AUTOMATIC BATTERY MODULE SWAPPING STATION FOR AUTONOMOUS MOBILE ROBOTS

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UNIVERSITI TUNKU ABDUL RAHMAN

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Mechatronics Engineering with Honours

Lee Kong Chian Faculty of Engineering and Science
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April 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **AUTOMATIC BATTERY MODULE SWAPPING STATION FOR AUTONOMOUS MOBILE ROBOTS** was prepared by **LIM JUN HOW** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Mechatronics Engineering with Honours at Universiti Tunku Abdul Rahman.

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ABSTRACT

This report presents the design, development, and testing of an Automatic Battery Module Swapping Station and Lithium-Ion Battery Module. The primary objective was to create a system capable of efficiently replacing battery modules in an Automated Mobile Robot (AMR) environment. The Automatic Battery Module Swapping Station was constructed with key features, including a bi-directional belt conveyor, an exchange platform with a battery loading and unloading mechanism, and battery storage compartments. Testing revealed robust performance across individual subsystems and integrated components, with successful load-bearing tests and tilt angle validation. The Lithium-Ion Battery Module, comprising 3D-printed parts and electronic components, underwent extensive mechanical stress testing and functional evaluation, demonstrating structural integrity and effective communication capabilities. Conclusions highlight the successful achievement of project objectives, while recommendations for future work include scalability enhancements, predictive maintenance implementation, and mechanical safety improvements. Overall, this report provides valuable insights into the design and testing of battery swapping technology, paving the way for further advancements in automation and battery management systems.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Autonomous Mobile Robot (AMR) plays an important role in the field of modern logistics and manufacturing. AMR excellent ability to carry goods provides enterprises with great efficiency and flexibility. With autonomous navigation and decision-making capabilities, AMRs can autonomously perform cargo handling tasks in complex environments such as warehouses, factories, or distribution centres without human intervention.

At the core of AMR's energy strategy lies the rechargeable battery, serving as the primary power source for many AMRs. There are two main types of batteries: Lithium-ion and lithium-polymer batteries, revered for their high energy density and rechargeability, play a key role in keeping AMR running. These batteries efficiently store and deliver energy to power the robot's locomotion, computational processes, and sensory systems.

AMRs typically maintain their batteries in two different ways. One method involves self-service charging. The charging process first involves AMR autonomously navigating to a predetermined charging station using its built-in navigation and positioning system. After arriving at the charging station, the AMR will automatically connect to the charging device through the robotic arm or wireless charging pad, sensors and corresponding mechanical structure. However, in some cases, AMR employs manual battery swaps to extend their run time, which is a more efficient method. When the battery power drops to a certain level, or the task is completed, the AMR will autonomously navigate to the scheduled manual replacement station. At the manual replacement station, technicians will use appropriate tools and operating procedures to replace the AMR battery.

The introduction of these diverse charging methods not only enhances the performance and efficiency of the AMR but also lays the foundation for the continuous advancement of autonomous robotics. These various charging methods provide AMR with the flexibility and reliability needed to meet the demands of different application scenarios and environmental conditions.

However, industries around the world are actively pursuing development in the direction of Industrial Revolution 4.0 (IR 4.0), and our government is promoting (National Fourth Industrial Revolution (4IR) Policy) and subsidizing enterprise transformation into IR 4.0 to accelerate development within our country. One of the goals of IR 4.0 is to hope that it can lead to a decrease in the number of human workers required to perform certain tasks or functions within industries (Shida, 2022). Therefore, replacing the battery of the AMR without manpower has become a concept that complies with IR 4.0. In turn, it can become a research and development project with high value in the market.

1.2 Importance of the Study

Currently, AMRs either rely on human operators to replace their batteries or remain stationary at recharging stations for several hours until the batteries are fully charged again. For instance, the recharging process for lithium-ion batteries typically takes up approximately 10-20% of the robot's working time, rendering the AMRs unusable during this period. Although humans can manually swap the AMR battery, it still has several downsides that need consideration:

- Errors caused by human operation
- Flexibility in mission planning
- Resource utilization

To ensure minimal AMR downtime, the AMR can spend most of its operating time actively performing tasks by eliminating the need for extended wait times associated with battery recharging. By developing an AMR automatic battery module swapping system to perform automatic battery module replacement, which can reduce human error and thus improve productivity and task throughput.

1.3 Problem Statement

Most AMRs face limitations in autonomy during long-term task execution. According to the literature reported in Chapter 2, the runtime of AMRs can be extended by two approaches: software-side power management and hardware-based solutions (Farooq et al., 2023). However, much of the research literature is concentrated on the application aspects of AMRs, including AMR path planning and navigation, as well as sensing and perception. While there is relatively limited discussion towards the development of mechanical aspects of AMRs and the technical design of automatic battery swap. Take a real case now that happened in a UTAR student's FYP project about AMR smart charging. His AMR also faced many challenges when charging, such as the inability to automatically find the charging hole accurately and the need to disconnect the battery before charging. For our battery swapping case we might need to consider not only these but also the location of battery swapping, and the weight/size of the battery.

1.4 Aim and Objectives

The aim of this system is to provide both offline battery recharging and online battery exchanging capabilities, eliminating the need for extended wait times. Instead of waiting for batteries to charge, the AMR can return to the battery swap station to replace depleted batteries with fully charged ones. The following are the objectives of the project.

1. To design a horizontally moving conveyor belt capable of bearing the weight of at least two sets of batteries (each battery pack weighs 3kg) and transporting them simultaneously to their respective place.

2. To develop a mechanism that can loading and unloading batteries from the AMR and adjust the tilt angle of the mechanism to accommodate the battery's tilt in AMRs.

3. To design four battery containers that are safe, equipped with battery charging capabilities, capable of accommodating batteries of the size (180mm x 85mm x 75mm), and capable of bearing a weight of at least 3kg.

1.5 Scope and Limitation of the Study

1.5.1 Scope of the Study

The research scope covers various aspects related to the battery swapping method, battery storage and battery loading and unloading mechanism. Firstly, the battery swapping method is explored, detailing techniques and processes devised to replace depleted batteries with fully charged ones efficiently. This includes a comprehensive explanation of the technical details involved in the swap process, encompassing the mechanics of removing and installing the battery smoothly and quickly.

