not be designed for users without the proper hardware and components for connectivity and interaction. Furthermore, the model itself is not intended to reduce traveling to interact with it. Additional work could be done on the model for it to be intractable anywhere, but that is not the intent of the model developed during this thesis.

## 1.8 Resources

For the thesis, the Emulate3D software is required to build the digital twin. In addition to this, Studio 5000 will be used for PLC-programming and FactoryTalk Logix Echo will be used to emulate the GuardLogix® 5580 PLC controller. Trips to Gothenburg will be necessary to access the machinery to be simulated. For hardware, a computer capable of running Emulate3D, which requires a powerful machine, will be needed.

## 1.9 Division of Labor

An approximated division of planned labor expressed as a percentage is depicted in Table 1.1. Values regarding the division of labor serve as nothing more than an estimate, and should not be taken at face value. During the thesis, work will be performed fluently, based on developed skills, and schedule.

| Task | Andreas Nielsen | Andreas Tingström |
|---|---|---|
| Analysis | 50 | 50 |
| Design | 50 | 50 |
| Emulate3D | 20 | 80 |
| PLC programming in Studio 5000 | 80 | 20 |
| Poster | 50 | 50 |
| Safety design | 50 | 50 |
| Safety programming | 70 | 30 |
| Report and presentation | 50 | 50 |
| Testing/Evaluation | 50 | 50 |

Table 1.1: Division of labor

# 2

# Technical background

In order to provide a comprehensive understanding of the safety and automation components utilized in this report, this section presents an in-depth introduction to the various elements and their application within the digital twin environment. These components play a critical role in ensuring the safety and efficiency of industrial processes and systems, and their understanding is essential for the proper evaluation of the digital twin's functionality. After describing the essential components, an overview of digital twins and their history will be given. Finally, a brief description of safety evaluation will be given using a hazard rating number (HRN) as a reference.

## 2.1 Components

Due to the thesis' close ties to safety and automation components, an introduction to these components and their usage in the digital twin is helpful to facilitate the reader's understanding. It is important to note that although some components are used in conjunction with other components to increase personal safety, these should not be considered as safety components in their own right. For further details on potential risks the reader is referred to section 5.1 regarding personal safety.

### 2.1.1 Safety Components

This section will provide a description for different safety components used in the project to give the reader a better understanding of how these were implemented and used.

### Cable-pull Safety Rope and Switch

If the machines in an operating area cannot feasibly be isolated, or if the machines do not pose a sufficient risk to justify isolating them, then a cable-pull safety rope can be installed along the machine to secure it, as demonstrated in Fig. 2.1. While the exact functionality of the cable-pull system may vary, they may use several activation methods depending on how the cable is pulled. Some cable-pull systems detect a slight pull which may occur as a result of leaning on the cable, as well as how quickly the cable is pulled. A quick pull of the cable could lead to a complete stop of the machinery, while a slower pull might result in a slowdown. Additionally, some cables also feature an emergency stop switch for an immediate shutdown.

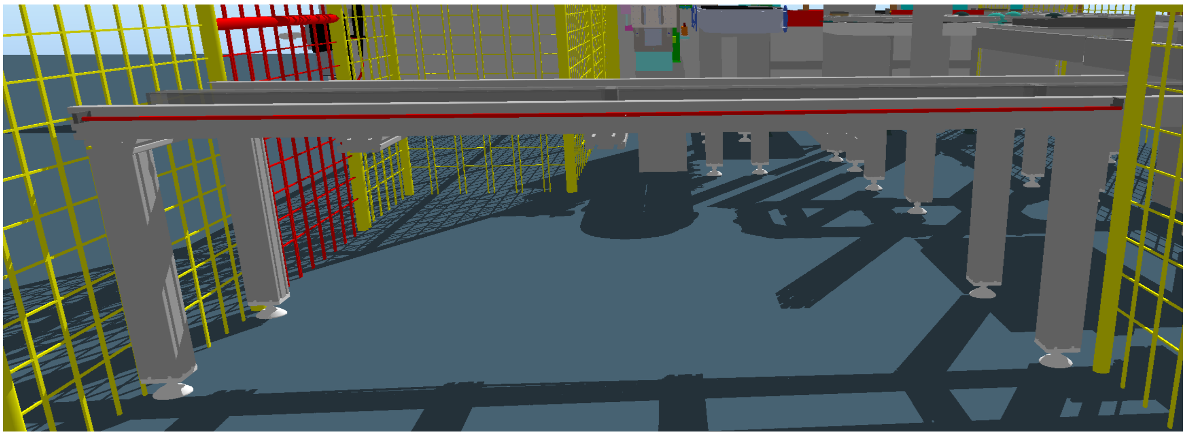


Figure 2.1: A Cable-pull safety rope attached to a QuickStick in Emulate3D

### Enabling Switch

An enabling switch, also colloquially referred to as a “Dead man’s switch”, is a device that requires the operator to continuously hold down a button located on the switch. Upon release of the switch, the enabling switch typically turns off machinery in proximity to the operator of the switch. Implementation of the enabling switch may vary, but a common usage is to combine it with a multifunctional access box, as has been done in the digital twin created during the thesis. Depending on the model the enabling switch may have a dedicated jog button, and a button to reset any faults.

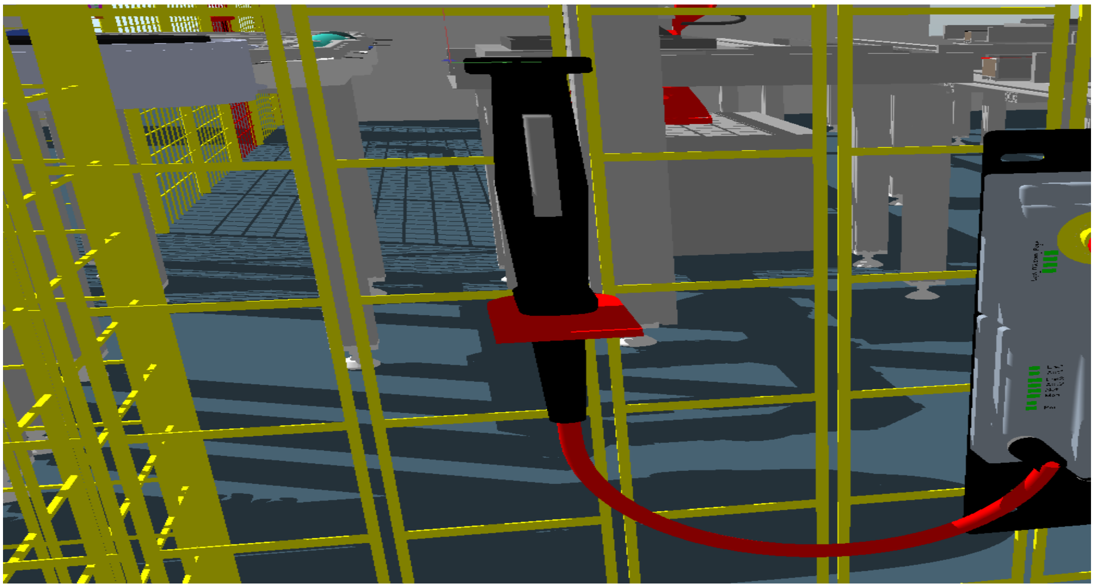


Figure 2.2: An enabling switch attached to a multifunctional access box in Emulate3D

### Light Curtain

A light curtain is a device that uses several beams of light to detect any personnel entering a safety zone. Light curtains can be programmed to either detect the blocking of individual beams of light, or the blocking of any beam of light. By detecting which beams have been blocked it is possible to measure the height of the blocking object. This functionality can be used outside of safety applications to sort loads, or prevent false positives leading to unnecessary shutdown. After an intrusion is detected, a reset button, placed out of reach from personnel inside the safety area, must be pressed to restore full machine functionality.

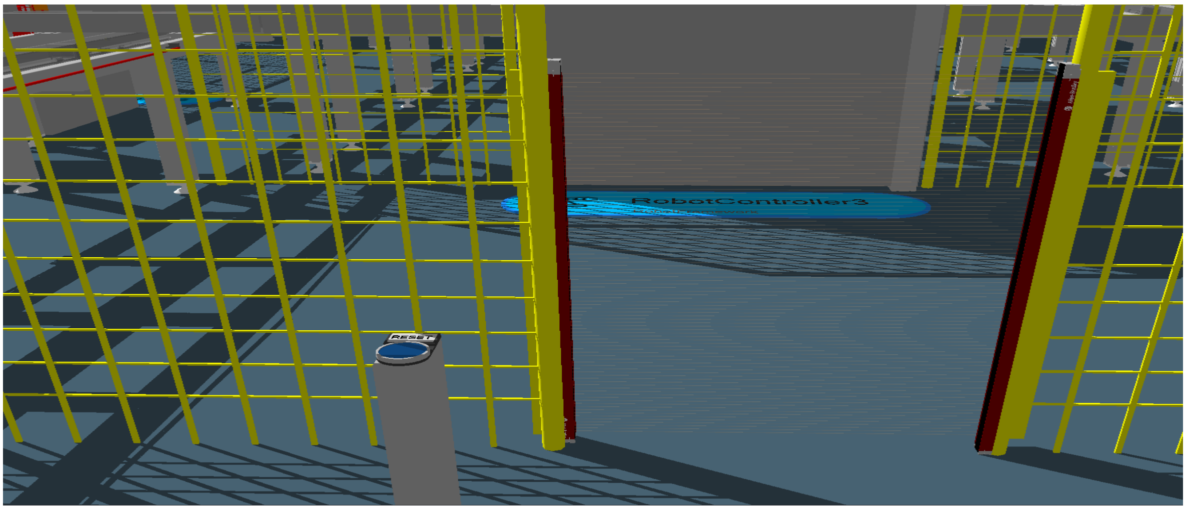


Figure 2.3: A light curtain and its associated reset button in Emulate3D

### Multifunctional Access Box

Multifunctional access boxes (MAB), see Fig. 2.4, are a safety component widely used in industrial applications to ensure safe access to hazardous areas of machinery. This device is classified as a safety interlock switch, which functions by providing a lockout mechanism that ensures the machinery cannot be operated unless it is safe to do so. This serves to protect workers from hazardous machinery by ensuring that the equipment remains in a safe state during maintenance, repair, or other operations that require human intervention inside or near the operational zone of an industrial machine.

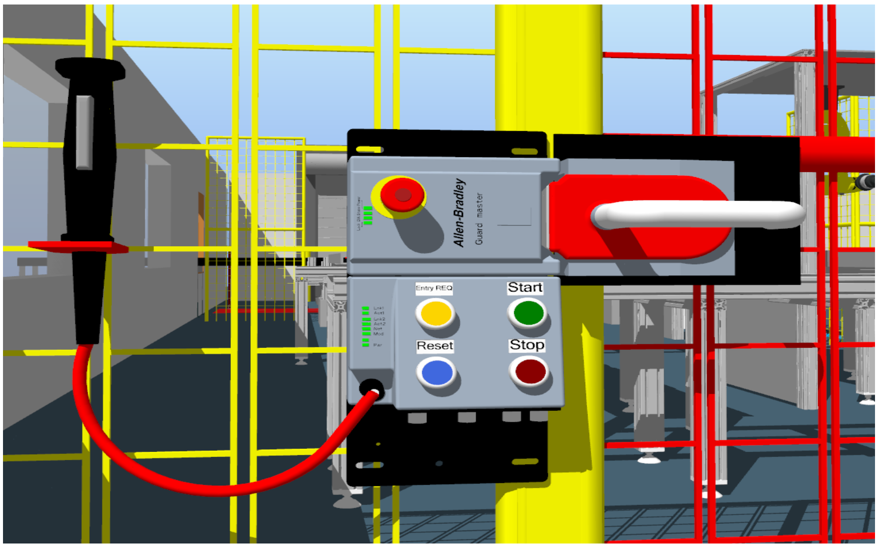


Figure 2.4: A four button MAB with an enabling-switch in Emulate3D

The MAB is designed to withstand harsh industrial environments and maintain high levels of durability, with a robust construction and anti-corrosive materials. It is commonly installed in conjunction with other safety devices, such as safety sensors and guards, to create a comprehensive safety system for machinery and equipment [1]. For this project, an enabling switch was added as an additional safety feature.

When access to the area secured by a MAB is not requested, the door is locked. If access is requested, the door unlocks and adequate safety measures are performed. This normally involves greatly decreasing movement speed or completely stopping dangerous machinery.

For the digital twin two models were used with slight variations in functionality. One MAB features four buttons whereas the other features two.

The four button MAB contains, in addition to “Entry REQ” and “RESET” like the two button version, also “START” and “STOP”. This four button version is purely virtual in this project and can only be triggered during simulation, whereas the two button MAB is partially emulated but can also be triggered if it is physically connected to a real one located on the customer experience center wall.

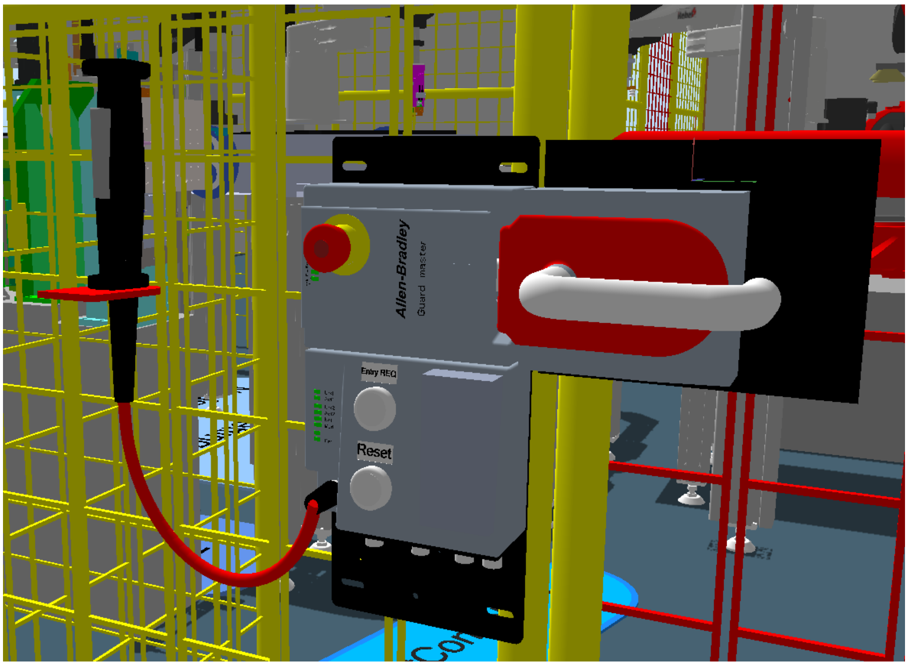


Figure 2.5: A two button MAB with an enabling switch in Emulate3D

### Safety Programmable Logic Controller

For the digital twin an emulated safety programmable logic controller (SPLC) was utilized to monitor the status of safety components. Rockwell Automation lists the three fundamental differences between an SPLC and a PLC to be the architecture, inputs, and outputs [2]. Regarding architecture, an SPLC has redundant microprocessors, flash memory, and RAM which are continuously monitored by a watchdog circuit to ensure consistency. Unlike a standard PLC, the SPLC features internal methods of verifying input functionality. Furthermore, an SPLC features two safety switches prior to an output driver controlled by their own microprocessor as well as three test points. In the event of a detected fault at the test points, switch faults, or microprocessor faults, the SPLC will revert to a known default state for a safe shutdown.

**Reset Button**

While the function of a reset button is generic, and simple enough to not require a detailed explanation, its recurrence in the project merits mentioning how it is used. After entering a safety zone, the affected machines are programmed to halt their speed until reset. Machines affected by multiple overlapping safety zones necessitates the reset button for each triggered zone to be pressed before full functionality is restored. Finally, some reset buttons are integrated into their associated safety components such as the multifunctional access box. Other buttons such as those associated with the light curtain safety zone are placed out of reach from personnel within the safety zone.

### 2.1.2 General Components

This section will provide a description for various general components, such as robots and different conveyor systems, used in the project to give the reader a better understanding of how these were implemented and utilized.

**Robots**

Industrial robots are programmable, multifunctional devices designed to automate complex tasks in production environments. These devices demonstrate high levels of precision, accuracy and repeatability and can perform operations such as welding, assembly, painting and material handling with minimal human intervention.

Generally composed of a manipulator arm, end-effector, and control system, industrial robots can be customized to execute an extensive range of tasks in various sectors, from automotive and electronics to pharmaceutical and food processing [3]. In this project, the robots used are Comau Rebel S6 and Comau Racer-7, both designed to deliver high speed performance and precision.

### Variable Frequency Drive

A variable frequency drive (VFD) is a motor drive that is commonly used to adjust the torque and/or speed of AC motors by modulating the frequency of the input. In the digital twin, a VFD controls the frequency of conveyors transporting battery pallets for processing. When a battery pallet is being transported the VFD increases the frequency in order to convey it for further transport, and when a safety zone is entered the frequency is significantly lowered to increase personal safety. In this report, VFD will commonly be referred to as PowerFlex 525 as this is the drive used in the project.

### Intelligent Track Systems

Intelligent Track Systems (iTRAK) is a motion control system developed by Rockwell Automation, with the intention of transporting small loads of up to 4 kg, or higher at low speed. It uses linear motor technology along with control and communication capabilities, resulting in a modular and scalable platform suitable for material handling, packaging and assembly operations.

iTRAK is a system that utilizes an intelligent track with independently controlled movers that follow defined paths, as can be seen in Fig 2.6. The system's position loop rate is 250 µs, and it has a repeatability of +/-0.01 mm, which facilitates the execution of complex motion tasks. iTRAK is designed to support various motion profiles, such as point-to-point moves, complex paths, and continuous motion, making it adaptable to a variety of applications. [4]

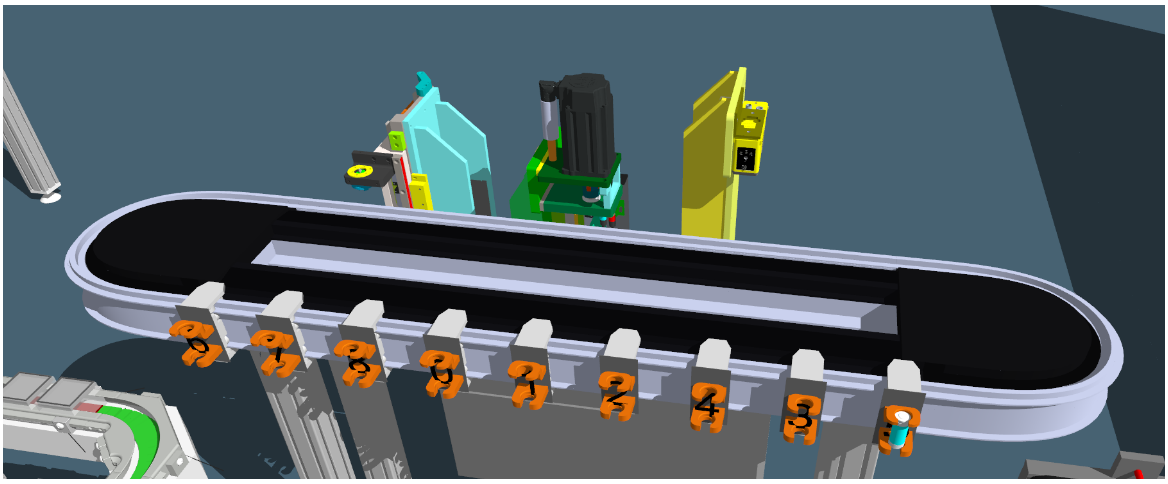


Figure 2.6: An iTRAK station in Emulate3D

### MagneMover Lite

Intended to transport smaller loads up to 10 kg, the Magnemover Lite (MML) is a modular transport solution developed by MagneMotion Inc, belonging to Rockwell Automation company [5]. Using linear synchronous motors, each vehicle or "puck" can be independently controlled with varying acceleration and deceleration profiles [5]. No external sensors are required either. The MML track used in this project can be seen in Fig. 2.7.

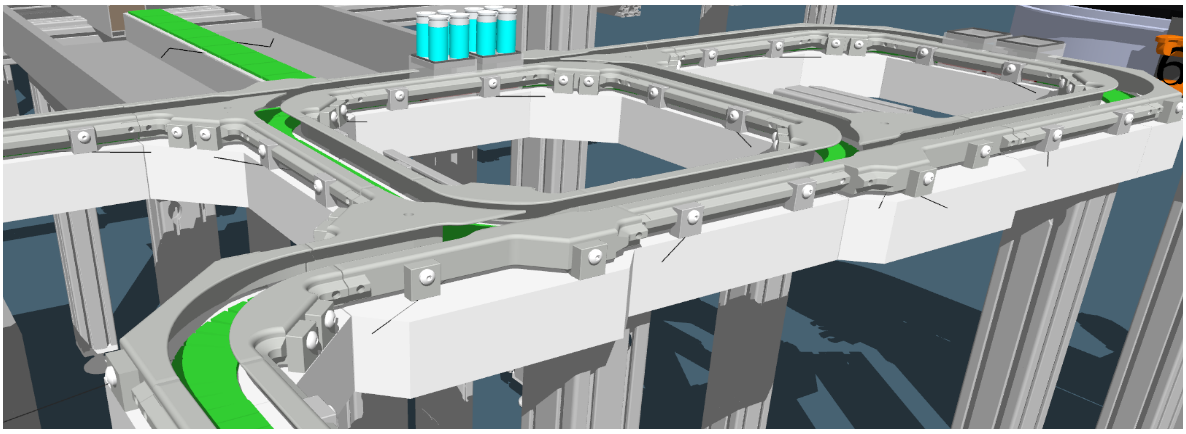


Figure 2.7: An MML track in Emulate3D

### QuickStick

QuickStick is a conveyor system developed by Rockwell Automation designed to move larger loads along a linear track. QuickStick 100 has a capability of up to 100 kg and QuickStick HT has a capability of up to 4,500 kg. [6]

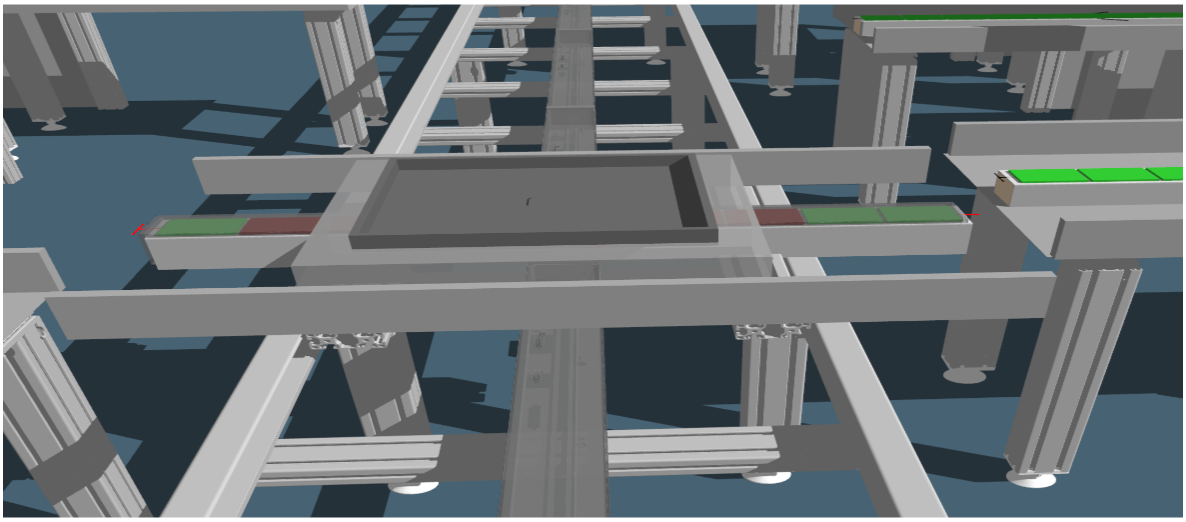


Figure 2.8: A QuickStick transporting an empty battery tray in Emulate3D

The system operates by using magnetic forces to move "pallets" or "carriers" along a track. These pallets can be accelerated, moved, and stopped independently of each other, which allows for a high degree of flexibility and precision in the movement of items along the conveyor.

## 2.2 Digital Twin

This section will explore digital twins, an emerging technology attracting significant attention from various industries around the globe, and a main part in this study. Digital twins function as virtual representations of physical objects, processes or even complete systems that combine powerful mathematical and statistical models, data assimilation and prediction capabilities, providing a valuable tool in development and optimisation of industrial systems.

Components that are represented are for example conveyors, robots, sensors and HMI which enables the user to build a complete replica of their system to analyze and develop. This allows for greater cost-efficiency as product lines can be completely simulated with up to 95% accuracy before actually manufacturing and deploying the physical machines [7]. Whilst not applicable in this study, it is common for digital twins to co-exist with the physical machinery. The digital twin is then updated with real-world data and uses simulation and, in some cases, machine learning to aid decision making. [8]

While this study will focus on industrial digital twins, it is worth noting that digital twins come in many shapes and sizes. Digital twins are used in various fields, such as structural health monitoring and predictive maintenance of bridges and other infrastructure, energy efficiency of building, increased efficiency, and downtime reduction in wind farms as well as prediction of the environmental impact. In the natural world, there is a growing interest in creating digital twins of forests, farms, ice sheets, coastal regions, and oil reservoirs, with some researchers even discussing the possibility of creating a digital twin of planet Earth.

The idea of a digital twin can be traced back to the Apollo program in the 1960s and 1970s. NASA would launch the Apollo spacecraft into space and deploy a virtual model on the ground in Houston to follow along on the mission. This approach became crucial in the Apollo 13 mission when the spacecraft suffered a malfunction and was stranded in space.

NASA was able to take the data from the real spacecraft and feed it into the simulator on the ground, dynamically evolving the simulator to represent the damaged spacecraft and ultimately guiding the astronauts back home safely [9]. However, it was Dr. Michael Grieves, a faculty member at the University of Michigan at the time, who applied the digital twin notion to manufacturing in 2002 and formally introduced the digital twin concept [10]. In 2010, NASA's John Vickers coined the term "digital twin" [11].

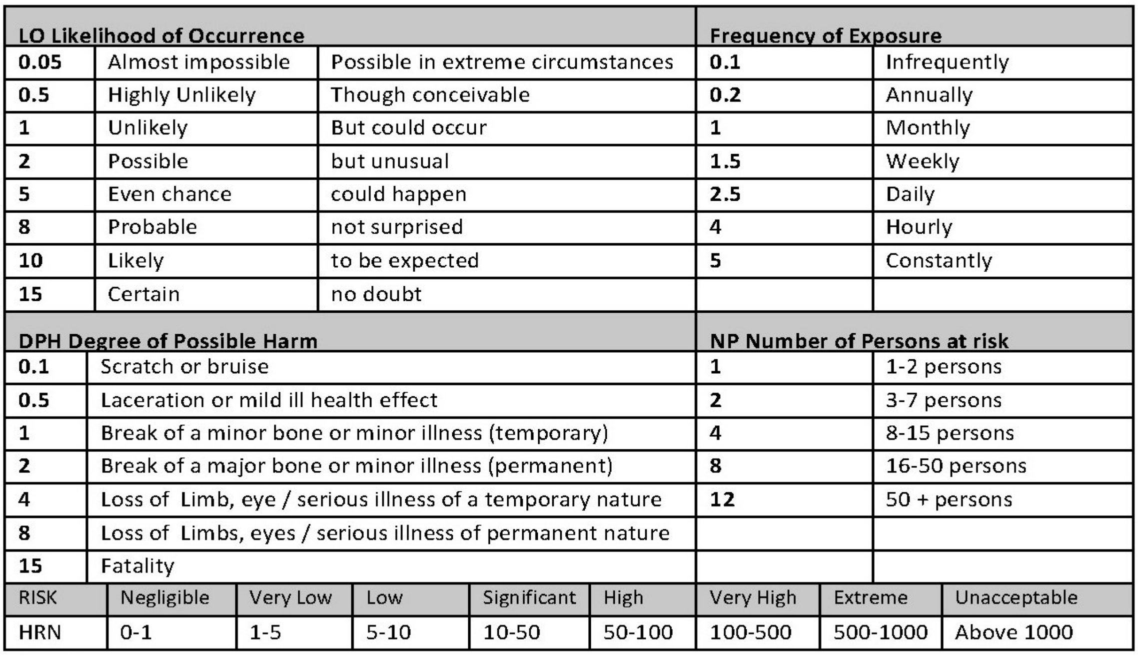
## 2.3 Safety

In order to develop safety zones and measures for the digital twin, two meetings were held with solution consultant seniors specializing in machine safety at Rockwell Automation. During the meetings, presentations pertaining to theoretical safety concepts and how these can be applied to real life safety applications. After these presentations, attention was given to the model to identify and secure potential hazardous areas using the relevant safety components.

To formally evaluate the risk associated with operating machinery the Hazard Rating Number (HRN) system was used. By weighing the potential severity (DPH), number of people affected (NP), frequency of exposure(FE) , and the probability of exposure (LO), the HRN can be calculated using the following formula [12].

$$HRN = DPH \times LO \times FE \times NP$$

Determining the values to calculate the HRN can be pulled from a table, such as Table 2.1. Depending on the source, a varying number for the likelihood of occurrence may be encountered.



| LO Likelihood of Occurrence | | | Frequency of Exposure | |
|---|---|---|---|---|
| **0.05** | Almost impossible | Possible in extreme circumstances | **0.1** | Infrequently |
| **0.5** | Highly Unlikely | Though conceivable | **0.2** | Annually |
| **1** | Unlikely | But could occur | **1** | Monthly |
| **2** | Possible | but unusual | **1.5** | Weekly |
| **5** | Even chance | could happen | **2.5** | Daily |
| **8** | Probable | not surprised | **4** | Hourly |
| **10** | Likely | to be expected | **5** | Constantly |
| **15** | Certain | no doubt | | |

| DPH Degree of Possible Harm | | NP Number of Persons at risk | |
|---|---|---|---|
| **0.1** | Scratch or bruise | **1** | 1-2 persons |
| **0.5** | Laceration or mild ill health effect | **2** | 3-7 persons |
| **1** | Break of a minor bone or minor illness (temporary) | **4** | 8-15 persons |
| **2** | Break of a major bone or minor illness (permanent) | **8** | 16-50 persons |
| **4** | Loss of Limb, eye / serious illness of a temporary nature | **12** | 50 + persons |
| **8** | Loss of Limbs, eyes / serious illness of permanent nature | | |
| **15** | Fatality | | |

| RISK | Negligible | Very Low | Low | Significant | High | Very High | Extreme | Unacceptable |
|---|---|---|---|---|---|---|---|---|
| HRN | 0-1 | 1-5 | 5-10 | 10-50 | 50-100 | 100-500 | 500-1000 | Above 1000 |

Table 2.1: Values for calculating the HRN of machinery [13]

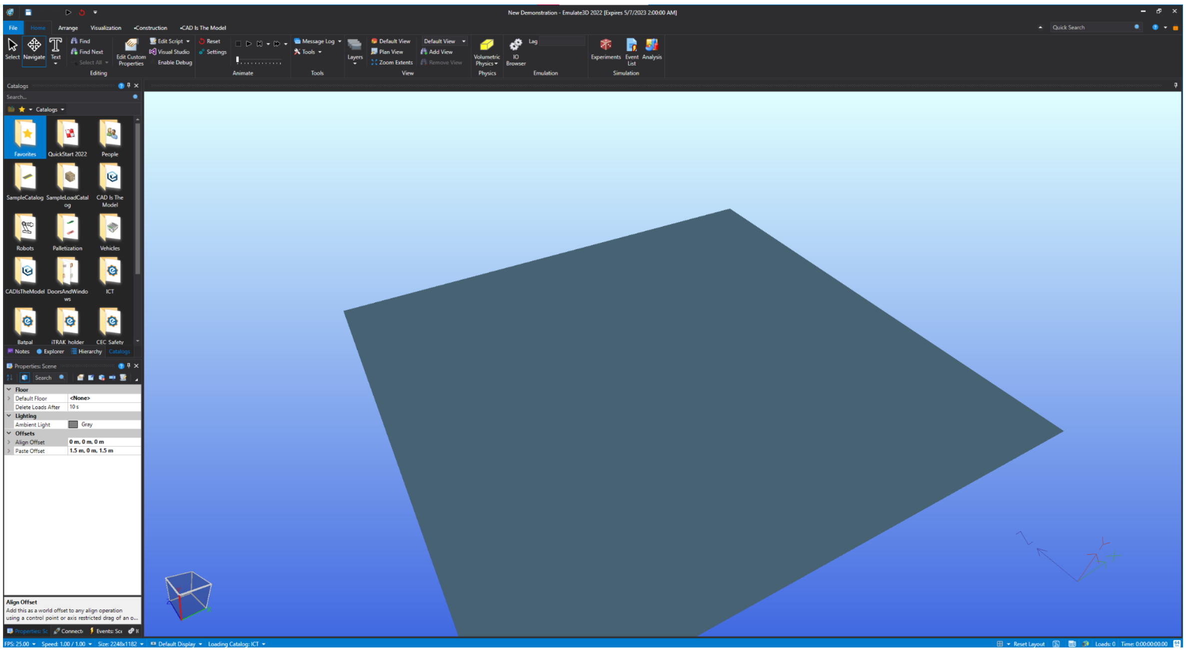
# 3

# Simulation and emulation

In this chapter, the focus is placed on virtual simulation and emulation, two essential tools that have revolutionized industrial development. Various software solutions employed in the study will be examined, highlighting their capabilities and advantages. Additionally, the 3D-model used in this project will be presented, detailing its different components, design principles and functionality.

## 3.1 Emulate3D

Emulate3D is a virtual commissioning software developed by Rockwell Automation. Featuring the ability to import custom CAD models, adjust the physics of objects, and tweak device parameters, the user is able to simulate their model to the desired degree of accuracy. Emulate3D also offers the possibility to connect to a virtual or physical PLC, enabling the testing of features and functionality not possible in a real environment using real or virtual components. With built in VR functionality, the user is also able to physically interact with the simulation for testing.



Floor
Default Floor <None>
Delete Loads After 10 s
Lighting
Ambient Light Gray
Offsets
Align Offset 0 m, 0 m, 0 m
Paste Offset 1.5 m, 0 m, 1.5 m

**Align Offset**
Add this as a world offset to any align operation using a control point or axis restricted drag of an o...

FPS: 25.00 Speed: 1.00 / 1.00 Size: 2248x1182 Default Display Loading Catalog: ICT Loads: 0 Time: 0:00:00:00.00

Figure 3.1: An empty Emulate3D scene

During simulation and designing of models, two modes are available to the user. These modes are named navigate, and select. While in select mode, the scene is displayed in a manner intended to provide an overview of the scene's dimensions and logic. As can be seen in Figure 3.4 showing the flow control component.

In select mode, logical nodes and connections are displayed, and objects are able to be manipulated including but not limited to their position and rotation. Additional tools can be employed in select mode to position and create objects like those available in the included "Arrange" and "Construction" tabs.

Navigate mode, on the other hand, is intended to provide a more true to life illustration of the scene. In navigate mode, the grid intended for dimensioning components which can be seen in Figure 3.4 is removed. Finally, interaction with objects is limited when using navigate mode. Objects may still be repositioned but this is done in a more realistic manner, such as opening door handles instead of repositioning them, and picking up an object.

With several default catalogs and components featuring movement solutions, robots, and sensors commonly found in factories, there is little need for the user to develop their own. Some catalogs are installed by default, but additional ones can be found in the package manager. If more advanced functionality not provided by default catalogs is required, the user is able to create their own custom logic and scripts with C#, Jscript, and the built-in Quick Logic system.

To customize visual representation of the model, various graphic options are available for the user to change. These options can be found in the visualization tab and offer functionality such as ray tracing, shadows, anti aliasing, and frame rate limiter. In addition to advanced settings, there are a select number of customizable graphical presets for different working conditions. While creating a presentation of a model, the user can select a high quality mode, and while working a user may select a performance mode for a smoother experience.

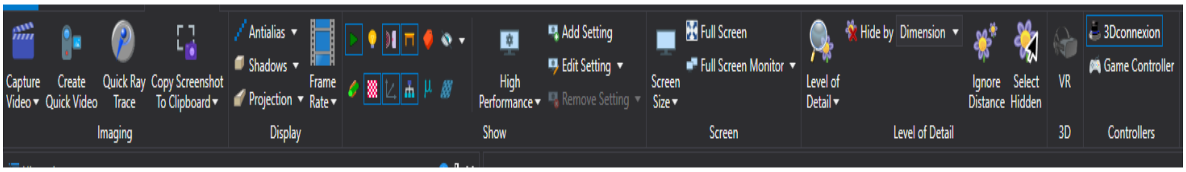
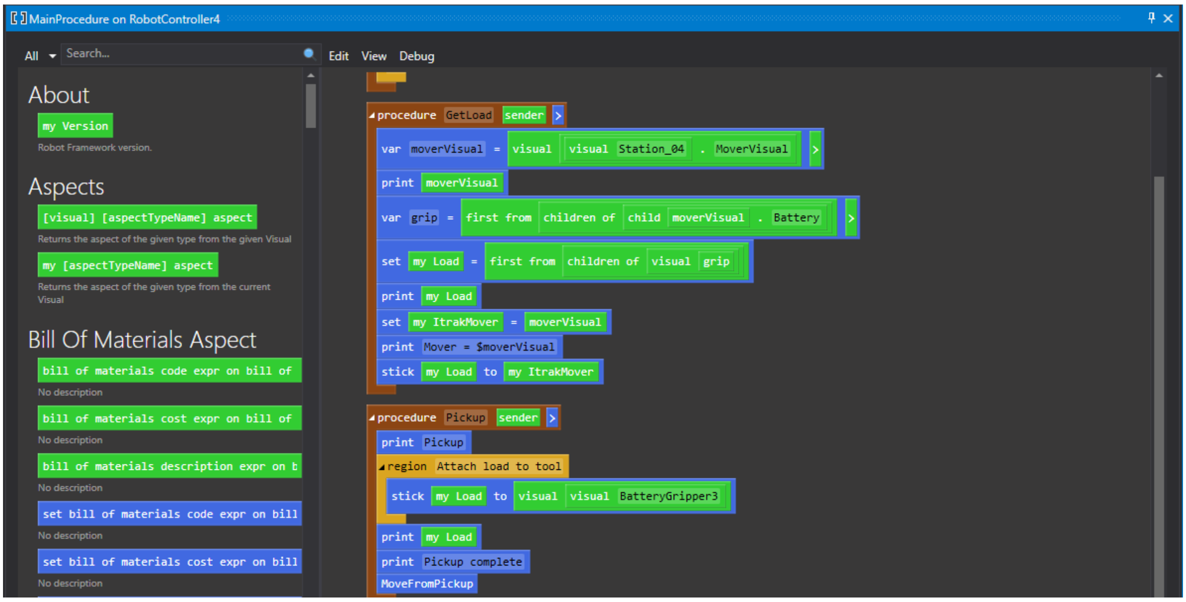


Figure 3.2: The visualization tab in Emulate3D

### 3.1.1 Quick Logic

Quick Logic is a visual programming language used in Emulate3D to create logic and procedures which can be used for simulation. Methods, functions, and variables are dragged into the body of code graphically in contrast to text based programming languages. Because Quick Logic can be bound to other events, procedures, and frameworks, the written code can be activated due to a preexisting trigger rather than the user needing to program the trigger.