Another facet within this scope involves battery storage. The study delves into the design and management of the storage facility where charged batteries are kept. It discusses how batteries are organized, stored, and maintained to ensure their ready availability for AMRs when needed, with a specific emphasis on factors such as safety and accessibility.

Within the study's focus, there's a dedicated exploration of the development and optimization of the battery loading and unloading mechanism within AMRs. This involves designing interfaces, robotics, and mechanisms that enable the smooth integration of batteries into the AMRs. The study delves into the technical intricacies, examining how AMRs can engage with the battery-swapping system safely and efficiently, ensuring a secure connection and disconnection without compromising the integrity of the robot or the batteries. Additionally, the research investigates the automation and control of these mechanisms, aiming to enhance the overall efficiency and reliability of the AMR battery swap process.

Concluding this research scope, an essential consideration lies in battery transportation, included the means of conveying fully charged batteries from storage areas to AMRs. The study investigates various approaches, including conveyor systems, and transport mechanisms, with the overarching goal of ensuring the efficient delivery of batteries to the AMR swap station.

1.5.2 Limitation of the Study

First, in terms of the design aspects, the physical attributes of the battery enclosure, such as its shape, size, material, and overall construction, are beyond the scope of this project. Instead, a brief discussion with the person in charge will provide a general understanding, steering clear of delving into the detailed design intricacies of the battery case.

Moving on to the design of AMRs, although these robots are integral to the battery swap system, the project will not encompass their overall design, development, or functionality. The primary focus lies in gaining a foundational understanding of the basic parameters of the AMR, with a specific emphasis on the intricacies of battery charging and swapping.

Concerning the battery hot swap system, which facilitates the seamless replacement of batteries while the AMR is operational, its implementation is not within the project's scope but will instead concentrate on the offline and online battery exchange methods.

1.6 Contribution of the Study

The research conducted in this study makes several significant contributions to the field of AMRs and battery management systems. Firstly, it enhances operational efficiency by developing an AMR automatic battery module swapping system. By implementing offline battery recharging and online battery exchanging capabilities, this system reduces downtime and optimizes workflows in logistics and manufacturing environments. Secondly, the study improves reliability by designing robust components such as a horizontally moving conveyor belt and battery loading mechanisms. These enhancements ensure safe and reliable battery swapping operations, minimizing risks associated with battery handling and ensuring uninterrupted AMR operations. Lastly, the research advances battery management technologies through innovative approaches to battery swapping methods and storage facilities. These developments drive progress towards Industry 4.0 goals and enhance competitiveness in global markets.

1.7 Outline of the Report

The report first highlights the importance of AMR in modern logistics and manufacturing in the introduction in Chapter 2.1, emphasizing the role of rechargeable batteries as their primary power source. It addresses the limitations of current battery management methods and outlines the aim and objectives of developing an AMR automatic battery module swapping system to enhance operational efficiency. The scope of the study is defined, focusing on various aspects of battery swapping methods, storage facilities, and battery loading mechanisms.

The literature review section explores existing software and hardware solutions for AMR battery management, along with hot-swapping methods. The methodology and work plan detail the project timeline, mechanical design process, hardware selection, software choices, and testing procedures. Results and discussion cover the fabrication of hardware parts, including the swapping station and battery enclosure, along with testing outcomes for the swapping station success rate in drawing or returning, conveyor load test, drawing load test, and reliability testing. Additionally, results of the Lithium-Ion Battery Module, such as mechanical stress testing and handle testing, are presented.

Conclusions drawn from the research findings are presented, followed by recommendations for future work. The report is supported by references cited throughout, and any additional supplementary material is included in the appendices. This structured outline provides a comprehensive framework for organizing and presenting the research findings, methodologies, and conclusions in the report, facilitating clarity and coherence for readers.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This study primarily centres on hardware-related approaches, with a particular emphasis on the operational and design aspects of the battery-swapping station. These studies share a common objective: enhancing the operational lifespan and reducing downtime during battery charging for the AMR. Moreover, implementing such solutions can potentially expand the scope of AMR applications into new domains and tasks. However, the extent of research dedicated to its advancement remains relatively limited.

Consequently, our focus in this endeavour has been to present hardware-based power solutions documented in the literature and employed in practical, implementable, or commercially available AMR. The central contribution of this work is to consolidate the major battery-swapping technologies utilized in AMR and underscore the prerequisites and factors that must be considered to achieve an autonomous swapping station.

To facilitate more valid comparisons and ensure broader relevance in industrial settings, mobile robots are specifically selected for this research content, except underwater mobile robots, which are excluded from the study. The battery-swapping process can be divided into three main phases: extraction, transfer, and storage. The extraction phase involves removing the depleted battery from the AMR and preparing it for replacement. This part of the station employs spec-optimized machinery and equipment to securely disconnect the depleted battery from the AMR.

Secondly, the transfer phase involves moving the fully charged battery into the AMR. The transfer process should minimize downtime for the AMR, making the battery swap as quick and convenient as possible. Third, the storage component of the battery-swapping station encompasses the management of both the replaced batteries and the fully charged batteries awaiting use. Finally, the following literature discussion will be divided into two parts: software and hardware. The main focus of the explanation is the battery's storage method and the battery's loading and unloading mechanisms.

2.2 Software

The application of software in AMR is very important because software tuning will directly determine whether the AMR can achieve the highest efficiency and energy management in the working process.

2.2.1 Path Planning and Task Scheduling Optimization

In terms of path planning, intelligent path planning algorithms consider the location of the task, map information, and obstacle avoidance requirements to find the shortest or optimal path. By avoiding unnecessary driving, the system reduces energy consumption and improves operating efficiency (Qiuyun et al., 2021). In addition, in terms of task scheduling, optimizing the scheduling order of tasks is also key. Taking into account the priority, deadline and geographic location of tasks, the system can arrange tasks reasonably, reduce the situation of no-load driving, improve the concentration of tasks, and further save power. This intelligent path planning and task scheduling method can enable AMR to efficiently complete tasks with minimum energy consumption.

2.2.2 Dormancy Mode and Wake-Up Strategies

With an effective dormancy mode, when the AMR is not tasked, it can enter a low-power sleep state, shutting down or reducing the energy consumption of key systems. This measure greatly reduces energy waste because the robot can still maintain extremely low energy consumption when it is idle. This intelligent strategy of sleep and wake not only improves power usage efficiency but also ensures that the AMR is always responsive to mission demands.