About

my Version

Robot Framework version.

Aspects

[visual] [aspectTypeName] aspect

Returns the aspect of the given type from the given Visual

my [aspectTypeName] aspect

Returns the aspect of the given type from the current Visual

Bill Of Materials Aspect

bill of materials code expr on bill of

No description

bill of materials cost expr on bill of

No description

bill of materials description expr on b

No description

set bill of materials code expr on bill

No description

set bill of materials cost expr on bill

No description

```
procedure GetLoad sender
    var moverVisual = visual visual Station_04 . MoverVisual
    print moverVisual
    var grip = first from children of child moverVisual . Battery
    set my Load = first from children of visual grip
    print my Load
    set my ItrakMover = moverVisual
    print Mover = $moverVisual
    stick my Load to my ItrakMover

procedure Pickup sender
    print Pickup
    region Attach load to tool
        stick my Load to visual visual BatteryGripper3
    print my Load
    print Pickup complete
    MoveFromPickup
```

Figure 3.3: Quick Logic for a robot controller

### 3.1.2 Transfer State

Designed to be directly compatible with most robots and transport solutions, Transfer State is a framework that is intended to transport loads from one destination to another, including all intermediate steps. Robots using Transfer State protocols gain access to methods for pickup and dropoff of loads, negating the need to program such logic if set up correctly. In a similar vein, conveyors gain access to methods detecting when a load is near the end of a conveyor while using Transfer State functionality.

Loads are automatically placed on the conveyor at a specified interval with a “load creator” if there is sufficient space. All properties from size, type of load, and orientation are customizable. Increased control of created loads can be gained by disabling automatic placement of loads or by using flow control.

### 3.1.3 Flow Control

Intended to manipulate, create, and delete loads, a Flow Control component provides precise control of loads in a model. As the Flow Control component can be linked to any object, it is not exclusively for providing functionality to handle loads.

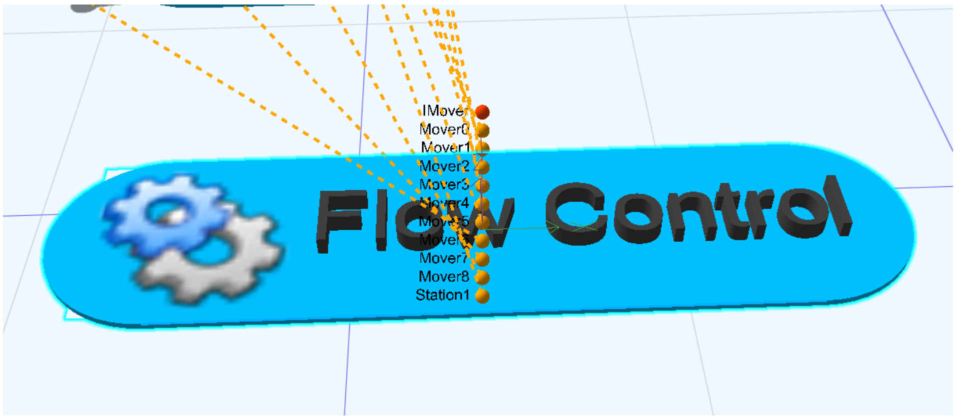
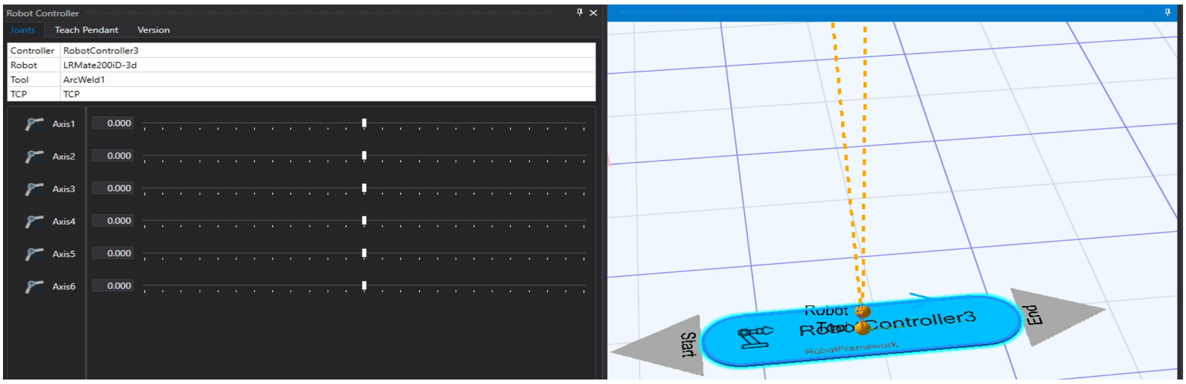


Figure 3.4: A Flow Control component linked to MML movers

### 3.1.4 Robot Framework

Robot Framework is a hardware agnostic Emulate3D framework for controlling robots. While enabling Transfer State functionality no additional programming is required once the robot, tool, start, and end connectors are correctly linked. Custom and more advanced loads can be programmed further with or without Transfer State functionality. Non Transfer State robots can utilize a main procedure, completely overwriting pre- existing procedures for pickup and dropoff.



| | |
|---|---|
| Controller | RobotController3 |
| Robot | LRMate200iD-3d |
| Tool | ArcWeld1 |
| TCP | TCP |

Axis1 0.000
Axis2 0.000
Axis3 0.000
Axis4 0.000
Axis5 0.000
Axis6 0.000

Figure 3.5: A robot controller and its associated menu

Movement of the robot can be programmed in multiple ways, from how to reach the destination to how to calculate the destination. Finer movement can also be achieved through manipulation of individual axes, as seen in Figure 3.5. For path calculation two forms of calculation can be used, namely linear and point-to-point (PTP) movement. Linear movement is slower and more consistent [14], while PTP movement is quicker [15], but less predictable.

Robot destinations in Emulate3D can be programmed in various ways based on personal preference and application. Both absolute and relative coordinates can be given. Absolute coordinates denote the position in the scene, while relative coordinates are in relation to a frame. Relative coordinates use a cartesian coordinate system, commonly referred to as a frame [14]. Usage of coordinates can be bypassed altogether by programming a preset location known as a teachpoint, or by retrieving the position of an object through scripting/programming.

### 3.1.5 iTRAK Framework

For simulating Rockwell Automation’s iTRAK system components. All positions on the track are measured in millimeters in relation to the designated “zero section”, as can be seen by the dotted line in Figure 3.6. Numbered stations can be placed along the track where logic can be associated with departure/arrival of a mover at the station. Fine station logic can be achieved by disabling a timed automatic dispatch of movers at a station and instead programming dispatch to occur when a condition is met or an event occurs.

Custom movers can be added to the track by adding the model to the iTRAK catalog. This can be seen in Figure 3.6 with the added orange grip on the movers. Finally, the Transfer State protocol can be used for simpler transport to and from the iTRAK.

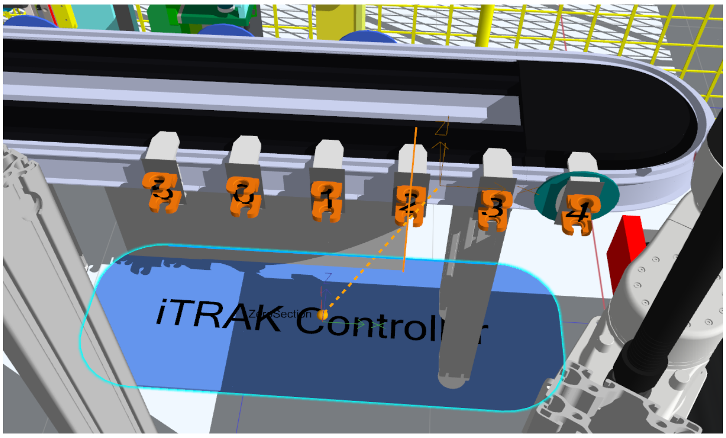


Figure 3.6: An iTRAK track and its controller

### 3.1.6 MML Framework

Similar to the iTRAK framework, the MML framework provides the tools for simulating Rockwell Automation's MML components. In addition to stations, with the same functionality as iTRAK stations, there are also nodes which can be placed along the track. These nodes can be seen in Figure 3.7, and are represented as coloured orbs. Nodes provide functionality, such as specifying where to merge/diverge, and providing a point for a mover to be transported with a robot to another track.

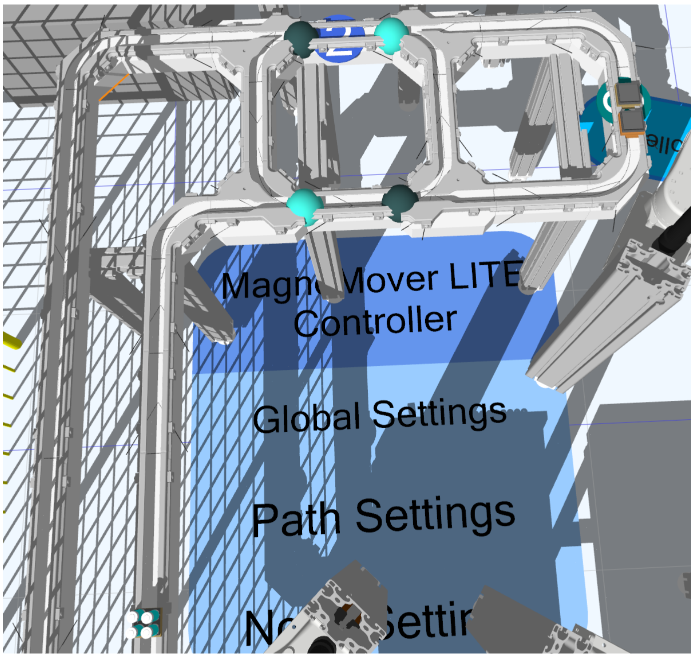
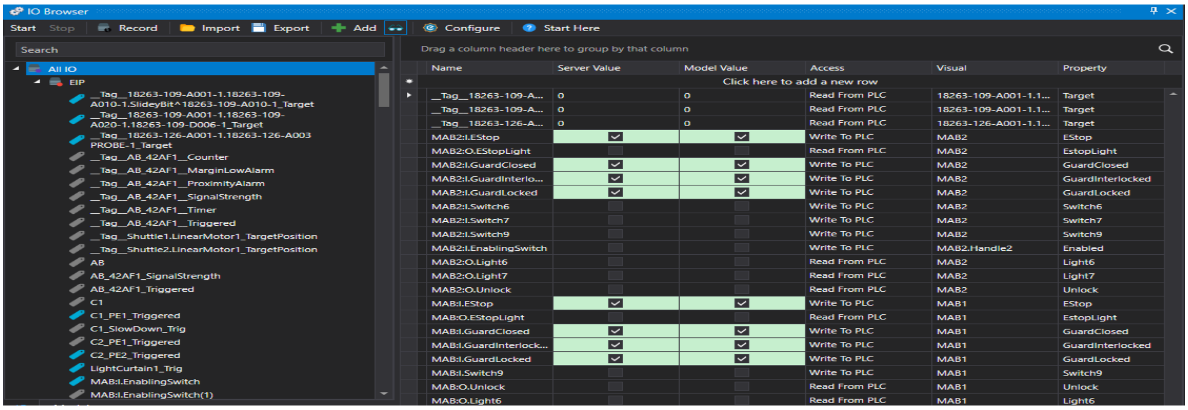


Figure 3.7: An MML track and its controller

### 3.1.7 IO Browser

Emulate3D's IO browser details which PLC tags exist in the scene. As can be seen in Figure 3.8, the name of the tags, their server and model value, their PLC access, and which property in Emulate3D they are associated with can be seen. When a physical or virtual PLC is connected, these tags can be used to execute logic in the scene, or be written to the PLC



- All IO
  - EIP
    - __Tag__18263-109-A001-1.18263-109-A010-1.SlideyBit^18263-109-A010-1_Target
    - __Tag__18263-109-A001-1.18263-109-A020-1.18263-109-D006-1_Target
    - __Tag__18263-126-A001-1.18263-126-A003 PROBE-1_Target
    - __Tag__AB_42AF1__Counter
    - __Tag__AB_42AF1__MarginLowAlarm
    - __Tag__AB_42AF1__ProximityAlarm
    - __Tag__AB_42AF1__SignalStrength
    - __Tag__AB_42AF1__Timer
    - __Tag__AB_42AF1__Triggered
    - __Tag__Shuttle1.LinearMotor1_TargetPosition
    - __Tag__Shuttle2.LinearMotor1_TargetPosition
    - AB
    - AB_42AF1_SignalStrength
    - AB_42AF1_Triggered
    - C1
    - C1_PE1_Triggered
    - C1_SlowDown_Trig
    - C2_PE1_Triggered
    - C2_PE2_Triggered
    - LightCurtain1_Trig
    - MAB:I.EnablingSwitch
    - MAB:I.EnablingSwitch(1)

| Name | Server Value | Model Value | Access | Visual | Property |
|---|---|---|---|---|---|
| __Tag__18263-109-A... | 0 | 0 | Read From PLC | 18263-109-A001-1.1... | Target |
| __Tag__18263-109-A... | 0 | 0 | Read From PLC | 18263-109-A001-1.1... | Target |
| __Tag__18263-126-A... | 0 | 0 | Read From PLC | 18263-126-A001-1.1... | Target |
| MAB2:I.EStop | ☑ | ☑ | Write To PLC | MAB2 | EStop |
| MAB2:O.EStopLight | ☐ | ☐ | Read From PLC | MAB2 | EstopLight |
| MAB2:I.GuardClosed | ☑ | ☑ | Write To PLC | MAB2 | GuardClosed |
| MAB2:I.GuardInterlo... | ☑ | ☑ | Write To PLC | MAB2 | GuardInterlocked |
| MAB2:I.GuardLocked | ☑ | ☑ | Write To PLC | MAB2 | GuardLocked |
| MAB2:I.Switch6 | ☐ | ☐ | Write To PLC | MAB2 | Switch6 |
| MAB2:I.Switch7 | ☐ | ☐ | Write To PLC | MAB2 | Switch7 |
| MAB2:I.Switch9 | ☐ | ☐ | Write To PLC | MAB2 | Switch9 |
| MAB2:I.EnablingSwitch | ☐ | ☐ | Write To PLC | MAB2.Handle2 | Enabled |
| MAB2:O.Light6 | ☐ | ☐ | Read From PLC | MAB2 | Light6 |
| MAB2:O.Light7 | ☐ | ☐ | Read From PLC | MAB2 | Light7 |
| MAB2:O.Unlock | ☐ | ☐ | Read From PLC | MAB2 | Unlock |
| MAB:I.EStop | ☑ | ☑ | Write To PLC | MAB1 | EStop |
| MAB:O.EStopLight | ☐ | ☐ | Read From PLC | MAB1 | EstopLight |
| MAB:I.GuardClosed | ☑ | ☑ | Write To PLC | MAB1 | GuardClosed |
| MAB:I.GuardInterlock... | ☑ | ☑ | Write To PLC | MAB1 | GuardInterlocked |
| MAB:I.GuardLocked | ☑ | ☑ | Write To PLC | MAB1 | GuardLocked |
| MAB:I.Switch9 | ☐ | ☐ | Write To PLC | MAB1 | Switch9 |
| MAB:O.Unlock | ☐ | ☐ | Read From PLC | MAB1 | Unlock |
| MAB:O.Light6 | ☐ | ☐ | Read From PLC | MAB1 | Light6 |

Figure 3.8: The IO browser

## 3.2 Studio 5000

Studio 5000 is an integrated engineering and design environment tailored to streamline and enhance the process of designing and maintaining industrial automation systems. This software mainly supports automation system development, including control and information design, system configuration as well as support for emulation and simulation. Studio 5000 includes Logix Designer, a powerful programming tool. It offers a wide array of programming languages such as Ladder Diagram (LD), Function Block Diagram (FBD), Sequential Function Chart (SFC), and Structured Text (ST), enabling engineers to select the most suitable language for their specific application requirements.

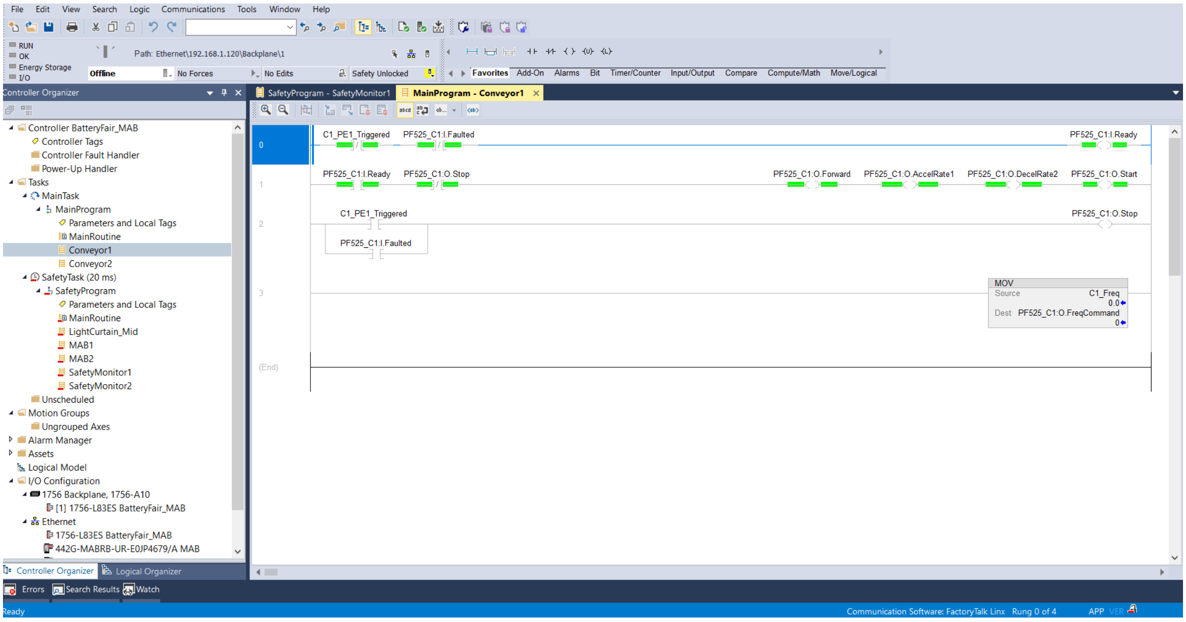


Figure 3.9: An overview of Studio 5000

Controllers, drives and other components are easily added via the “Controller Organizer”. As components are added, they include their specific data types, resulting in usable tags being automatically available in programs and routines. Because each controller can be added to the program, it creates a seamless environment between controllers and PLC programming. In Figure 3.10, LD-routines are hidden under MainProgram and SafetyProgram. At the bottom, two MAB:s and two PowerFlex525 Frequency AC Drives are added.