2.2.3 Dynamic Speed Control

Regarding task relevance, the system automatically and dynamically adjusts the AMR's speed according to the task's urgency and the energy budget. Specifically, when the battery is full, the system can choose to increase the speed of the AMR to complete tasks more quickly. However, when the battery is about to run out, the system automatically reduces the AMR speed to extend the robot's runtime and avoid running out of energy. This strategy maximizes power usage while ensuring task completion, improving AMR efficiency and availability by making speed adjustments based on task priority and battery status (Liang et al., 2022).

2.2.4 Environment Perception and Adaptability

Utilizing sensor data, such as light sensors and temperature sensors, allows the AMR to gather environmental information. This data is then used to make adaptive decisions, such as adjusting illumination based on light intensity or regulating fan speed according to temperature. These adjustments effectively minimize energy waste by ensuring that energy-consuming systems respond appropriately to the surrounding conditions.

2.3 Hardware

This part mainly explains all hardware/mechanisms that have been implemented in the market or conceptual designs that other researchers have found useful for our project. The following will be divided into three main parts to discuss the loading and unloading mechanism, battery transfer mechanism, and the storage method.

The grippers serve as a physical link between the robot arm and the work object, making them a crucial component of robotics. Material handling robots, in particular, offer numerous advantages, and one notable benefit is the minimization of part damage. Given that a gripper comes into direct contact with the product, such as the battery in our project, selecting the appropriate gripper is critical for the application. The following types of grippers are being considered solely for the purpose of extracting batteries from AMRs:

1. C-Shaped Gripper
2. Parallel Tightenable Gripper
3. Vacuum Gripper
4. Pneumatic Gripper

2.3.1 C-Shaped Gripper (Not Fastenable)

A C-shaped gripper with linear motion as the end effector for loading and unloading the battery as shown in Figure 2.1. The C-shaped gripper is designed to grasp the battery case's handle and execute rotational movements for locking or unlocking, illustrated in Figure 2.2. In the battery swap procedure, the gripper's rotational actions can be broken down into five sequential stages. When the battery case is in an unlocked state between steps C and D, the servo halts, and DC motor 1 initiates, propelling the gripper's motion along lead screw 1. This action results in either pushing or pulling the battery case out of or into the charging holder.

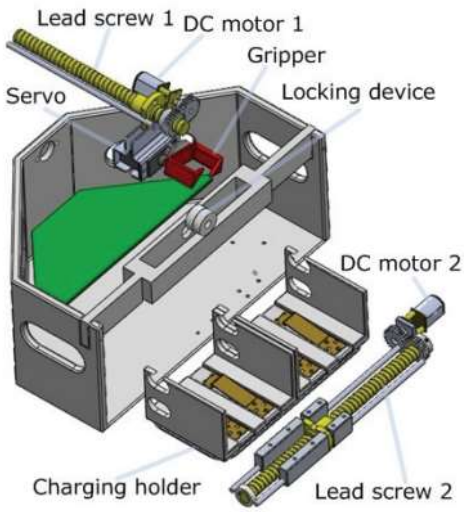

Figure 2.1: The Mechanical Structure of Linear Motion C-Shaped Gripper (Wuet al., 2012).

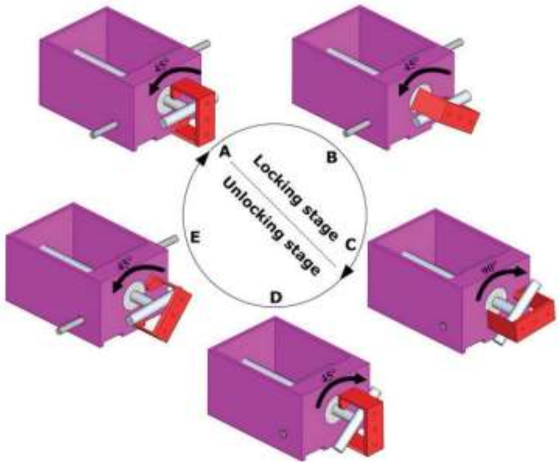

Figure 2.2: Decomposing the Action of the Gripper while Performing the Battery Swap Procedure Involves Either Pushing or Pulling the Battery Case Within the Charging Holder, Occurring Between Points C And D (Wu et al., 2012).

2.3.2 Parallel Tightenable Gripper

A parallel electric servo motor grippers to grab the battery inside the robot. The parallel gripper is designed to grasp objects between two parallel jaws. These jaws can open and close in a motion similar to human fingers, allowing the gripper to hold onto objects of various shapes and sizes securely. In the beginning, the stepper motor was used to drive the horizontal lateral movement of the end effector to approach the robot. The clamps are then tightened, and the depleted battery will be clamped out of the robot and transferred to the battery charging station. A visual representation of the synthesis sequence of this study is shown below.

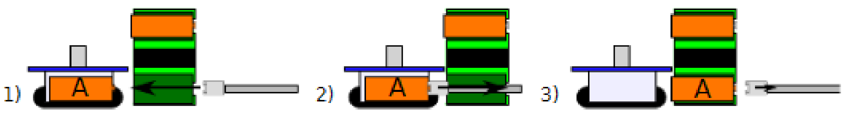

Figure 2.3: The Mechanical Structure of A Linear Motion with Tightenable Gripper (Vaussard et al., 2013).

The following are not found in the scientific literature but are commonly used in industry / commercial space or used to extract batteries but are possible to be applied:

2.3.3 Vacuum Gripper

The vacuum gripper has become a popular tool in the industry because of its high level of versatility and is designed for picking up and carrying objects using suction. In the context of carrying objects, a vacuum gripper is particularly useful for items that have relatively smooth and flat surfaces, such as batteries, because the casing of the AMR battery is usually plastic with a slippery surface. The gripper's ability to generate a strong holding force through suction makes it effective for lifting objects that might be difficult to grasp with traditional mechanical grippers or human hands.

Figure 2.4: Vacuum Clamp Holding Item (Owen-Hill, 2023).