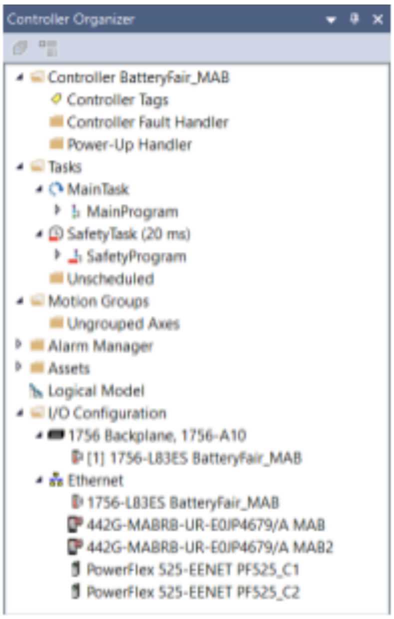


Figure 3.10: Control Organizer

Via the “Who Active” window, users can easily find and download PLC programs to their respective controllers and go online. In Figure 3.11, the GuardLogix safety controller can be found under the IP address 192.168.1.120.

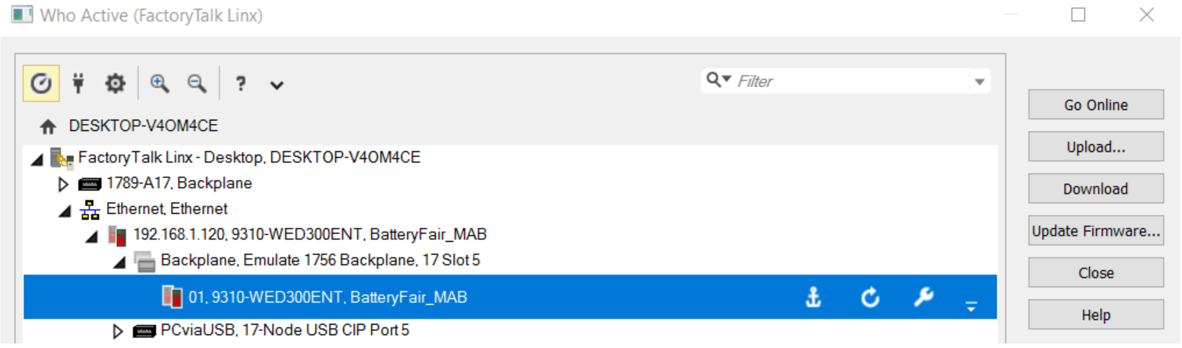
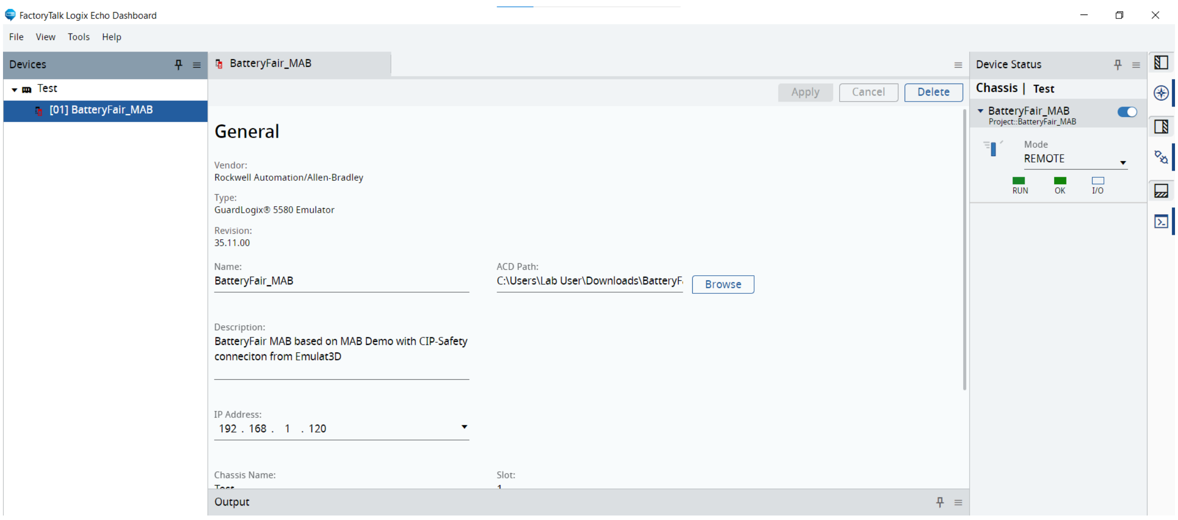


Figure 3.11: The “Who Active” window

## 3.3 Logix Echo

Logix Echo is an advanced software intended for emulating a select number of Allan Bradley PLC and SPLCs. This tool enables engineers, programmers and technicians to create a virtual replica of their control systems, allowing them to simulate, test and optimize their designs without the need of a physical controller. This enhances the efficiency and reliability of control and safety control systems by allowing users to detect potential issues and correct them prior to real world deployment. In a virtual system where Emulate3D contains the digital twin and Studio 5000 the PLC-coding, Logix Echo is the bridge between these two programs, emulating the controllers that were previously configured in Studio 5000.



General

Vendor:
Rockwell Automation/Allen-Bradley

Type:
GuardLogix® 5580 Emulator

Revision:
35.11.00

Name:
BatteryFair_MAB

ACD Path:
C:\Users\Lab User\Downloads\BatteryF

Description:
BatteryFair MAB based on MAB Demo with CIP-Safety conneciton from Emulat3D

IP Address:
192 . 168 . 1 . 120

Chassis Name:

Slot:

Mode
REMOTE

Figure 3.12: Logix Echo

# 4

# Method

This chapter aims to provide an in-depth understanding of the methods used during the development of the model. 3D model development is brought up, as well as PLC programming, virtual commissioning, the focus of safety integration and VR implementation. The sources used for collecting knowledge and ensuring reliability are also highlighted, emphasizing the significance in the field of industrial safety and digital twin technology.

## 4.1 Structure

In the initial phases, several meetings regarding the software required for the project as well as safety, were held with the project team from Rockwell Automation. These meetings consisted of presentations to provide knowledge of the theoretical aspects required to implement proper safety measures for the digital twin. To provide familiarity with the working tools, laborations for Emulate3D and Studio 5000 were provided.

After the initial education for Emulate3D and Studio 5000, work was initially conducted in a sequential fashion to familiarize both of the authors with the software required for the project. With the intent to collaborate better and be able to provide assistance when working in parallel, only one aspect at a time was developed for the digital twin. Although one author was “in charge” of one aspect, the goal was to ensure both authors were confident on developing all aspects of the digital twin with the provided tools.

In the initial stages of developing the digital twin, the 3D model was developed first. The model acted as a guide for the required PLC code and how to design the safety zones. Work on the digital twin was performed from the start of the factory moving outward. In order to gain an understanding of how the safety code could manipulate the machinery to increase safety, all relevant Emulate3D frameworks and solutions were at least partially implemented before moving further.

Relevant aspects of the factory for safety were the robots, MML, iTRAK, and QuickStick components. Properties such as motor speed and operating status needed to be investigated in regards to their usage and compatibility with the SPLC. With a good enough basis to develop SPLC code for, development of the digital twin was temporarily paused and the focus was shifted to programming the SPLC.

Programming of the SPLC was performed in Studio 5000 using Logix Echo to emulate the controller. In addition to the provided model of the battery factory, a model with its pertaining SPLC code was provided. As programming the MAB was outside the scope of the project, this code could be repurposed to suit the digital twin being developed.

Although initial education and lab sessions on Emulate3D, Studio 5000 and Logix Echo were completed, the development process of the model and its integrated logic presented new challenges and inquiries. To address these concerns, access to the Emulate3D help site was granted. This comprehensive resource comprises a vast array of guides, tutorials and frequently asked questions, designed to assist engineers in the creation and optimisation of digital twins. It is worth noting that Emulate3D is a product developed by Rockwell Automation and is primarily used by its client base. Consequently, external support is scarce. This situation led to the primary source of data and information being the Emulate3D knowledgebase, in addition to the weekly check-ins with the team.

## 4.2 Communication and Meetings

True to the nature of the thesis, communication and development of the digital twin was almost exclusively remote. In order to collaborate remotely on developing the PLC code, screen sharing via Microsoft Teams on the work computers was used. Similarly, to develop the 3D model, calls were held using Discord while sharing the screen of a second monitor using Parsec, a remote desktop software. In order to get assistance and demonstrate progress, frequent meetings were held with the project team from Rockwell Automation. These meetings were held using Microsoft Teams while sharing the screen of the model or code.

An exception to the purely remote approach were the three scheduled meetings at Rockwell Automation’s office in Gothenburg. One meeting was intended to introduce the authors to the team, give a tour of the office and safety components, and to provide familiarity with VR implementation in Emulate3D. Another meeting was to further show the safety components which were to be linked to the digital twin and provide in-person support. The final meeting will be held to demonstrate the finished model at a future date.

## 4.3 Virtual Commissioning

In this section, the concept of virtual commissioning is explored, focusing on the development of the 3D model, safety implementation and the integration of PLC.

### 4.3.1 3D Model Development

Due to a preexisting model of the battery assembly line, no work would be required to dimension the machinery and conveyors. Instead, full focus could be directed towards implementing safety zones and safety components in the factory. In order to strike a balance between safety, accessibility, and minimizing unnecessary shutdown of machinery, meetings with a security consultant at Rockwell Automation were scheduled.

While the final implementation of safety zones and components was not set in stone, a requirement was to use the components on the CEC wall at Rockwell Automation's offices in Gothenburg, which is shown in Figure 4.1. These components were intended to be linked via PLC to the Emulate3D model, and therefore needed to be the same as the ones on the wall. To facilitate visual implementation of safety components, an online catalog with CAD files for Rockwell Automation and Allan Bradley products was provided.

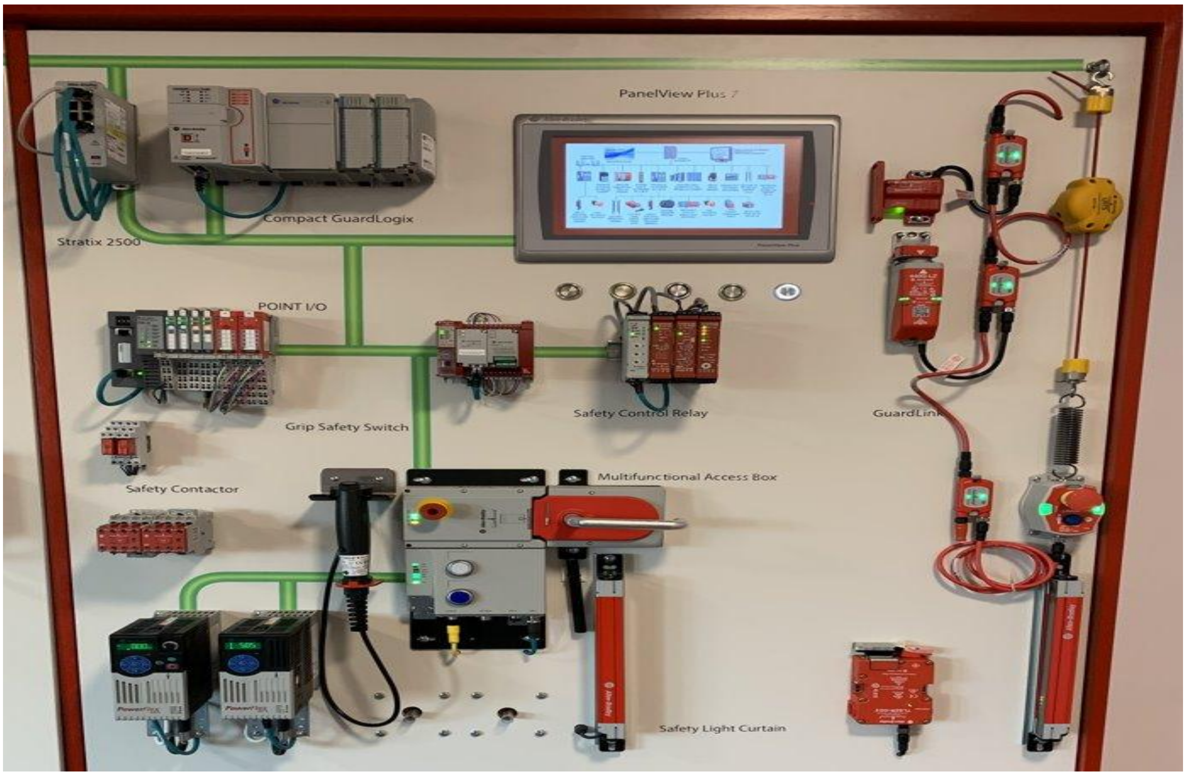


Figure 4.1: The CEC wall at Rockwell Automation's office in Gothenburg

At the start of the model, a conveyor transports a solid model of a battery pallet for further transport with robots via MML, iTRAK, and finally QuickStick. Along the way, actions such as welding, processing, and quality control are performed on the batteries and their pallet. Batteries in the pallet were not individually modeled. Instead, their models were made visible and invisible upon pickup and dropoff by the robots. Therefore, no transport of individual batteries actually occurs in the model.

To increase accuracy to real-life conditions, all transport up until the QuickStick was to be redone. A fully modeled battery pallet containing individually selectable batteries is to replace the previous one. Furthermore, all robots should dynamically move to the position of these batteries, instead of consistently picking from the same location. Therefore, the robots need to be reprogrammed to move in a natural way regardless of where the batteries are picked up from.

Another requested change to the model was moving from pure software emulating the conveyor in the start and end of the model to emulating functionality with PLC connectivity. In order to emulate this functionality, a variable-frequency drive (VFD) would be connected to the conveyor to modulate its input frequency based on if any batteries were being transferred. When no batteries await transport, the conveyor should stop by lowering its input frequency, and vice versa.

Throughout the process of building the digital twin, a constant evaluation of accuracy versus processing power is necessary. The final product will be a large model with many running procedures and scripts. Therefore, simplifying the implementation or logic of certain components may be necessary. Even with a powerful computer, a simulation true to reality may lower the framerate, providing an uncomfortable experience for a user in VR.

A challenge that appeared early on was how to balance user immersion and true to life functionality while using VR. By default, all models in Emulate3D are fully interactable. This means that each component from an individual battery to a gate in the factory is able to be interacted with. Although interaction provides further realism, it also requires additional computing. Therefore, a balance between interaction and computational intensity needed to be found in order to optimize runtime simulation of the model.

Additional challenges regarding developing the digital twin for VR integration were not only those pertaining to immersion, but also those regarding practicality. Depending on the VR headset and controllers used, the user has a varying level of control of their avatar. Some safety features require a degree of fine motorics that may not be offered by all VR setups. An example of such a case regards the enabling switch connected to the MAB.

A real enabling switch requires the user to hold their thumb on the top of the switch in order to enable it, with the remaining fingers available to press additional buttons for other commands. Research and testing would therefore be required to see how feasible simulation of this functionality was. If implementation was not possible nor reasonable, alternative ways to implement functionality would need to be considered.

### 4.3.2 PLC Programming

Upon reaching an adequate level of development in the 3D-model, attention was directed towards the integration of PLC and SPLC components. Rockwell Automation supplied an Emulate3D project featuring a fully operational MAB and a compatible PLC program to incorporate into the digital twin. The provided PLC program consisted of a single MAB module, a safety controller, and a safety routine responsible for managing the MAB. The integration of the MAB into the Emulate3D model enabled the connection of PLC tags to MAB properties.

As the initial PLC program was designed solely for one MAB, each function had only one corresponding tag. However, considering the digital twin featured two MABs, it was essential to duplicate each tag and make it unique. These tags encompassed a variety of inputs and outputs, such as switches, lights and other commands. Additionally, the routine for the second MAB had to be developed utilizing the newly created tags. Given that one of the MABs employed only two buttons, modifications to the routine were necessary to preserve full functionality.

The development of the PLC code was done using Studio 5000 and involved continuous testing, accomplished by repeatedly downloading the code to the emulated controller and establishing a connection to the controller in Emulate3D.

Throughout the simulation, various inputs and outputs were examined, alongside the functionality of the modified code. The project also necessitated the creation of two safety routines for the light curtains, which required development from scratch. This process resembled the previous development approach, with code being written incrementally and consistently evaluated in simulation until the desired functionality was achieved.

Control of the two initial conveyors via PLC required the development of two routines - one for each conveyor. This aspect of the project did not pertain to safety and thus did not require the same level of redundancy as the MABs and light curtains. Combined with a straightforward “ON/OFF” functionality, this factor simplified and fastened development.

## 4.4 Sources

Collection of knowledge will primarily be gathered from documentation of hardware and software, as well as meetings held with experts. Where applicable, first hand sources published by the manufacturer/developers were sought out. For miscellaneous topics, primary sources from experts within the field were sought out, and peer reviewed where applicable. Below is a full overview of the sources used in this study. For full details of each source, the reader is referred to section 8, List of references.

**1, 2, 4, 6** - These are all from Rockwell Automation, a highly reputable company specializing in industrial automation and information technology. It is a globally recognized leader in this field, which suggests that the information provided on these pages is likely to be accurate and reliable. However, because these are company resources, the information might be biased towards their products and services.

**3** - This source is from Robotnik, a company that specializes in service robotics and automation. Given their expertise in the field, the information they provide about industrial robots is likely to be reliable. However, similar to Rockwell Automation, they might be biased towards their own products and services.

**5** - This is a user manual for a product by Magnemotion Inc., a company that was acquired by Rockwell Automation. User manuals are generally reliable sources of information about the specific product they relate to, as they are produced by the manufacturer and intended to provide accurate, practical information to users.

**7, 10, 17, 18** - These are academic papers published in peer-reviewed journals. The peer-review process is designed to ensure that the research is of a high standard and the conclusions are justified by the data. The authors also have relevant credentials in the field of the papers. Therefore, these sources are likely to be reliable and credible.

**8** - This source is from The Welding Institute (TWI), a UK-based independent research and technology organization. As an expert organization in their field, the information they provide is likely to be reliable.

**9, 11** - These are both presentations or articles by NASA, a highly reputable and credible organization. The authors, B. D. Allen, M. Shafto amongst others, are recognized experts in the field. Given the reputation of the organization and the authors, this source is likely to be reliable.

**12** - This source is from DD IT Solutions, a company that offers risk assessment software. As professionals in the industry, they are expected to have a comprehensive understanding of the topic, which suggests that their content is informed and reliable.

**13** - This is an article from Safety & Health Practitioner (SHP) Online, a respected publication in the field of safety and health. SHP Online is known for its rigorous reporting and in-depth analysis, suggesting that its content is reliable and trustworthy. The article discusses risk estimation, a topic central to the publication's area of expertise, further adding to the credibility of the information presented. It is not promotional content but is part of their mission to inform and educate professionals in the field and the public.