2.3.4 Pneumatic Gripper

This uses almost the same mechanical design with parallel tightenable gripper. Both studies use a parallel gripper to grasp the batteries inside the robot, but this employs a pneumatic gripper, thus lacking the ability to control the tightness. When the end effector approaches the robot. The clamps are then tightened using compressed air, and the depleted battery will be clamped out of the robot and transferred to the battery charging station, illustrated in Figure 2.5. Then, the pneumatic secondary gripper to clamp the battery that was originally in the first gripper and transfer it to the battery charging station, this is to avoid the problem of the jaws of the battery swap jig striking the battery inside the charger during continuous battery swap operations shown in Figure 2.6.

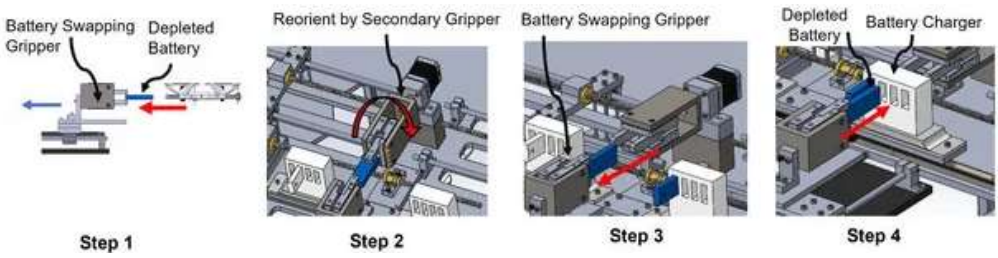

Figure 2.5: Decomposing the Action of the Pneumatic Gripper while Performing the Battery Swap Procedure (De Silva et al., 2022).

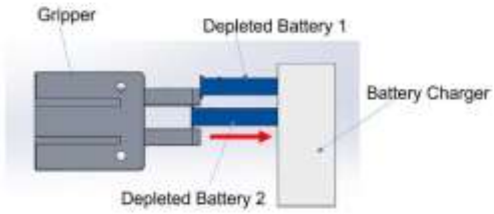

Figure 2.6: Assumptions that the Jig Hits the Battery (De Silva et al., 2022).

2.3.5 Six Degree of Freedom Mechanical Arm with Gripper

The method used in both studies shown in Figures 2.7 and 2.8 is to install a six-degree-of-freedom mechanical arm on the base of the robot. They can all provide real-time feedback to remote operators via connected cameras. The six-degree-of-freedom robot has six servo motors, so it can grab a depleted battery from different angles with ultra-high mobility and transport it to a charging station to begin the charging process.

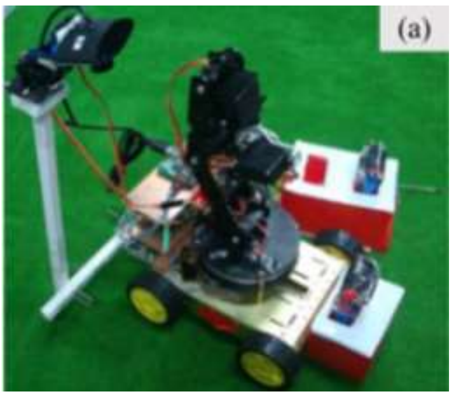

Figure 2.7: A Six Degree of Freedom Mechanical Arm Is Mounted on the Base of the Four-Wheel Robot (Zhang et al., 2013).

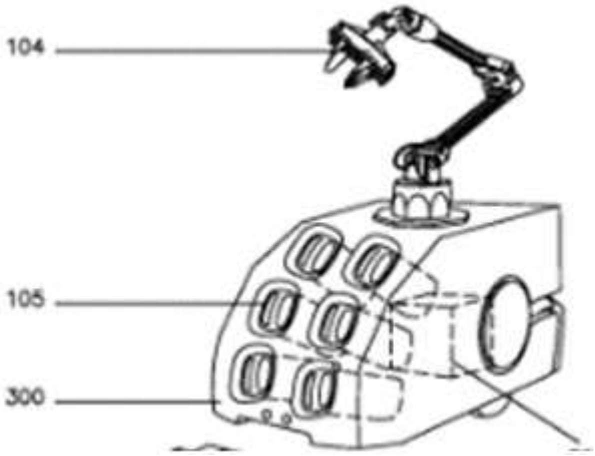

Figure 2.8: A Six-Degree-of-Freedom Mechanical Arm Is Mounted on the Mobile Battery Charging Robot (Green Cubes Technology,2022).

2.3.6 Gantry System

The gantry system is designed with a linear motion axis that allows it to move along the direction needed for battery extraction and transfer. The linear motion axis of the gantry is driven by a motorized actuator, such as a ball screw or a linear belt drive. This actuator generates controlled linear movement, enabling the gantry system to traverse the required distance.

2.3.7 Polar Coordinate Body-and-Arm Assembly

The Polar Coordinate Body-and-Arm Assembly is a robot with a single rotary base joint, a prismatic joint, and a spherical joint at the end. This setup enables movement in a polar coordinate system, encompassing radial, angular, and vertical motions. The process begins by rotating the base to align the arm with an AMR carrying a battery. The prismatic joint extends to approach the battery, and the spherical joint adjusts angularly for proper alignment. The end effector, equipped with a gripper, securely grasps the battery. The prismatic joint lifts the battery while maintaining alignment. The spherical joint aligns the battery with the conveyor. Finally, the prismatic joint lowers the battery onto the conveyor with accuracy.

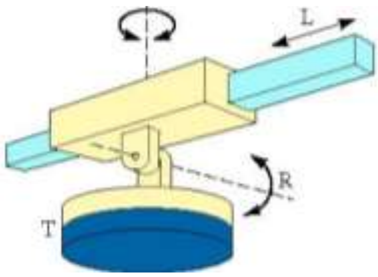

Figure 2.9: Cylindrical Body-and-Arm Assembly.

2.3.8 X-Y Axis Elevator with Bidirectional Conveyor

An elevator incorporating a platform dedicated to the extraction and insertion of the robot's batteries. The battery is elevated using an "elevator" style design, lifting it from its initial position on the robot. The platform on the charging station has the capability to raise a depleted battery out or lower a fully charged battery back into place. Once the elevator raises the robot's battery to the necessary height, the battery is then horizontally transported to a compartment within the charging station, illustrated in Figure 2.10.

The elevator's platform, incorporating a bidirectional moving conveyor belt, will transfer the battery into or out of the compartment. The slight difference between the two is that each individual charging compartment of the Yangshan Port battery replacement station does not require a two-way moving conveyor belt. Another study with each individual compartment equipped with its own conveyor belt. The elevator's platform, along with the conveyor belts situated in each bay, collectively enables a streamlined and effective battery replacement process. The interaction between the robot and the charging station is illustrated in Figure 2.11.

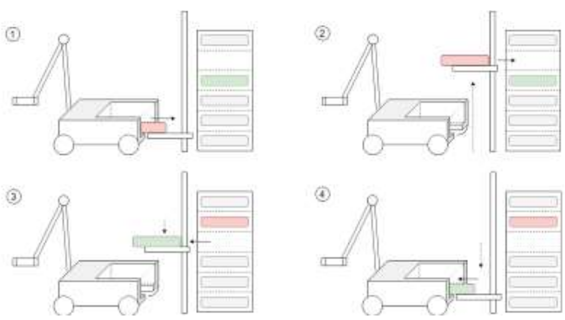

Figure 2.10: Procedures for Removing, Storing and Replacing Robot Batteries (Behl et al., 2019).

Figure 2.11: Yangshan Port Battery Replacement Station for Heavy Truck (Jasmine Lihua & Danilovic, 2021).

2.3.9 Linear Pull/Push Mechanism

There is a pull/push mechanism in each mobile carrier for battery removal. Once the mobile carrier is positioned next to the robot, the pull/push mechanism attached at the chain drive linear actuator will be activated to remove the depleted battery from the autonomous robot. The battery is then placed in the battery slot of the battery frame which travels along two parallel ball screw guides inside the mobile carrier.

Figure 2.12: The overall mechanical structure of the battery swap station has a push/pull mechanism (Cheng Wu et al., 2009).

To transport a battery pack, conveyors are ranked as the first choice because the conveyor system can handle the weight and size of the battery pack efficiently and safely. The type of conveyor chosen depends on various factors, including the layout of the facility, the required speed of transportation, the environment, and any specific handling requirements for the battery pack. Here are a few types of conveyors that could potentially be suitable for transporting the battery pack:

1. Belt Conveyors
2. Powered Roller Conveyors
3. Gravity Conveyors
4. Chain Conveyors

2.3.10 Belt Conveyors

Belt conveyors use a continuous looped belt made of various materials to transport items from one point to another. The belt is supported by rollers or slider beds and is driven by a motorized pulley (drive pulley) or by friction between the belt and the pulleys. Common belt materials include rubber, PVC, fabric.

Figure 2.13: The Battery is Being Transported on a Belt Conveyor (FLEXLIN K, 2021).

2.3.11 Powered Roller Conveyors

Powered roller conveyors use a series of motorized rollers to move items along a path. The rollers are driven by belts, chains, or other mechanisms. The power to the motorized rollers is transmitted through a system of belts or chains that connect the rollers. This synchronizes their movement.

Figure 2.14: The Battery Is Being Transported on a Powered Roller Conveyor (condrives, 2013).

2.3.12 Gravity Conveyors

Gravity conveyors work by relying on gravity to move items along a horizontal decline path. Gravity conveyors are set up at a slight incline or decline. Items move due to their weight and the force of gravity pulling them along. Gravity conveyors use rollers or skate wheels to provide a low-friction surface that allows items to move smoothly. They are often used for light to medium-weight items.

Figure 2.15: Gravity Conveyors.

2.3.13 Chain Conveyors

Chain conveyors use chains to transport items along a path. They are commonly used for heavy-duty applications and transporting bulk materials or products. The chain is the central component of a chain conveyor. It consists of interconnected links that form a continuous loop. Chains are typically made of steel and come in various designs, such as roller chains or engineering steel chains. It generally is driven by a motorized sprocket or gear that engages with the chain. The drive mechanism provides the force to move the chain and the items along the conveyor path. Chain conveyors are particularly suitable for heavy loads.

Figure 2.16: The Batteries are Being Transported on a Chain Conveyor (MK, 2019).

2.3.14 Horizontal Linear Storage

Both studies utilized nearly identical switching mechanisms, as Figures 2.17 and 2.18 illustrated. The shift is facilitated by a DC motor, a lead screw, and a charging holder/battery frame equipped with two charging slots. This system is responsible for relocating depleted batteries from the robot and retrieving fully charged batteries simultaneously. Upon activation, DC motor initiates the rotation of lead screw, subsequently causing the movement of the charging holder/battery frame along the same lead screw path.

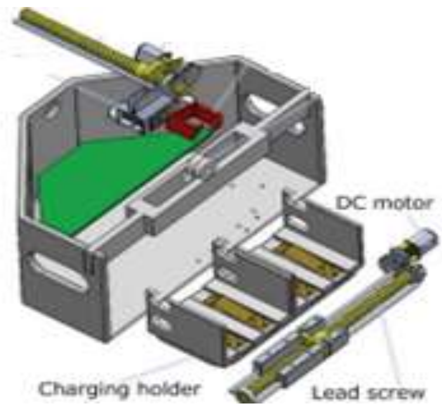

Figure 2.17: The Mechanical Structure of a Horizontal Linear Battery Swapping Station (Wu et al., 2012).

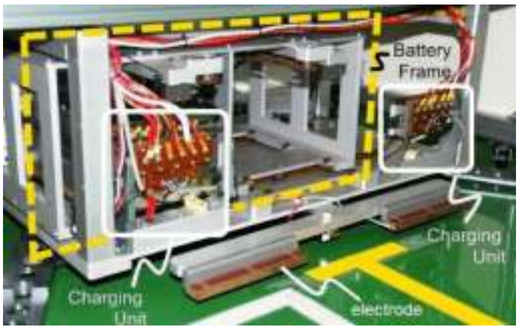

Figure 2.18: The Mechanical Structure of Two Charging Units Integrated Horizontally Linearly on Both Sides of the Carrier (Cheng Wu et al., 2009).

2.3.15 Wheel-Shaped Storage

The battery charger features a wheel-shaped design, with charging slots strategically positioned around the barrel as shown in Figure 2.19. A rotating barrel has the capacity to accommodate and recharge up to 15 batteries in parallel simultaneously. A rotating bucket rotates the fully charged battery to the bottom and also transports the depleted battery away for recharging. At the beginning, the exhausted battery will be taken out from the robot, and then the fully charged battery will be put in.