**14** - This source is an article from Control Automation, a website that provides technical articles in the field of automation and control systems. The author, S. Dietrich, discusses robot motion command types, a subject that falls within the site's area of expertise. Given the specialized nature of the website, it is reasonable to assume that the content provided is based on a deep understanding of the subject matter. This type of technical article is typically written to educate and inform, not to promote specific products or services, which further supports the credibility of the information provided.

**15** - This source is from the Lola Institute, an institution dedicated to robotics research and education. The article provides a description of robot movement, which is within the institute's purview. As an educational institution, the Lola Institute has a vested interest in providing accurate and reliable information, reinforcing the credibility of this source.

**16** - This is a directive from the European Union, which is a reliable source for legal and regulatory information. It is an authoritative document, and therefore highly credible.

# 5

# Analysis

In this chapter, various aspects of industrial design are explored, with a focus on safety considerations and evaluation, as well as the development of the Emulate3D model. The intricacies of PLC code development and the connectivity between Studio 5000 and Emulate3D are examined, shedding light on the decision-making processes involved. Lastly, the topic of virtual commissioning is addressed, discussing the numerous benefits and applications of digital twins in areas such as safety, end-user experience, engineering, and authenticity, offering a comprehensive understanding of their impact on industrial design.

## 5.1 Safety

Risk assessment for machinery and equipment is a critical process in ensuring safety and reducing the likelihood of injuries or harm. This section will provide an overview of the thought process regarding safety during this study, including the identification of various risk zones, the evaluation of different risks, and the implementation of risk mitigation strategies.

### 5.1.1 Considerations

Following a meeting with the safety team at Rockwell Automation, various risk zones were identified within the digital twin. As the production line integrates different advanced automated technologies such as conveyors, robots and welders, there are multiple hazards to acknowledge. The potential hazards associated with each of these components have been carefully addressed through a safety plan, as mentioned in section 2.3 and demonstrated below in section 5.1.2.

While personal safety is crucial, it is important to ensure that the facility operates without significant disruptions. To achieve this balance, different safety zones have been established within the digital twin, and variable speeds have been implemented to maintain both safety and productivity.

The first aspect to consider is the use of physical barriers, such as walls or fences, to enclose high-risk areas. The effectiveness of this approach lies in its ability to deter unauthorized access and reduce the likelihood of accidents involving moving parts and heavy machinery. However, it is essential to ensure that the barriers do not hinder necessary access to these areas.

The integration of safety doors with MABs and enabling switches is an innovative solution to maintain controlled access while promoting safe speeds for machinery operation. Upon evaluation, this solution was proven effective in preventing accidents caused by sudden entry to high-risk zones. The ability to reduce machinery speeds as well as trigger full emergency stops ensures a high safety for personnel operating within the area.

Light curtains provide an additional layer of safety in industrial production systems and can with satisfying results be simulated in digital twins. They are particularly useful in areas where visibility is essential, such as inspection zones or where workers need to monitor processes closely.

### 5.1.2 Evaluation

The risks identified in the facility were evaluated using the Hazard Rating Number (HRN) method as mentioned in section 2.3. The HRN method takes into account factors such as the Degree of Possible Harm (DPH), Likelihood of Occurrence (LO), Frequency of Exposure (FE) and the Number of Persons at risk (NP). Important to note is that LO is not expressed in terms of percentages, but from values gathered from tables such as Table 2.1 after judging the likelihood.

Multiplied together, they form the HRN-value, an indicator of how safe or unsafe a certain component or system is. A value above 1 is considered non tolerable and counter measures should be implemented. For more details regarding the values, see Table 2.1. In Table 5.1, the HRN of a Comau Racer-7 robot is demonstrated. A more thorough example can be found in the appendix.

| Type of danger | DPH | LO | FE | NP | HRN | Description of danger | Acceptable level (Y/N) |
|---|---|---|---|---|---|---|---|
| Crushing | 2 | 8 | 2.5 | 1 | 40 | Industrial robots may crush or trap a worker between the robot and another object, such as a wall or conveyor. | N |
| Collision | 2 | 8 | 2.5 | 1 | 40 | Industrial robots move with speed and force, which can lead to serious injuries or damage if they collide with a person. | N |
| Electrical hazard | 15 | 0.033 | 2.5 | 2 | 2.48 | Similar to the QuickStick, improper isolation/installation may cause the robot's chassis to become electrically conductive. | N |

Table 5.1: HRN evaluation of a Comau Racer-7 industrial robot

## 5.2 Emulate3D

As stated in previous sections, a working model of a digital twin, depicted in Figure 5.1, was provided at the start of a project. Therefore, no design considerations will be brought up pertaining to the design of the model itself. The model employs a variety of transport solutions created by Rockwell Automation, intended to showcase and provide familiarity with these technologies.

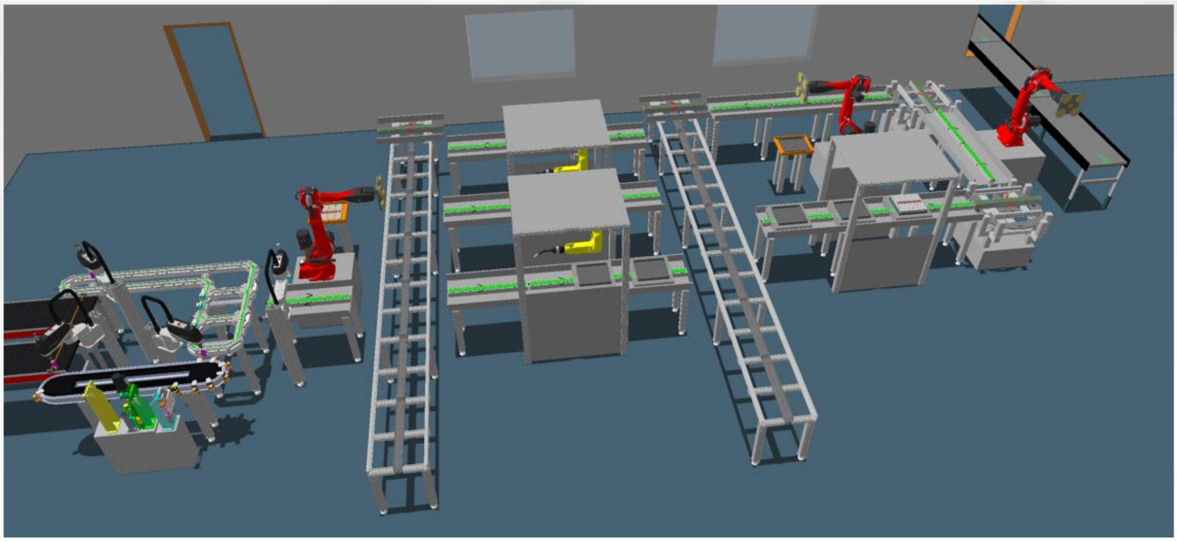


Figure 5.1. The starting point for the digital twin

In the beginning of the factory, a filled battery pallet with individually interactable batteries is created at the start of two separate conveyors. One conveyor transports a pallet for further transport of individual batteries with iTRAK, and one with MML. Initially, these pallets were one solid model with the batteries being fused with their container. Using pre-existing models for the pallet and batteries, a custom model was developed by placing the batteries on the tray. To facilitate placement so as to not individually place 104 batteries, a tool for copying and placing the batteries was used. This tool also provides greater consistency of battery placement over manual repositioning.

### 5.2.1 Robots

Transportation of batteries from the conveyor to the MML and iTRAK are functionally identical with the exception of determining the dropoff location. Therefore, unless explicitly stated, the described solutions and problems are valid for both robots. In addition to robots for transportation, a few robots placed alongside the iTRAK perform non-transport related actions on the batteries. These non-transport related actions are welding, placing a cover on top of the pallet, assembling, and quality control.

As the transportation from QuickStick was previously developed, only a brief overview of the functionality will be given. In a similar vein, no robots were selected as part of the project and therefore there are no aspects to explain such as choice of model.

A general purpose robot in Emulate3D has six stages to consider while programming its functionality. These stages are moving to and from the pickup, the pickup itself, moving to and from the drop off, and the dropoff itself. While using Emulate3D's Transfer State protocol, these stages are by default separate procedures, comparable to classes in Java.

These default procedures contain pre-written code for simple operations to and from conveyors, which work after connecting the appropriate components to the robot controller. Advanced functionality can be added to the robots as desired by utilizing a main procedure with subprocedures, or by editing the automatically generated procedures in the robot's controller.

Initially, the robot would move to pick up batteries from this pallet in a logically inconsistent manner, moving from the center to the edges in a seemingly random fashion. Three design approaches were considered to remedy the pickup order. Initially, a Transfer State enabled depalletization component was considered.

This depalletization component allows the user to select a pallet template to pick from, and in which order loads on the pallet should be picked. While a suitable option for many applications, integration was more difficult with transport to iTRAK and MML components due to pre-written code in the Transfer State protocol.

To facilitate programming, the Transfer State protocol automatically dispatches movers on these transport solutions after a successful dropoff. While it is possible to overwrite this logic, doing so requires familiarity with the protocol's framework and C# programming. This would prove unnecessary and overly time consuming for the scope of the project, and therefore Transfer State functionality was disabled.

For iTRAK transportation automatic dispatching of movers after a successful dropoff would be suitable as batteries are transported with individual holders on a singular mover. Transportation with MML is where this approach falls short however, as the batteries are transported in groups of four. Finally, although the battery pallet was able to be depalletized in a smaller scale on test models, the component had difficulties correctly identifying the pallet in the digital twin.

For consistency between movement solutions and to facilitate programming the transportation, this approach was scrapped. Instead of using the Transfer State procedures for movement of the robot, all procedures were written in a main procedure. To avoid errors at any robot destinations, Transfer State was disabled for these stations.

A second consideration was to move the robot to the pickup location by incrementing its target position in relation to the first battery. Programming the robot in this manner would be a simple task, but would add unnecessary complexity to the code hindering readability, and make the actual pickup require a different approach. What is more, in order to reference the first battery's position, code similar to the one in the chosen solution would still need to be developed.

The method that was selected to determine the position of a battery and how to pick them up involved manually creating a custom property dictating in which order the robot should select it. This property would be added to each individual battery in the created model and is sorted based on its physical location, creating a visually appealing, logical pickup order.

With this custom property, all the batteries could be added to a list of the pallet's child visuals, and then sorted by their pickup order. Obtaining the location of the battery to be picked was thereafter done by selecting the first battery visual from the list after sorting it, and obtaining the battery's position using the robot framework.

After obtaining the location of the battery, the robot first ensures that there is a pallet blocking the PE sensor at the end of a conveyor. If the PE sensor is blocked, the robot performs a PTP movement from its resting position to a teachpoint above the battery, and then a linear movement to the top of the selected battery.

A PTP movement was chosen for its speed of movement. With no real risk of collision as the battery gripper positions itself a fair bit above the battery, its more unpredictable movement would not cause any issues. For the final stages where finer positioning was required, the linear movement was a requirement for more fluid and predictable movement.

Once the robot was in position, pickup was as simple as sticking the battery to the battery gripper visual as a child, reparenting it from the battery pallet to the gripper. While the robot framework has gripper functionality for picking up objects, reparenting was found to produce more consistent results. Usage of the built-in gripper functionality sometimes led to the gripper picking up additional batteries or even the tray itself.

When the battery is successfully stuck to the battery gripper, the robot moves linearly above the load once again, before performing a PTP movement to its resting teachpoint. In the resting position, the gripper functionality is enabled and the battery is unstuck from the battery gripper. Immediately after being unstuck, the built in gripper handles the battery for dropoff. In doing so, the battery's physics will enable upon release for easier dropoff.

With the robot in its resting position, it waits for a MML/iTRAK mover to be at the station. Once an available mover is confirmed, the robot performs a PTP movement to a teachpoint above the dropoff position for the battery. For the iTRAK this is a simple maneuver. Positioning the battery for dropoff is performed by performing a linear move to a singular teachpoint where the battery holder is located.

Moving to the dropoff location on an MML track is slightly more complicated, but not by much. As the dropoff location varies based on how many batteries are already placed on the tray, a custom integer property was added to the pertaining robot controller. This property increments on a successful dropoff, and resets when the MML mover is dispatched from the station.

To determine the proper dropoff location, the dropoff procedure reads the property from the robot controller in four if and else-if statements. Inside these if statements, the robot is then instructed to linearly move to one of four teachpoints.

After the first battery is placed, it is renamed to “Batpack”, and all subsequently placed batteries are reparented to this visual. This is done to facilitate transport to the QuickStick using previously written code, which was received at the start of the project.

Once in position, the battery gripper releases the battery onto the drop point by disabling the battery gripper tool. After a successful dropoff, the robot moves linearly above the battery on the mover before dispatching the mover. If premature dispatch of a mover is performed, collision may occur.

Dispatching the mover occurs every time a battery is placed for the iTRAK system, or after four batteries are placed on the MML system. If a battery pallet is fully emptied, a custom boolean in the robot controller is set to true, allowing the flow control component to delete it. Regardless of whether a mover is dispatched or not, the robot then performs a PTP movement to its resting position.

On dispatch of an iTRAK mover, the mover will be forwarded to three stations before further pickup, as depicted in Figure 5.2. These stations are purely visual except the last two, where a robot moves up and down on the battery for processing. Once the mover has reached the final station, it is processed for further transport to the MML track.

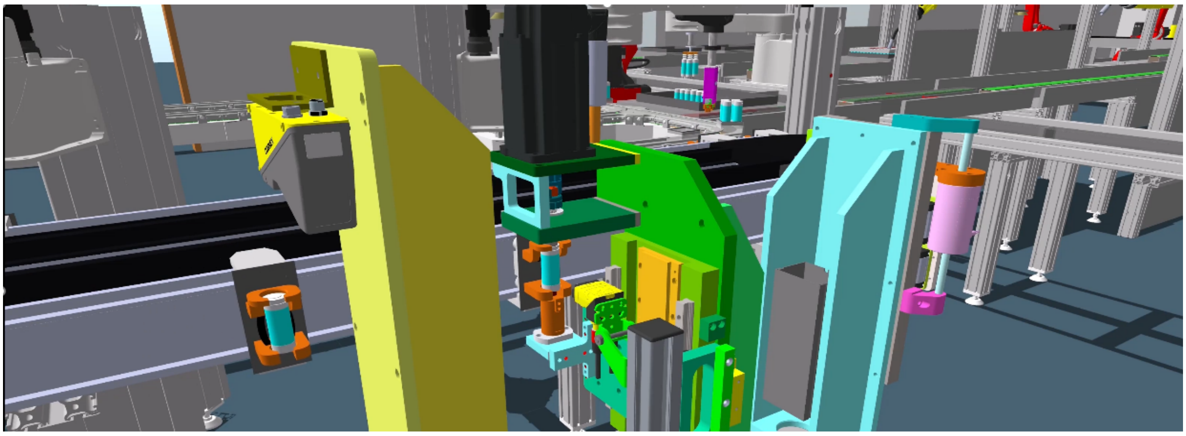


Figure 5.2: Substations of an MML track in Emulate3D

Transporting batteries from the iTRAK to the MML follows the same design principles as those for transporting from the conveyor to the MML track with one exception. During pickup, the robot attaches the battery to the gripper thanks to a custom property for the robot controller referencing the iTRAK station visual.

After a mover is ensured to be at the iTRAK station, a pickup is performed by referencing the connected station. iTRAK stations contain a property referencing the visual of the mover at the station. With this mover visual obtained from the linked station, the robot controller searches the visual for a child named “Gripperbody”.

This gripper body, which is a part of the invisible battery on the iTRAK mover, is then searched for its first and only battery child visual, which is subsequently stuck to the battery gripper on the robot. With this battery successfully attached to the battery gripper, it is then dropped onto the MML in the same fashion as the robot moving batteries from the conveyor to the MML mover.

Once the MML mover is filled with batteries, it is then dispatched to the station for transportation to the QuickStick. This is the same station where the MML mover is dispatched to after being filled with batteries from the conveyor at the start of the model.

As previously mentioned, all code regarding moving batteries from the MML to the QuickStick was not written as a part of the thesis, and is therefore not relevant to the analysis.

In order to integrate the code developed for the thesis, the batteries placed on the movers needed to be deleted from the model. If the model is being simulated for a longer period of time, superfluous amounts of batteries would accumulate. These batteries would be rendered in vain even when overlapping, increasing computational intensity. Furthermore, when batteries are being transported to the QuickStick track using the existing method of making batteries visible and invisible, it would be unrealistic to have batteries left on the tray after being supposedly transported.

Deleting these batteries on the mover was easily remedied by using a flow control component with a few lines of code using flow control. For information about implementation of the flow control, the reader is referred to section 5.2.4.

### 5.2.2 MML functionality

For the purposes of the digital twin, three MML stations were necessary. One station is located near the conveyor for dropping batteries onto an MML mover from the conveyor, and one located near where batteries were dropped off from the iTRAK. A final station was required for transportation of batteries from the MML to the QuickStick.

Throughout the track, movers will queue up at their destination in a manner which will not prevent traffic of movers to other stations. This logic does not require any additional logic and is part of the default MML functionality. When programming the routing and dispatch of movers from the initial station, queuing was utilized to maximize throughput

When an MML mover first enters the station near the conveyor at the start of the model, a procedure is triggered. This procedure’s purpose is to ensure that all potential dropoff points are populated with movers and its structure is as follows.

At the start of the arrival procedure, a timer is set for three seconds. After three seconds, the procedure checks if there is a mover at the station transporting batteries from the iTRAK to the MML track. If no mover is found, that station is set as the target for outgoing movers, and the mover is dispatched. After dispatch, the exit station reverts to the default station, located at the edge of transportation between QuickStick and the MML track.

After dispatch, a second mover arrives at the station and goes through the same procedure. The timer was intentionally set to a lower value so that this second mover would arrive at the station for transportation of batteries from the iTRAK. If only one mover would be at the station, downtime would be increased as transport from the conveyor to the MML track would need to be completed first.

To facilitate retrieving references to the visual of MML stations and their properties, custom properties were created on several flow control and robot controller components. By doing this, referencing the visual is done by writing “my variablename” rather than the longer full name of the object.

As mentioned in the earlier section above regarding robots, Transfer State functionality was disabled for all of the MML stations with the exception of the one located at transportation to the QuickStick. Transportation to the QuickStick worked in the starting point of the model and therefore there was no need to alter its Transfer State functionality. Disabling Transfer State on the stations for transfer greatly facilitated programming all actions surrounding the MML track, as there was no pre-written code unintentionally activated.

To aid dropoff positioning, custom MML movers needed to be developed for a more realistic visual experience. These custom movers contain four invisible batteries and were developed using the existing MML movers from the starting point of the model. For the batteries to stick to their movers, invisible batteries were placed for alignment at their intended dropoff positions. These invisible batteries utilize invisible gripper bodies which are attached to them, aligning any object entering the gripper body perfectly with the positioning of the invisible object.

Using these invisible gripper bodies, programming the dropoff locations for the robot was simplified. Instead of having to program a teachpoint which perfectly aligns in all three axes, a rougher teachpoint could be programmed. Dropoff using this rougher teachpoint is virtually indistinguishable from a more precise teachpoint, even from up close.