Figure 2.19: The Wheel-Shaped Charging Station with A Docked Marxbot (Vaussard et al., 2013).

2.3.16 Vertical Linear Storage

Vertical linear battery storage utilizes stackable compartments that require the incorporation of moving components responsible for transporting the battery between the robot and compartment layers. In addition, the charging station transfers the battery to a specific overhead compartment for charging beyond its original location. This design concept is widely used in various fields, including cars, buses and heavy trucks.

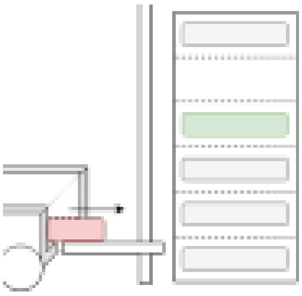

Figure 2.20: A Vertical Linear Car Battery Storage (Behl et al., 2019).

Figure 2.21: A Heavy-Duty Vertical Stacking Battery Swapping Storage (Jasmine Lihua & Danilovic, 2021).

2.3.17 Semi-Open Storage

Both mentioned studies utilize a semi-open design for the battery storage container, where half of the battery is exposed to the air when placed within the container as Figures 2.22 and 2.23 illustrated. This design is implemented to facilitate easier gripping of the battery by the gripper, as half of the battery's body contacts the gripper. Furthermore, there are no internal mechanisms within the battery storage container to facilitate the transportation of batteries. The insertion and retrieval of batteries are both accomplished through the end effector. Although both studies feature battery storage containers with the same design, one study employs a lateral placement approach, while the other study adopts a downward vertical insertion method.

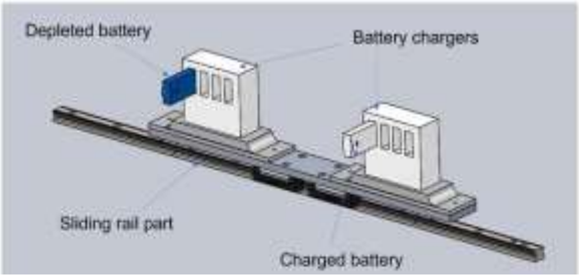

Figure 2.22: A Semi-Open Drone Battery Storage Station (De Silva et al., 2022).

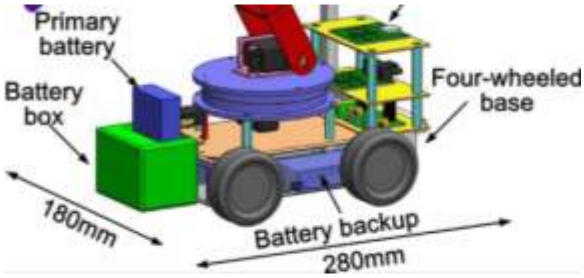

Figure 2.23: A Semi-Open AMR Battery Storage Compartment on a Four-Wheeled Base Robot (Zhang et al., 2013).

2.4 Hot Swapping Method

2.4.1 Wireless

With wireless charging technology, the robot can continue to receive energy while undergoing battery changes. This technology is based on the principle of electromagnetic induction, in which the charging base station sends electrical energy to the robot, and the charging receiver on the robot converts the electrical energy into the energy required by the battery.

Figure 2.24: Wireless Charging of AGVs Using Wiferion Technology (Edwar ds, 2021).

2.4.2 Wired (Direct Contact)

For some robots, direct contact charging can be achieved by connecting a power cord or a charging plate. This approach involves connecting the robot to an external power source to maintain power while the battery is changed. This can be achieved by plugging a power cord or contact with robot's charging socket.

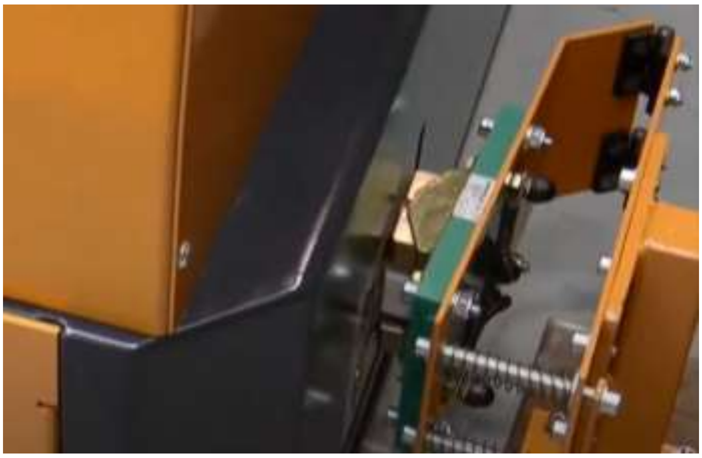

Figure 2.25: AGV Docking Station and Direct Charging (AGVR, 2019).

2.4.3 Super Capacitor

A supercapacitor is a device capable of storing and releasing large amounts of electrical energy in a very short period of time. Integrating supercapacitors into robots can provide temporary energy support during battery replacement. When the robot needs a battery change, the supercapacitor can release stored energy to keep the robot running until a new battery is installed. Supercapacitors provide a quick way to replenish energy.

2.4.4 Secondary Battery

Some robots may be equipped with multiple battery packs, one of which can act as a secondary battery. When the robot is changing batteries, the robot can automatically switch to the secondary battery pack to maintain continuous operation. This requires an intelligent battery management system capable of monitoring the status of the main battery and automatically switching to the backup battery when necessary.

Figure 2.26: Open-Source Automatic Mobile Robot (AMR) Design with Multiple Battery (Nikos, 2021).

2.5 Summary

This section summarizes three key components: the loading and unloading mechanism (gripper part), battery transfer mechanism (conveyor part), and the battery storage method. Additionally, a summary provided regarding the data and experimental results obtained from four different types of prototypes, as shown in table 2.1-2.4. This information will serve as a point of reference for making informed choices in the subsequent stage (methodology).

Table 2.1: Comparison of Different Types of Grippers.