Finally, using invisible gripper bodies facilitated physically sticking batteries to the MML mover. While the difference in labor is slight compared to other methods, the existing method worked just as intended. So there was no need to rewrite code that worked, as it provided a reusable method for the iTRAK movers.

### 5.2.3 iTRAK Functionality

Similarly to the MML track, the iTRAK transports batteries for both pickup and dropoff, albeit with simpler logic throughout the track. The iTRAK features five stations, one for dropoff of batteries from the conveyor, three for visual processing, and one for pickup of batteries to the MML track. Another similarity with the MML track was that a custom mover with an invisible battery was developed to aid dropoff of batteries.

Movers arrive at the initial station near the conveyor where they wait for a battery to be transported from the conveyor. After drop off, the mover is transported to its first substation. At this substation, no visible actions are taken on the battery, and no robots are involved in the process. Therefore, dispatch logic is a timer which dispatches the mover after two seconds. This timer is a part of the default Emulate3D iTRAK station functionality and only requires adjustment of a property at the station.

After the mover is dispatched, it moves on to two stations with identical functionality. At these two stations, a robot moves its joints up and down upon the robot in a purely visual manner, as nothing is transferred in the process. Implementing this movement was done by setting two teachpoints on the robot, one where the robot's joint is fully extended and touching the battery, and one where the joint is fully retracted.

Moving to these teachpoints is done using a stripped down version of the default Transfer State robot protocols. All pre-written code is replaced with three simple instructions for each step. Moving to pickup, the robot moves to the teachpoint clamping on the battery. After the robot has moved, it waits for a second before eventually retracting and dispatching the battery.

This process repeats at the subsequent station before being dispatched to the final station in the iTRAK loop. At this station, batteries are transported from the iTRAK to the MML track. The robot performs its pickup and dropoff routines, as described in section 5.2.1, and then sends an instruction for the iTRAK station to dispatch its mover. After dispatch, the mover is sent to the initial station and is ready to transport another battery.

### 5.2.4 Flow Control

In the digital twin, flow control components are used for creating loads, deleting loads, as well as a dummy visual to bind PLC tags to the scene Two flow control components are in charge of creating and deleting loads for the initial conveyors. Another component is located near the transport from the MML track to the quickstick, and a final component without any logic programmed is located near the safety zones controlled by the MAB.

Although the loads created on the conveyors will be processed differently based on their transport destination, logic for them is identical. The relevant flow control component consists of the following infinite loop. Initially, the flow control component creates a load associated with a variable for further use thanks to a connected load creator object. This load creator object creates the custom battery pallet developed for the project with the proper horizontal rotation for pickup.

Once a load is created, it is conveyed to the end of a conveyor, and the flow control component waits for a signal that a load has blocked its connected PE sensor. When the sensor is blocked, the flow control component waits for its connected robot controller to set its custom boolean property signaling that the pallet is empty to true. After the pallet is detected to be empty, the flow control component sets the boolean to be false, and the created pallet is deleted. After deletion, the loop ends and the process begins again.

Another implementation of load deletion using control was needed for transportation to the QuickStick from the MML track. To implement this functionality, a flow control component was given custom properties referencing the visual of the MML station and its mover, as well as a custom deletion boolean. This boolean is set by the associated robot controller to be true in order to trigger deletion of the batteries.

Code for the flow control component consists of the following infinite loop. Initially, the program waits until a mover has entered the associated ML station. When a MML mover enters the station, a visual reference to it is obtained, and the flow control component waits for its deletion boolean to be set to true. This boolean is set to be true directly after the battery pack attached to the robot is set to be visible. The flow control procedure then searches the MML mover for the “Batpack” visual, and deletes it. Upon deletion, the flow control component waits for its deletion boolean to be set to false. This boolean is then set to be false when a mover leaves the station and then the infinite loop begins anew.

A final flow control component is the one located near the safety zones controlled by the MAB. This component does not implement any flow control methods for load manipulation. Instead, its sole purpose is to provide an easily accessible property associated with an SPLC tag for manipulating machine speeds.

### 5.2.5 Safety Components

After the relevant meetings regarding safety implementation were held, the following sketch for safety implementation was developed as depicted in Figure 5.3. Relevant abbreviations and Swedish words required to understand the sketch are listed in Table 5.2.

| Term | Explanation |
|---|---|
| Dörr | Door |
| Lin_ES | Cable-pull safety rope |
| Ljusridå | Light curtain |
| Sensa-Guard över TLS | Sensa-guard over TLS |

Table 5.2: Terms used in the safety sketch

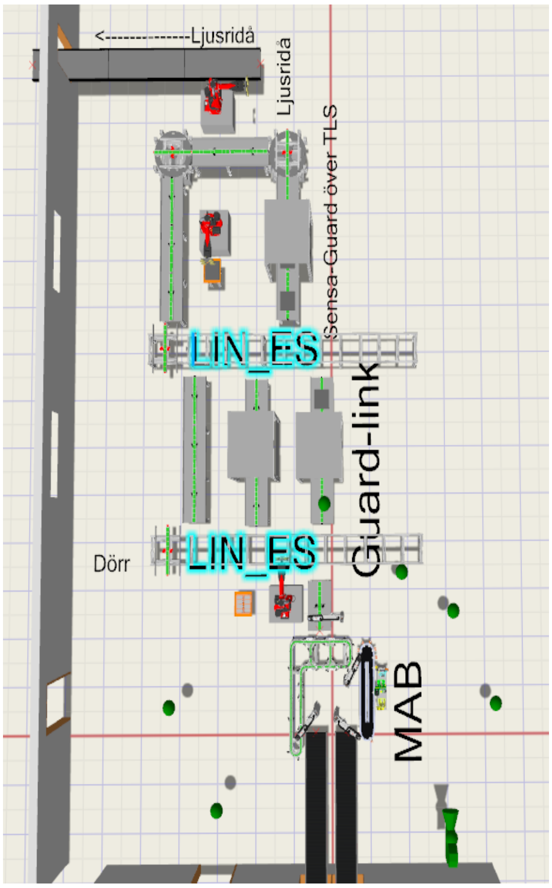


Figure 5.3: Initial safety sketch

Not all safety components in the sketch were added due to a lack of time, or no satisfactory way to implement them. Guard-link was not added due to the clutter it would add to the scene and Sensa-Guard over TLS was not added due to a lack of time.

Implementing the safety features for the model was primarily done through SPLC programming, and therefore safety design choices will be discussed more thoroughly in sections 5.3.1 and 6.1. This section will instead focus on visual implementation and how these tags are integrated in the digital twin.

Thanks to Rockwell Automation’s product configurator website, finding a suitable visual representation for safety components was simple. On this website, fully modeled CAD files are available for download if the correct model name is entered. From this website, a model for the required light curtain and its mirror could be downloaded and imported directly into the scene. By default, these 3D objects are colorless. Therefore, their Emulate3D visual properties need to be changed to properly reflect their real life colors.

With a visual representation for the light curtain and its mirror in place, functionality needed to be added in order to trigger relevant safety mechanisms. Using Emulate3D's package manager, a resizable light curtain was found which was added to provide the needed functionality. This light curtain was made invisible to not overlap with the existing light curtain, and was chosen due to its simple PLC integration.

When the light curtain is triggered, a tag is written to the PLC, and a property in a flow control component connected to the curtain is set. This property is subsequently used in robot and movement solution controllers to initiate a slowdown. Slowdown is programmed in the controllers thanks to a thread which runs in parallel with its procedures. Every half second, the status of the flow control's properties are checked. If the light curtain and/or MAB have been triggered, the controller will modulate the speed to a quarter of its normal value.

Although the light curtain had per beam programmable functionality, which could prove useful for preventing unneeded slowdown of machinery, it was deemed unnecessary due to the added computational complexity per beam calculations would add. Instead, the light curtain was set to only trigger if an Emulate3D person object entered its beams.

In real life conditions, per beam functionality could be utilized to detect if a person is entering the zone rather than a smaller object such as a hand. But using built in Emulate3D functionality to detect a person provides an identical user experience and is a simpler solution.

Implementing the MAB and its enabling switch was mostly done by repurposing pre-existing code and is therefore not subject for analysis with the exception of the two-button MAB. To implement the two button MAB, the model of the four button MAB was modified slightly, as can be seen in Figure 5.4. Button colors were changed to a gray neutral color, and a gray box matching the color of the MAB body covers the superfluous buttons.

This two button MAB is intended to be openable with a physical MAB connection linked to Studio 5000 triggering a motor when opened, or virtually in Emulate3D.

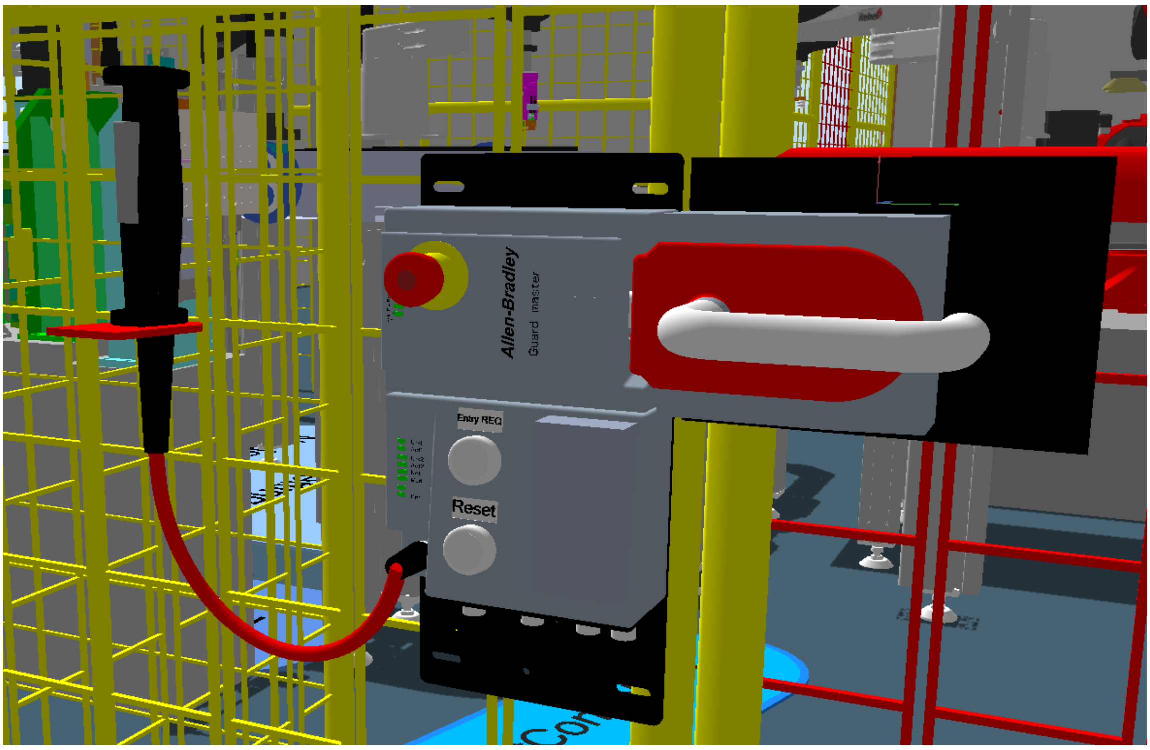


Figure 5.4: The modified two button MAB

Another modified safety component is the cable-pull safety rope. Since no applicable model could be found, a repurposed rope from the MAB's enabling switch was used. Attached to three invisible attachment points on the quickstick (end, middle, start), the rope spans the whole walkable area along the QuickStick.

Since whenever a user is near the cable-pull safety rope the machines will be moving at a reduced speed, they were made purely visual. Instead of pulling the rope to bring nearby machinery to a complete halt, an Estop button is pressed.

To physically protect users from machinery, safety gates and windows were used in various locations. Safety gates are used to section off areas accessible only by opening the MAB, and utilize default Emulate3D gate components. In one section, a robot welds the battery pallet. To protect users from generated heat, a window is placed in the gaps between the support beams, and gates alongside the QuickStick were placed to prevent proximity to the robot.

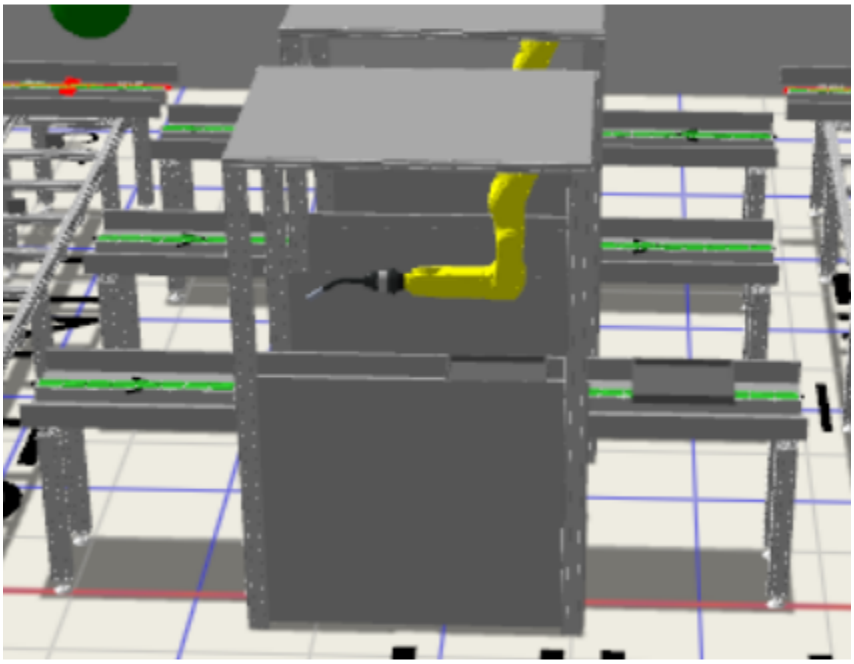


Figure 5.5: A welding robot before safety implementations

For the welding robot, a transparent sheet was used to provide a representation similar to factory conditions. As transparency is computationally intense to render, this and a similar sheet further down are the only occurrences of a transparent object in the scene. To create a transparent barrier for other sections, a window frame was placed between the supporting legs of the QuickStick tracks. This window prevents entry under machinery even though the window itself is not rendered.

Initially, the transparent window near the welding robot was intended to be openable with a Sensa-Guard using TLS, which would disable the robot when opened. However, due to time constraints, this was not successfully implemented in due time. If time permits this functionality may be added, but at the time of this report it has not been implemented.

## 5.3 PLC Programming and Connectivity

During the course of this study, numerous challenges were encountered and various solutions were devised to implement safety measures and write logic for robots, conveyors and safety components, such as the MABs and light curtains. In this section, the development of PLC code and the connectivity between Studio 5000 and Emulate3D and the respective decisions are analyzed.

### 5.3.1 Safety

Initially, the safety doors on the model were replaced with actually functioning doors with MAB. When connecting the MAB to an emulated controller through Logix Echo, the proper behavior when pressing buttons on the MAB was observed. The buttons (or switches) corresponded to the correct tags as seen in the IO Browser. However, the connection between the MAB and respective robots or conveyors still needed to be established to enable stopping functionality.

Throughout the project, errors related to multiple output parameters connecting to the same tag or parameter were encountered. This was resolved by creating new tags using the same data type. By using a data type made specific for a MAB, each respective tag was automatically created. For example, using the data type "AB:442G_MABB_E0JP4679:O:0", automatically created all the output tags, such as MAB:O.EStopLight and MAB:O.Unlock.

Issues with invalid tags and addresses were also experienced. For example, the error message "MAB:I.EStop(2) is incorrect address type" occurred because when duplicating the MAB to use on the second door, tags were also duplicated and automatically assigned the suffix '(2)'. Naturally, this tag did not correspond to the correct tag in Studio 5000 which was "MAB2:I.EStop". This was simply resolved by using unique tags present in both Emulate3D and Studio 5000. Furthermore, a new, unique safety monitor was created in Studio 5000 to address duplicate issues within the program.

During a meeting with the team at Rockwell Automation, it was decided to use two buttons on the first MAB; unlock request and reset. This decision was made because the MAB featured on Rockwell's safety wall had only two buttons. To take this into account, the safety PLC program was modified to contain tags from both the virtual and the physical MAB. As either one of the MABs are triggered, the same tag in the program activates and the routine responds correctly. By adapting the virtual MAB to this configuration, the switch between a simulated MAB and the physical one on the wall would be a quick and seamless transition.

To optimize production flow and minimize full-stops, a decision was made to not make the machinery stop completely while accessing through a MAB-connected door. In response to the safety evaluation as mentioned in a previous section, the speed is decreased to the safe speed of 25% (as opposed to 100% during normal operation), assuming the enabling switch is being pressed. As the enabling switch is released, the machinery immediately halts to a full stop.

### 5.3.2 Conveyor Control

In an attempt to drive the conveyors with PowerFlex 525 and PCL, a new controller and two PF525s were added in Studio 5000, with incrementing IP numbers. To do this, the frequency converters' IP addresses and drive ratings (e.g. 3P 230V 1.0HP) were needed to add them as modules.

The idea of adding a new controller with the sole purpose of controlling two conveyors was proven to be excessive as the safety wall only had one safety controller, fully capable of also controlling the conveyors at the same time as the MABs. Furthermore, adding another controller created its own challenges and problems which resulted in the new controller being discarded and work was focused on the one safety controller. Ladder diagrams were then created and the program was modified to use Flow Control instead of a sensor for battery pack output. This allowed for controlling the conveyors with PowerFlex 525 and changing their Transfer State based on the presence of an obstruction detected by a photoeye sensor.

The two conveyors C1 and C2 were successfully controlled, although C1 experienced a slow deceleration despite having the same settings. Frequency and other parameters were adjusted to achieve an appropriate speed.

## 5.4 Virtual Commissioning

In the age of Industry 4.0, digital twins have emerged as a powerful tool for enhancing safety and efficiency across various stages of industrial design and operation. By creating a virtual replica of a machine or system, engineers can optimize performance, identify potential hazards, and improve user experience without the need for physical prototypes or lengthy, conventional trial-and-error processes. This section delves into the numerous benefits and applications of digital twins in different aspects of industrial design, including safety, end user experience, engineering and the authenticity of digital twins.

### 5.4.1 Safety Aspects

Digital twins can significantly enhance the process of incorporating machine safety from the initial stages of design. As European legislation mandates that safety should be considered from the outset [16], integrating digital twins allows safety engineers to utilize visual tools and implement virtual safety commissioning. This proactive approach can help avoid costly redesigns and delays typically associated with addressing safety after prioritizing functionality.

Incorporating digital twins can also be beneficial in addressing ergonomic concerns and ensuring safe operation of robotics. Engineers and end users can further enhance the benefits of digital twins by combining them with VR technology. This integration can create immersive and interactive environments, allowing engineers and operators to visualize and experience the machine operation in a safe and controlled virtual setting.

This combination enables users to identify potential hazards, validate safety measures, and evaluate ergonomics, often before actually building the physical machinery, allowing for a more cost-efficient approach to industrial planning. In a world where climate change and reducing environmental impact is a main focus of many companies, VR can be used for training purposes, familiarizing employees with the machinery and safety procedures without having to travel long distances.

Using digital twins for pre-validation can help identify and address safety issues before they become problematic and expensive. However, digital twins may not cover all safety requirements, so other tools or methods may be necessary. Additionally, current legislation [16] does not recognize digital twins as a means of demonstrating safety, so final tests on the actual machine are still required.

### 5.4.2 Authenticity

When developing a digital twin for this project, there were two approaches to authenticity which needed to be considered. These approaches were operational and functional authenticity. What can be considered authentic should be approached from the perspective of why authenticity in this manner is important, as well as how, and to whom the twin and its components are considered authentic. These two approaches should by no means be considered mutually exclusive. In fact, having a high degree of operational authenticity will in most cases lead to functional authenticity. The inverse however, is not always true.

Operational authenticity for a digital twin can be described as the degree of accuracy stemming from the implementation of a real component’s methods. Take for instance a PE sensor which calculates if an object is blocking its sensor by emitting and measuring changes in returned light. If operational authenticity is required, the sensor should be implemented by using these same working principles. The matter of why this sensor is operationally authentic is explained by it closely approximating the mechanisms of a real life PE sensor.

This degree of operational authenticity could however add unnecessary computational intensity based on its implementation. Instead, the same functionality from the perspective of a user can be achieved by sensing if a light beam is being interacted with by another object. These are two completely different methods, with different levels of accuracy, but produce the same functional authenticity.

An example of an aspect of the developed digital twin, which can be considered to have low operational authenticity, would be the robots for transport of batteries. These robots perform actions such as obtaining battery positions and attaching batteries using methods impossible in real life.

To obtain battery position, the PE sensor's visual hierarchy is searched for a relevant visual, and its exact coordinates are retrieved using methods in Emulate3D. Furthermore, batteries are created and deleted using seemingly magical components. If operational authenticity is demanded, these batteries should be disposed of in other means. More operationally authentic methods could for example involve further transport using robots.

For the purpose of the project, a primarily "presentation first" approach was taken. Where operational authenticity could be reasonably implemented, it was. But it was not the primary focus in development of the digital twin. For example, iTRAK and MML integration was developed with reasonable operational authenticity in mind.

Although MML/iTRAK stations as they are presented in Emulate3D do not appear on their real life equivalents, position sensors can be utilized for similar functionality. Therefore their functionality is simplified compared to real life implementation, they can be considered to have a significant degree of operational accuracy.

An example of where operational authenticity matters is when virtual commissioning/digital twins are used to train the user in robot programming. In this case, it is important to the programmer of the robot, because it should serve to familiarize them with real robot programming. If the user would use methods not available to them in real life scenarios, then the digital twin would serve no purpose to them, as they cannot apply their knowledge in the real world.

Operational functionality can be considered unnecessary in the cases where the user is not exposed to the mechanisms behind the components, or if they do not need training in these mechanisms. If the user has no access to the source code for a sensor, then they are clueless as to the degree of its operational authenticity. Therefore, it should be considered important only in the cases where the exact methods matter, as is the case with training or more dangerous components.

Functional authenticity can be described as how accurately a component or process operates in relation to its intended end result. Here, the methods used in the process should give an accurate representation to real life. For high functional authenticity, the physics used for sensors, or how robots obtain their positions are less important. Compared to operation authenticity, functional authenticity requires more analysis to determine its degree of accuracy.

If a digital twin is developed to familiarize potential users with its functionality and components, ensuring functional authenticity is highly important. For example, the buttons of a MAB should change the functionality of the door handle to be true to life. If the connected door is always able to be opened regardless of its status, then the MAB has poor functional authenticity.

An example of changes in how components operate may lead to lower operational and functional authenticity can be seen in the case of a conveyor system intended to divert boxes based on their size for further processing. For example, a real life conveyor may do this by pushing the loads to the side with a push arm after a sensor is triggered. If this piston is replaced with a conveyor which can change direction to horizontally transport boxes for the digital twin, the system no longer functions the same.

This is where analysis of the system is required to determine its functional authenticity. If the system’s push arm is the subject for safety analysis, this will lower its functional authenticity significantly. With a significant moving part removed, the system no longer functions the same in regards to safety. The same is true if the potential for loads getting stuck is necessary to dimension relevant properties. Functional authenticity is diminished in these scenarios because how the box is further transported matters for analysis.

But if transport of the boxes is irrelevant to the purpose of the digital twin, but instead their further processing, this change in operation does not diminish functional authenticity. Because the method in which boxes are transported does not change the fact that the boxes arrive from point A to B, satisfactory functional authenticity is ensured.

Functional authenticity should be considered throughout the entire digital twin's development based on a multitude of aspects based on its use case. A high degree of accuracy relating to relevant aspects of simulation should always be ensured. If safety is an important aspect, then all components need to function the same as they would in real life to identify and assess risks. Operational authenticity may also be important based on the nature of the simulated processes.

Using a digital twin to virtually commission and design processes, facilities, and components may require a higher degree of accuracy compared to replicating an existing process. Designing requires simulation as true to reality as possible to ensure if it is reasonable. Realistic physics and component values are more important here than in other cases.

For example, when designing a conveyor, ensuring that it accelerates and decelerates in an appropriate manner is important. Unrealistic values for mass, inertia, speed, acceleration, and undetailed physic settings may make the design inapplicable for real life usage. If these values were to be used, then the real life application of the model may cause high amounts of wear to machinery, unsafe operating conditions, and unpredictable behavior.

### 5.4.3 End User

**Enhanced safety** - Demonstrations, simulation, and training can be conducted completely remote using digital twins. Providing a safe environment to test safety measures, digital twins allow dangerous and costly accidents to be simulated without any real risk. Unlike a real environment, worst case scenarios stemming from unsafe working methods and improper safety features can be demonstrated as well as evaluated with a digital twin.

Accidents that would cause grievous bodily harm, death, or a complete shutdown of a facility can safely be demonstrated without any risk to person or production. Experiencing why security measures are in place, and which accidents may happen if they are disregarded could improve user safety.

Instead of relying on grisly footage from accidents, or purely described scenarios, the end user is able to instead experience these scenarios in a controlled manner. Providing this safe method of simulation would prove beneficial for end users ranging from workers to factory owners, improving safety mindsets at facilities.

**Ergonomics -** Depending on the use case, a digital twin could improve the comfort of a user simulating the system. For example, manual labor in many industries is often highly repetitive and monotonous work, frequently resulting in a certain degree of wear on the workers after a long day's work.

By analyzing a virtual representation of the workplace and different scenarios, personnel can help impact different design choices on worker ergonomics. This allows them to optimize the layout of equipment, workstations and tools to minimize physical strain, reduce repetitive movements, and ensure proper posture for the workers.

**Training -** Training can be given to familiarize end users with the safety features they may encounter. By conducting safety training digitally, demonstrations can be shifted to being conducted without impeding functionality of machinery.

Some training requires machinery to be completely disabled, such as starting/stopping procedures. With training instead being conducted digitally, there is no downtime resulting from safety measures being activated. Additionally, some errors and conditions may be hard to generate in real life conditions. With a digital twin, these conditions can be created as easily as they can be programmed.

Integration with physical components can also bridge the disconnect from virtual and physical components. Emulate3D can be integrated with physical components connected to a PLC and trigger functionality within the simulation. This integration can provide a mixed reality experience to ensure that users gain hands-on experience with components remotely.

**Faster commissioning and reduced downtime -** If components need to be upgraded or replaced with a different model, digital twins could prove an important tool to provide familiarity with these new components. Before the new components are even installed in the factory, a digital twin could be used to familiarize their users. Workers being familiar with components prior to installation could ensure a seamless transition upon installation.

**Convenience, cooperation, and sustainability -** With remote working becoming increasingly common, digital twins could be developed for familiarization, evaluation, and training remotely. Instead of traveling long distances users would be able to perform these tasks from home, or their local office.

By removing extra travel time, meetings and demonstrations may be held more frequently. More frequent meetings lead to the ability to demonstrate changes as they are applied, rather than scheduling another visit. This can facilitate cooperation as progress can easily be demonstrated on a rolling basis, rather than at planned intervals.

Holding virtual sessions using digital twins means no hotels and transportation costs for longer journeys need to be paid for. Lowering the overall cost and downtime. In a similar vein, no components need to be physically transported until their final installation. Therefore, overall emissions from transportation are severely reduced, with proper usage of digital twin technology.

For companies striving to increase their sustainability, digital twins could prove an invaluable resource if powered by sustainable energy sources.

### 5.4.4 Engineer

**Risk reduction** - In the context of safety and automation, digital twins play a vital role in reducing the risks for engineers. By creating a virtual environment that allows for thorough testing and validation of designs, the probability of equipment damage, personal injury or unexpected system failures is significantly diminished.

**Quicker development** - Leveraging digital twins accelerates the development process, as engineers can identify potential issues early on, make rapid adjustments, and optimize designs more efficiently. This results in a shortened development cycle and a quicker transition from design to implementation, which is essential in maintaining a competitive edge in today's fast-paced technology landscape.

**Improved collaboration** - Digital twins facilitate enhanced collaboration between various teams involved in the development process, such as electrical, mechanical and software engineers. By providing a shared, virtual environment for design, testing and optimization, team members can work together seamlessly and share information, leading to more efficient development processes and better overall system designs.

**Cost efficiency** - Utilizing digital twins enables engineers to address problems before physical deployment, resulting in more cost-effective solutions. Identifying and rectifying issues in a virtual environment reduces the need for expensive physical changes to a finished product, thereby optimizing resource allocation and lowering overall development costs.

**Improved validation** - Digital twins and virtual commissioning allow for thorough design validation, ensuring that the final product meets desired performance and safety specifications. Engineers can test and validate their designs under various operating conditions, providing confidence that the machine will perform as intended in real-world scenarios.

**Scalability and modularity -** With a digital twin, work on a model can be sectioned into smaller parts. These smaller sections of the whole can be developed to focus on a particular section which may need extra attention. Instead of simulating a whole process for training and developing, a model can be scaled down as needed to exclusively include the essentials.

This scalability has the potential to decrease development time as unnecessary components are not needed to be developed or even considered. As is the case with the thesis' digital twin, the method which places batteries into a pallet for initial transport does not need to be developed nor considered. Instead, a filled battery pallet is magically created at the start of the model.

In a larger team containing a magnitude of specialists in different areas, the model can be broken up into different parts. Emulate3D provides easy functionality to save components and their code in a custom catalog. Once a custom catalog is created, it can be shared with ease and added to a larger model by simply dragging it onto the scene. This modularity through catalog components allows a team to independently contribute to a larger model without interfering with other members' progress.

**Innovation -** As technology advances, companies may seek to upgrade existing components or add new ones to their facilities. Additionally, companies might be dissatisfied with their current methods and wish to simulate other potential methods. If a digital twin is already developed, installing these components, or testing different methods, is simplified. Instead of purchasing new components, or making changes at a facility, companies can with no additional charge compare their effectiveness. Providing simpler methods for engineers to change existing systems and components could remove uncertainty surrounding change, and incentivize innovative solutions.

**Enhanced documentation** - Digital twins serve as an accurate representation of the machine's design and behavior, providing a valuable reference for documentation. This allows for manuals and training programs to be equipped with up-to-date and accurate data, ensuring the best possible results. Additionally, the high-quality documentation ensures that all stakeholders have a clear understanding of the system's functionality and requirements, facilitating better communication and understanding across the development process.

# 6

# Results

In this chapter, the function of the developed model will be explained. All relevant safety zones, components, and features for the model will be explained. To aid the reader's understanding, several images directly from the source material will be embedded throughout the section. The final subsection will gather observations during the thesis regarding benefits, considerations, and drawbacks of remote collaboration.

## 6.1 Safety Implementation

To begin with, physical barriers are used to enclose high-risk areas, preventing accidental entry. For instance, in the initial section of the production line, which contains numerous moving parts, a fence was placed to restrict access. A safety door, featuring a MAB and an enabling switch, was installed to control entry while maintaining the safe speed of 25% in case of personnel access. This initial safety zone is depicted in Figure 6.1.

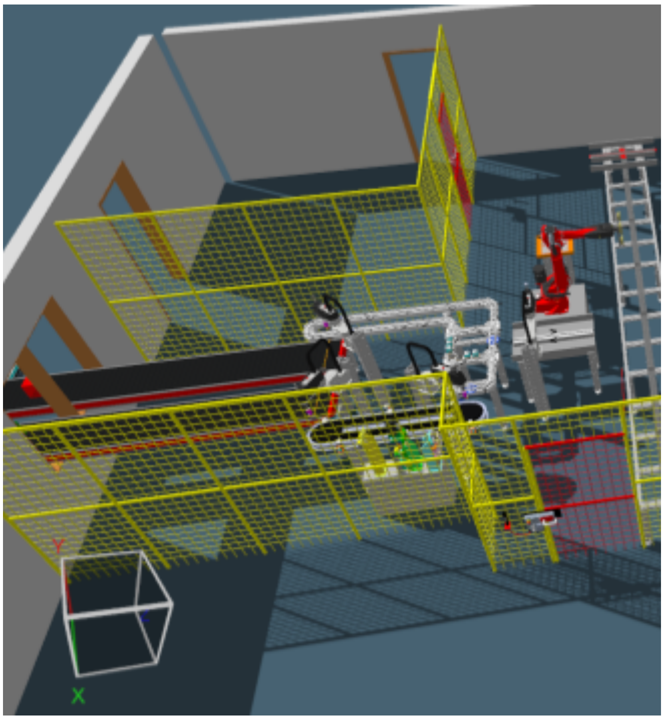


Figure 6.1: First section closed of by a fence, with MAB access

In the case of the welding robot, safety is enhanced by enclosing the area with fences and a transparent window, allowing visual inspection without direct exposure to the hazards of welding. The welding robot's safety zone is formed by the 'U'-shaped arrangement of QuickStick tracks, with an opening in the fence covered by a light curtain to provide access as shown in Figure 6.2. The QuickStick tracks are equipped with emergency stop lines, enabling workers to halt the process when needed. A reset button is placed out of reach of the safety zone, to lower the risk of resets whilst still being inside the safety zone.

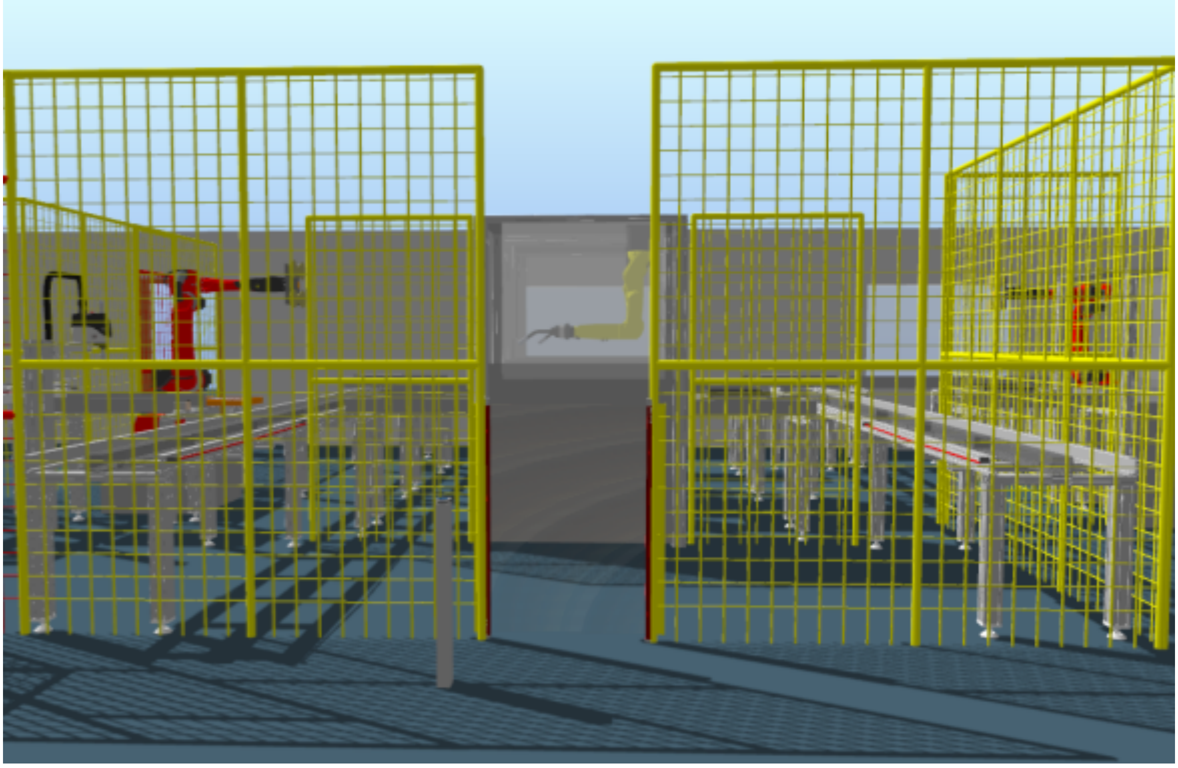


Figure 6.2: Welding robot safety zone, closed off by fence and light curtain

The final section of the production line, which includes an inspection camera, turntable, robot and end conveyors, employs a separate light curtain that bends around a corner using a mirror. This final section is shown in Figure 6.3. Triggering the light curtain reduces the speed to 25%, and emergency stop lines are installed on the conveyor for added safety. The turntable and conveyors, which may present entanglement or crushing hazards, are effectively secured by these measures.

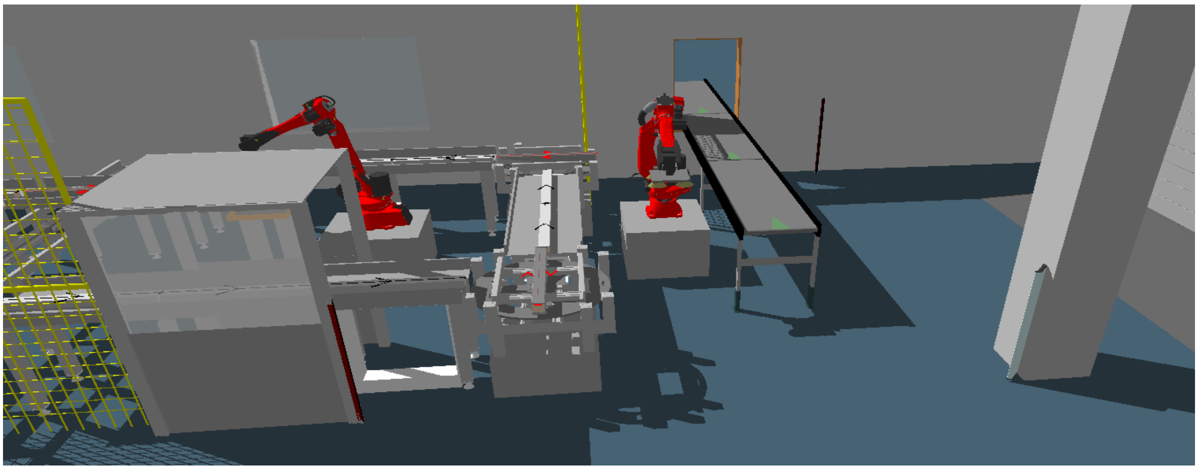


Figure 6.3: Final section secured by light curtain and emergency stop lines (not visible)

A wall enclosing the entire production line on the opposing side eliminates the need for additional safety precautions in that area. A secondary door with a MAB is provided for service access, ensuring a slowdown of the system when the door is unlocked to prevent accidents during maintenance work. This can be seen in the top left corner of Figure 6.4.