Gripper Type	Advantages	Disadvantages
C-Shaped Gripper (Not Fastenable)	Simple in design, easy to manufacture, suitable for high-speed operations, low cost to fabricate, carry heavier battery weight	Depends on the design of the battery housing handle
Parallel Tightenable Gripper	Medium cost to fabricate, low maintenance cost, can grip batteries of different sizes and shapes	Can carry low battery weight and low operation speed only
Vacuum Gripper	No surface damage, handle various objects, low operating costs	Not suitable for irregular shapes or rough surfaces, Mechanisms need to be checked regularly
Pneumatic Gripper	Easy to use, capable of gripping batteries of various sizes and shapes, and offering substantial clamping force despite its compact size	Requires maintenance, operates at a slow speed, unable to stay in the specified position, and may potentially cause surface damage

Table 2.2: Comparison of Different Types of Conveyor Belts.

Conveyors Type	Advantages	Disadvantages
Belt	Provide a smooth and consistent transport of materials, relatively high speed, can handle a wide range of products, one of the most cost-effective conveyor options	Can be susceptible to damage from sharp or abrasive materials, might have limitations when it comes to moving materials vertically or at steep inclines
Powered Roller	Can handle a variety of load sizes and shapes, effective horizontal transportation over a longer distance	More expensive than other conveyors, have limitations when it comes to incline angles, object may get stuck
Gravity	No external power source, making them cost-effective for moving lightweight items over short distances	Suited for lightweight items and short distances, cannot move materials with some incline angles, no control of conveyor speed
Chain	Capable of handling heavy loads, withstand harsh environments	noise during operation, more expensive, higher maintenance requirements

Table 2.3: Comparison of the Cost, Space Utilization, and Battery Size of Different Battery Storage Methods.

Way Of Storing the Battery	Cost	Space Utilizes	Battery Size
Horizontal Linear Storage	Medium	Low	Small to Big
Wheel-Shaped Storage	Cheap - Medium	High	Small
Vertical Linear Storage	Medium - High	High	Small to Big
Semi-Open Storage	Cheap	Medium	Small

Type 1: Horizontal Linear Storage

The advantage of this design lies in its capability to carry exceptionally heavy batteries, transporting both depleted and fully charged batteries simultaneously and effectively reducing the robot's battery replacement time, a limitation arises. However, this design does not facilitate optimal utilization of vertical space when required. As more batteries are loaded, the charging station expands horizontally, consequently diminishing the available area within the factory. This design is usually used to replace one AMR's battery and is unsuitable for replacing multiple AMRs in a row.

Type 2: Wheel-Shaped Storage

The primary design objective was to maximize battery capacity and optimize spatial utilization within a single station to support concurrent operations of multiple robots. However, this design needs to reserve a charging slot space for the exhausted battery as a storage space. In addition, it's worth noting that this setup has limitations, particularly in handling heavy batteries. The weight concentration from 15 batteries on the central ball bearing poses a challenge, potentially reducing the lifespan of the ball bearing significantly.

Type 3: Vertical Linear Storage

Vertical linear battery storage utilizes stackable compartments to optimize floor space utilization. This arrangement facilitates accommodating multiple batteries for simultaneous charging, minimizing operational downtime for multiple robots. Although its mechanism is more complex, this configuration significantly improves space efficiency compared to existing systems. Notably, it can accommodate significant battery weight and provide scalability, potentially reducing costs.

Type 4: Semi-Open Storage

This design is the simplest without any mechanism, and the cost is also the cheapest. However, the batteries cannot be arranged very densely because the gripper needs a certain space to extend and retract to avoid hitting other stored batteries, and the batteries are also at risk of falling out and cannot withstand heavy batteries.

Table 2.4: Data and Experimental Results for Four Different Types of Prototypes.

Prototype	**Mechanism of transferring**	**Way of storing**	**Time to complete**	**Success rate**
Automatic Battery Swap System for Home Robots	C-shaped gripper (not fastenable) with linear actuator	Horizontal linear	84.2s	95%
Battery Swapping and Wireless Charging for a Home Robot System	Six degree of freedom mechanical arm with gripper	Semi-open	About 62s	100% (Manual)

Battery swapping station for docked marXbot	Parallel tightenable gripper with linear actuator	Wheel-shaped	40 s	100%
Robot Docking Station for Automatic Battery Exchanging and Charging	Linear pull/push mechanism with one axis gantry system	Horizontal linear	Within 45s	100%

The above four prototypes have been selected and are highly relevant to the research objectives of AMR battery swapping stations. They have also been studied and experimented with. Each prototype uses a different mechanism for transferring the battery and a different way of storing it, which results in varying times to complete the entire swapping process and success rates.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter outlines the methodology and work plan for the development of an Automatic Battery Module Swap System for AMRs. The objective of this project is to create a versatile system that addresses the challenges of battery management in AMRs, offering both offline battery recharging and online battery exchanging capabilities. This chapter also provides a structured overview of the project's planning and execution, including project milestones, the design of the automatic battery module swap station, a detailed exploration of the hardware and bill of materials, a flowchart outlining the sequence of operation for the designed battery swapping station, procedures for testing and validating each component before installation into prototypes, and a list of essential equipment required for the fabrication processes. The integration of these elements will culminate in creating a highly efficient and automated battery management system, significantly enhancing the operational continuity and productivity of AMRs in various applications.

3.2 Project Planning and Milestone

In the pursuit of developing an Automatic Battery Module Swap System for AMRs, a structured project plan has been devised, outlining a series of key milestones spanning three semesters.

3.2.1 FYP 1 Milestones

Project Initiation and Research: During this phase, project initiation occurs, the problem statement has also been identified through discussions with the investor. Comprehensive research on existing battery management systems is conducted to gain a more comprehensive understanding of the current trends and relevant approaches within the study's scope, additional research and literature reviews are conducted to explore the work of other researchers, and the specific requirements and objectives of the system are defined.

- **Flowchart Development:** During this milestone, a comprehensive flowchart depicting the sequence of operation for the designed battery swapping station is developed. This flowchart serves as a vital visual representation of the system's functionality.
- **System Design and Component Selection:** Building upon the research findings, this milestone encompasses the design phase, finalizing the system's architecture and component selection, including hardware specifications.
- **Bill of Materials:** By the end of the first semester, a detailed Bill of Materials (BOM) is prepared, listing all necessary components and materials required for the project.