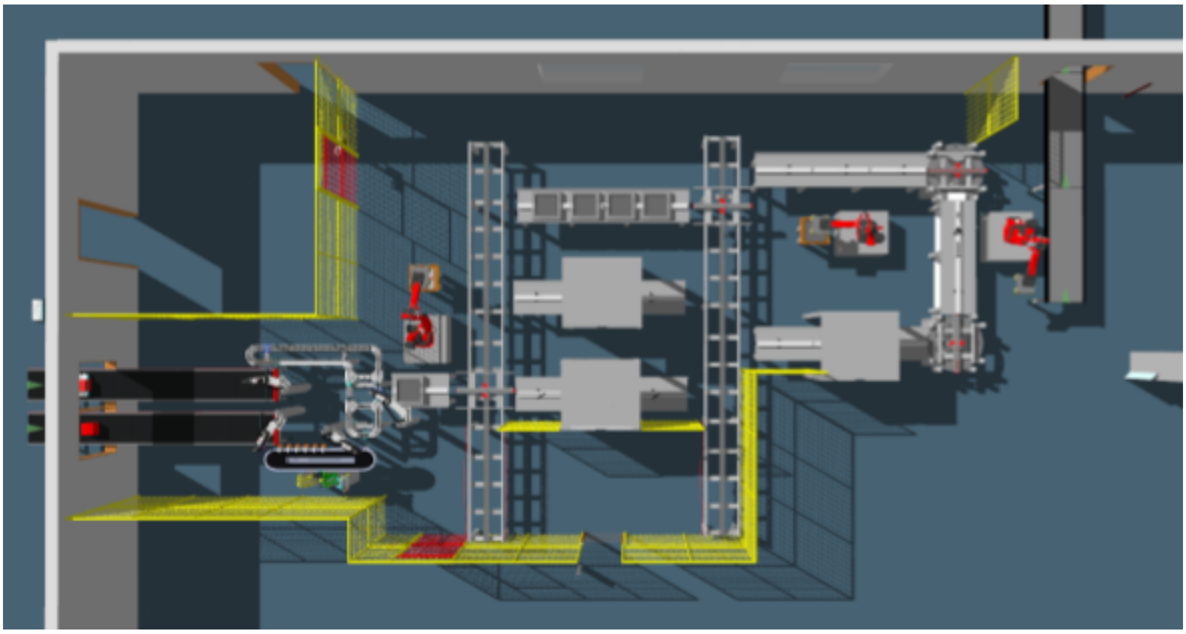


Figure 6.4: A bird's-eye view of the final model

## 6.2 Model Functionality

The result of the modeling is a digital twin that effectively assembles and transports batteries from the start of the production line to the end with greater battery handling authenticity than previous versions, and with adequate safety measures in place. The completed model is shown in Figure 6.4. Some parts, including the robots, MML and iTRAK, are controlled using the Emulate3D-integrated Quick Logic language.

Other parts, such as the typical conveyors and the safety component, including MAB, light curtains and stop lines, are controlled using PLC. Upon entry of personnel into any of the designated safety zones, regardless of whether access is granted through a MAB or light curtain, the speed in the respective zone decreases to 25% in comparison to the standard 100% during typical operation. In the event of an emergency stop being activated by an individual, either by disengaging the enabling switch or utilizing the stop lines, all motion will cease instantaneously.

The conveyor routines were built from scratch and consisted of fairly simple logic - PE sensor not triggered and PowerFlex 525 not faulted, resulting in PowerFlex 525 triggered as “Ready”. Activating the conveyor is efficiently achieved by toggling a custom tag labeled “Knapp”, which subsequently configures multiple default settings and commences the conveyor’s motion. This routine is depicted in Figure 6.5.

Upon the load’s arrival at the end point of the conveyor, the PE sensor is activated, prompting the conveyor to cease operation until the sensor is cleared. It should be noted that the functionality of the “Knapp” tag is exclusive to the developmental stage and will be replaced with an authentic, physical start button in practical applications. Furthermore, the routine includes a function block designed to regulate the frequency drive directly, thereby controlling the conveyor’s velocity.

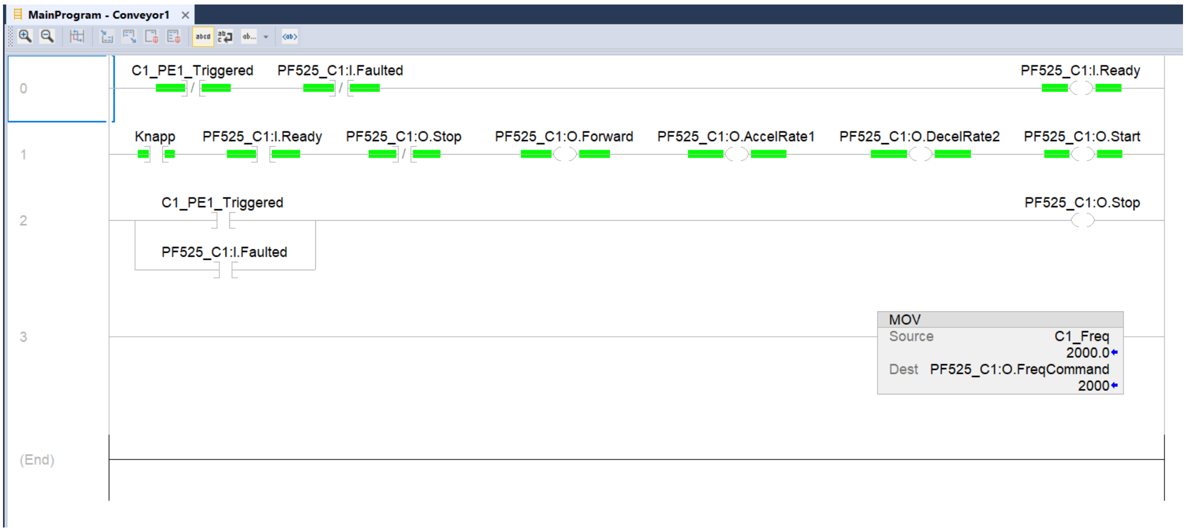


Figure 6.5: A conveyor routine

As mentioned in section 5.3.1, the dual-button MAB was intended to embody the physical MAB on the safety wall. Consequently, the tags employed in the routine necessitated activation by both the virtual and physical MABs. This challenge was addressed by incorporating a tertiary tag, which could be triggered by either version. Figure 6.6 below demonstrates how this was implemented.

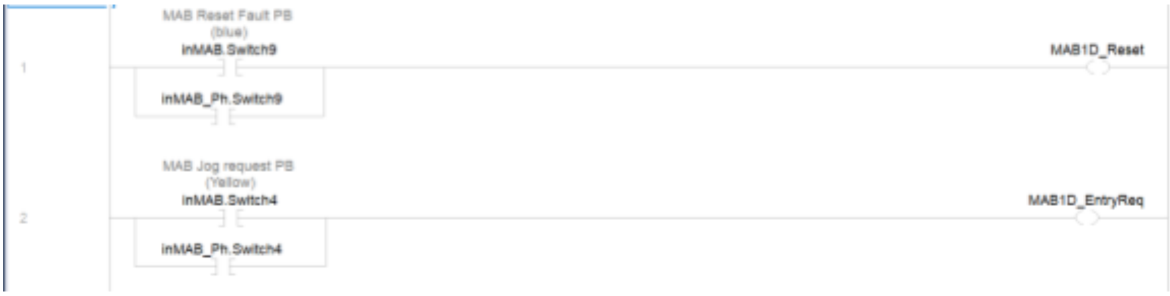


Figure 6.6: Custom tags activated by either virtual or physical MAB

## 6.3 Remote Virtual Commissioning

Throughout the project, all development of the model was successfully conducted remotely with no physical components required for testing nor programming the model's components. As mentioned in section 4.2, the only in person aspects to the team were the three planned meetings.

Cooperatively developing the model was able to be smoothly conducted with screen sharing technology. One of the biggest hurdles with remote working can be the difficulty to allow other people to demonstrate using your computer. An individual attempting to find functionality in a program, or write a line of code, may find it harder to receive help when working remotely. In person, this can be achieved by handing over physical access to the computer.

Many modern screen sharing software integrate functionality for requesting access to the sharing user's mouse and keyboard. Therefore, this difficulty to demonstrate remotely is greatly facilitated, and the gap between remote and in person functionality is bridged. All that is required to provide ease of demonstration remotely is a stable Internet connection.

When developing the digital twin, screen sharing proved an invaluable tool to familiarize both of the authors with the required software. With this software, development of the model could remain an interactive experience for both users even when working remotely. Instead of one user sharing their screen and the other only being able to watch, and explain potential solutions or questions, they were able to demonstrate these seamlessly by taking control of the screen.

Increased interactivity helped reduce development times thanks to the responsiveness it brought. If one user was uncertain about how functionality of a component should be implemented, they were able to show their intended solution directly on the working model. That same user would then be able to receive direct feedback on the current version of the model. With both users working on the same model, on the same computer, frequent uploading and downloading of the model was no longer required. Changes were instead directly implemented to one model, reducing downtime.

Direct feedback allowed efficient parallelization of work. With increased knowledge of how to implement a component, it was possible to isolate that component and program it separately. Once the component was successfully developed, it could be shared using a custom Emulate3D catalog and directly implemented in the working model. Implementation was also facilitated as the creator could easily add the implemented component to the scene as they intended in a manner which did not disrupt the workflow.

With the ease of parallelizing work, independent work on the model was heavily facilitated. Being able to seamlessly hand over access in the event of any questions negated any need to actively cooperate on the same aspect of development. Instead, problems and questions could be addressed as they arose, just like joint development in person.

In the process of developing the digital twin, working remotely did not interfere with productivity, comfort, ease of use, nor interactivity during development. What is more, remote working improved upon these aspects by providing a familiar working environment. Joint development in person requires travel time, usage of less familiar hardware, and sharing of limited physical space, whereas remote work can remove these problems entirely.

As remote work can theoretically be conducted from anywhere, worker comfort is increased as they can work from their most familiar and comfortable environment. By removing, or cutting down travel time, the worker is also able to sleep longer while maintaining their working hours. For a worker with a long commute, this change can be significant. A well rested worker in their optimal working environment will experience increased productivity and motivation.

Additionally, cooperative development in a remote environment does not require familiarization with previously unused computer hardware and peripherals. An example of where this might cause an issue is with keyboards and mice for computers.

When cooperatively working abroad, demonstrations using another computer could be slower as the keyboard layout may differ from what the worker is used to. Keys may be placed differently, making them harder to locate, in addition to variations of size regardless of layout. A computer mouse may be too small or large to use effectively, based on personal preference. With remote development, the hardware can remain consistent and familiarity can be ensured.

One aspect which remote development can fall short is the social factor. With the impeded ability to rely on non-verbal communication, miscommunication is more likely. Other factors such as difficulty for multiple people to speak, and poor equipment may also hinder ease of communication [17]. Therefore, in person work may still be desirable to maintain and develop social cohesion between colleagues.

Several virtual meetings over Microsoft Teams were held to provide assistance for developing the digital twin. These meetings, held multiple times per month, provided assistance comparable, if not identical to, real life assistance. In addition to virtual meetings, the opportunity to physically meet with the project team at Rockwell Automation's office in Gothenburg was a welcome compliment to virtual meetings. Physical meetings provided familiarity with the individuals comprising the team, and an up close introduction to the relevant components for the project.

Depending on the individual conditions, physical meetings may therefore still be desired to provide familiarity with coworkers. Furthermore, remote working will not be able to replace hands-on experience that some components and machinery may require. However, remote working and collaboration can serve as a powerful complement and at least partial replacement to physical collaboration, in addition to its unique benefits.

# 7

# Conclusions

This chapter will provide a concise summary of what has been discovered and developed throughout the thesis beginning with a full overview of the finished model. Subsequently, the benefits, considerations, and drawbacks of remote collaboration will be detailed in the context of developing the digital twin for the thesis. Finally, an overview of the current state of digital twin technology, its potential future development, and applications will be touched upon.

## 7.1 Developed Model

At the end of this bachelor thesis, a digital twin with various safety features was developed using a combination of PLC and Quick Logic programming in collaboration with Rockwell Automation. Further work will be conducted to fully implement features that at the time of this report were not implemented, such as the light curtain and safety switch.

This finished model is of a fictional battery assembly line. In this model, a battery pallet is transported by a PLC controlled conveyor to be individually picked and placed for further transport using robots on MML and iTRAK rails. All robots and transport solutions up until the Quickstick was developed as a part of the thesis.

Batteries on the MML track are transported in groups of four, and batteries are individually transported by iTRAK. On the iTRAK, batteries are inspected and processed before being transported in groups of four to the same MML track which batteries from the initial conveyor are transported to.

Once batteries from the iTRAK and conveyor area are fully loaded on the MML, they are further transported with robots onto a larger pallet on a QuickStick. All programming of components such as transport and robots from this point on was not developed as a part of the thesis with the exception of utilizing a flow control to delete superfluous batteries from the scene.

Once the pallet on the quickstick is filled with batteries coming from the MML, a lid is placed on top of the pallet. The pallet is subsequently transported to one of two welding stations where the lid is shown to be welded to the pallet. This welding is purely visual and does not perform any operation on the pallet in the scene. After welding, the pallet is transported to another QuickStick rail where it reaches a final processing station.

After exiting the final processing station, the pallet is transported using a turntable to the final stages of the QuickStick rail. At this final stage, a robot transports the final battery pallet out of the scene on a conveyor. After being transported, the pallet is then removed from the scene.

After successful assembly and transport of a battery pallet, a robot places an empty pallet on the QuickStick rail where it is transported with a turntable and a different QuickStick rail to the robot transporting batteries from the MML.

Throughout the model, a gate blocks access to potentially hazardous areas. In two areas of the model, entry is possible with a MAB. One MAB is a two button MAB connected to a physical MAB in addition to being a simulation, The other MAB is a four button variant which is purely simulated with an emulated SPLC. Both models accurately represent their real life counterparts in regards to color and design.

A four button MAB’s functionality and model was provided and adapted from a previously existing Emulate3D scene. To represent the two button MAB, the code was altered, the two extra buttons covered up, and future connectivity to a physical MAB was developed.

Upon entry to the safety zone protected by the MAB, machinery runs at a reduced speed when the MAB is opened, unless the enabling switch is activated. With the enabling switch, a button can be held resuming machine functionality at normal capacity while held.

Access to the welding station area and surrounding QuickStick is possible by entering an opening between security gates secured by a light curtain. This light curtain is represented using its CAD model with an invisible logical light curtain for PLC connectivity. When this zone is entered, machines run at a reduced speed. Near the welding station, an additional cable-pull safety system is placed. Along the cable, an emergency stop is placed which will completely halt the machinery.

Light curtains provide safety to the final area of the model near the conveyor, robot, and turntable transporting batteries out of the facility. These light curtains provide the same functionality as the ones near the welding station.

## 7.2 Remote Virtual Commissioning

The development of the digital twin model was effectively accomplished remotely, with only a few in-person meetings. Screen sharing proved invaluable for facilitating collaboration and familiarization with the software, resulting in increased interactivity and reduced development times. This approach also allowed for efficient parallelization of work and the seamless integration of independently developed components into the model.

The remote work environment offered several advantages, including worker comfort, reduced travel time, and consistent use of familiar hardware. Despite some drawbacks experienced while developing the twin, such as potential miscommunication and the lack of non-verbal communication, remote collaboration can be considered a powerful complement, and in some cases a partial replacement, for traditional in-person work. Virtual meetings and occasional physical meetings provided valuable support and opportunities to establish connections with team members.

When developing the digital twin, two aspects needed to be weighed. One aspect was to ensure that the end result of the model was as expected, or functional authenticity. The other aspect was to ensure that the logic behind components was programmed true to life, or operational authenticity. For the final result, functional authenticity was deemed the most important as the scope was not to provide real life familiarity with the functionality of all involved components.

While remote development may not completely replace hands-on experience with certain components or machinery, this project demonstrates that it can be an effective and productive method for creating and refining complex digital models. This success highlights the potential of remote work in enhancing productivity and collaboration in various industries, given the right tools and strategies for effective communication and teamwork.

## 7.3 The Future of Digital Twins

The current state of digital twins is a culmination of several decades of technological advancements, which has resulted in their growing significance in numerous industries for the development and optimization of industrial systems. While they currently are mainly used during the development phase, they have the potential to be implemented in various other contexts, including the representation of human workers.

By employing sensors and motion capture systems, researchers can analyze the movements and actions commonly performed in manufacturing environments, such as assembly, lifting and reaching. Moreover, physiological data, including heart rate, calorie consumption, and respiration rate, could be collected and integrated into the digital twin to predict factors like fatigue. Digital twins can provide valuable feedback to train operators more effectively and determine when a worker is prepared to transition to a new role or schedule.

As of 2023, the rapid progression of AI has garnered considerable attention and is poised to transform digital twins. It is merely a matter of time before the integration of AI into digital twins occurs, further augmenting their capabilities and applications across various sectors.

In the future, digital twins are expected to become an indispensable IT tool in numerous industries, with a particularly significant impact on manufacturing, product development, and product testing across various domains. Consequently, it is conceivable that nearly every manufactured product could possess its own digital twin, provided it generates data amenable to capture and analysis. This concept, referred to as the “digital triplet”, signifies the next stage in the evolution of digital twins [18]. By integrating real-time information from connected sensors and applying AI-based analysis, these individual models can facilitate real time predictions regarding the product life cycle, predictive maintenance, and other aspects.

Furthermore, the concept of digital twin or triplets could extend to human beings, as individuals could have their own digital representations, collecting real-time data from wearables or embedded chips and incorporating unique genetic codes. Theoretically, this information could enable highly personalized and cost-effective medical treatments for every person globally, revolutionizing healthcare and the provision of individualized care.

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# Appendix

## **A:** HRN evaluation of a QuickStick

| Type of danger | DPH | LO | FE | NP | HRN | Description of danger | Acceptable level (Y/N) |
|---|---|---|---|---|---|---|---|
| Crushing hazard | 1 | 5 | 2.5 | 1 | 12.5 | Potential for a finger to get caught between the moving object on the QuickStick. With over 430 N of thrust per meter, likely damages are a bruise/pain, but worst case scenarios could involve crushing/breaking of a finger/arm. | N |
| Collision hazard | 1 | 8 | 2.5 | 1 | 20 | Due to its high speed of 2.5 m/s and force, a QuickStick can injure a worker if a collision occurs. The degree of bodily harm will depend on acceleration/speed at the time of collision. Worst case scenario could lead to concussion. | N |
| Electrical hazard | 15 | 0.033 | 2.5 | 2 | 2.48 | QuickSticks rely on electrical power (48 V and up to 2.5 A) which may expose workers to electrical hazards like shocks or electrocution in the case of a major | N |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | malfunction. Furthermore, the QuickStick is made out of aluminum and steel, making it a capable electrical conductor. Proper installation/isolation of electrical components should suffice with ensuring safety. | |
| Flying objects | 4 | 0.033 | 2.5 | 1 | 0.33 | Improperly placed objects may come loose and fly out of their trays. Worst case scenario temporarily blinding a nearby worker. Unlikely unless robot malfunction, can be mitigated through proper programming of robots and the QuickStick. | Y |