3.2.2 FYP 2 Milestones

FYP2 milestones are then separated into four sections as follows:

- **Hardware Fabrication:** The fabrication of the automatic battery module swap station commences, adhering to the specifications outlined in the BOM. This phase involves the assembly of components and custom parts, such as 3D printed components.
- **Component Testing and Validation:** Each component of the system, from electric to hardware components, undergoes rigorous testing and validation to ensure they meet performance and safety standards.
- **Prototype Integration and Testing:** This phase involves the integration of all components into a prototype of the battery swapping station, followed by extensive testing to ensure seamless functionality.
- **Final Documentation and Report:** In the final semester, a comprehensive project report is prepared, documenting all phases of development, testing results, and recommendations for future improvements.

These planned milestones guide the progress of the project, ensuring that each phase is executed, and that the final system achieves its objectives. The Tables

3.1 and Table 3.2 depict the progression of FYP 1 and FYP 2 within this project, respectively.

Table 3.1: Gantt Chart Part 1 Semester 1.

Gantt Chart Part-1															
No.	Project Activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
M1	Problem formulation & Project planning	■	■	■											
M2	Literature review			■	■	■	■	■							
M3	Conceptual design drafting and preparation of							■	■	■	■	■			
M4	Report writing & presentation											■	■	■	■

Table 3.2: Gantt Chart Part 2 Semester 2.

Gantt Chart Part-2															
No.	Project Activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
M1	Hardware Fabrication	■	■	■	■										
M2	Component Testing and Validation				■	■	■	■							
M3	Prototype Integration and Testing							■	■	■	■	■			
M4	Final Documentation and Report											■	■	■	■

3.3 Mechanical Design (First Version)

The automatic battery module swap system is as shown in Figure 3.1. It consists of three sections: (a) bi-directional belt conveyor, (b) battery loading and unloading mechanism, and (c) battery storage.

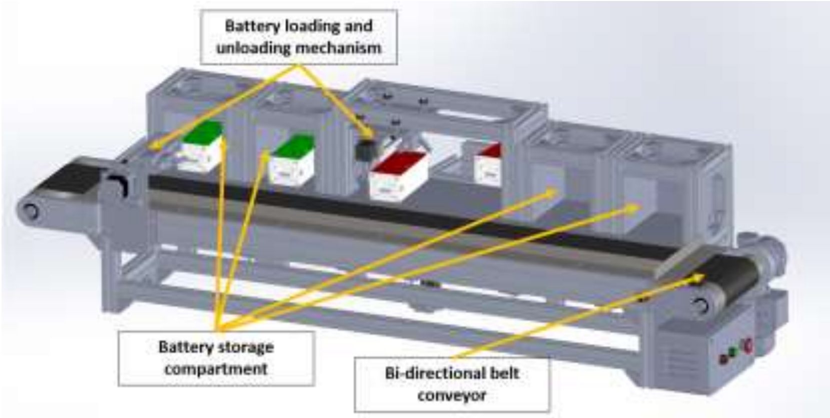

Figure 3.1: Conception Design of the Overall Automatic Battery Swapping Station.

3.3.1 Bi-directional Belt Conveyor

The bi-directional belt conveyor is approximately 1.8 meters in length, 0.2 meters in width, and positioned at a height of 0.20 meters above the ground, the conceptual design of the belt conveyor as shown in Figure 3.2. Its purpose is to transfer fully charged batteries from the battery charging compartment to the exchange platform or vice versa. This conveyor is capable of bidirectional movement to transport batteries to both the left and right sides of the battery charging compartment. The main structure is constructed using 4040 and 4080 Aluminium profiles to support the weight of the batteries and the motor. The conveyor belt is made of PVC material. The motor used in this design is an AC single-phase induction motor with capacitor startup. This design enables more effective handling of multiple batteries quickly and continuously, making it suitable for high-throughput operations to meet the demands.

Figure 3.2: Conceptual Design of Bi-Directional Belt Conveyor.

3.3.2 Battery Loading and Unloading Mechanism

The design of this exchange platform with a battery loading and unloading mechanism is intended to provide a platform for interfacing with the AMR. It has approximate dimensions of 0.5 meters in width, 0.2 meters in length, and a height of about 0.2 meters, as illustrated in Figure 3.3. The platform is capable of adjusting its angle because the batteries inside the AMR are not parallel to the ground and have a slight angle. The angle adjustment of the platform is achieved by using electric cylinders linear actuator placed underneath the platform. When the electric cylinders linear actuator is raised, it can lift one side of the exchange platform, allowing for angle adjustment. The width of this platform is designed to be relatively wide for the convenience of extracting the two batteries from within the AMR. Above the exchange platform, the sliding table linear actuator for battery extraction and placement into the charging compartment is the same.

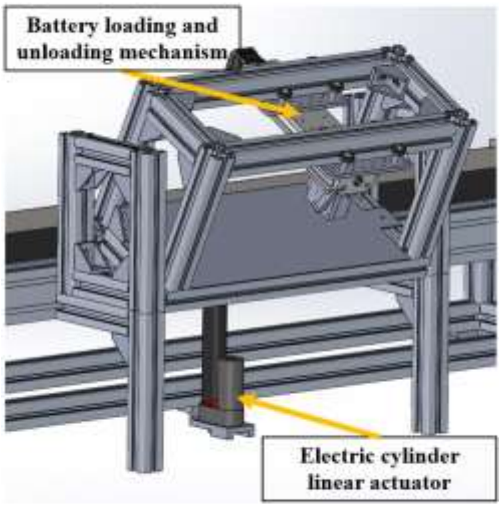

Figure 3.3: Exchange Platform with Battery Loading and Unloading Mechanism.

This battery loading and unloading mechanism is the same and used both in the exchange platform and in the battery extraction and placement into the charging compartment. The forward and backward movement of this mechanism is achieved through the use of a sliding table linear actuator. The sliding table linear actuator is equipped with a DC worm gear motor and a hook, securely fastened by a customized bracket. The hook at the front end of the DC worm gear motor is designed to latch onto the handle of the battery pack, preventing it from disengaging during transportation. However, the lateral movement of this mechanism in exchange platform is accomplished through a stepper motor with belt drive but in the battery extraction and placement into the charging compartment use DC motor to move horizontally.

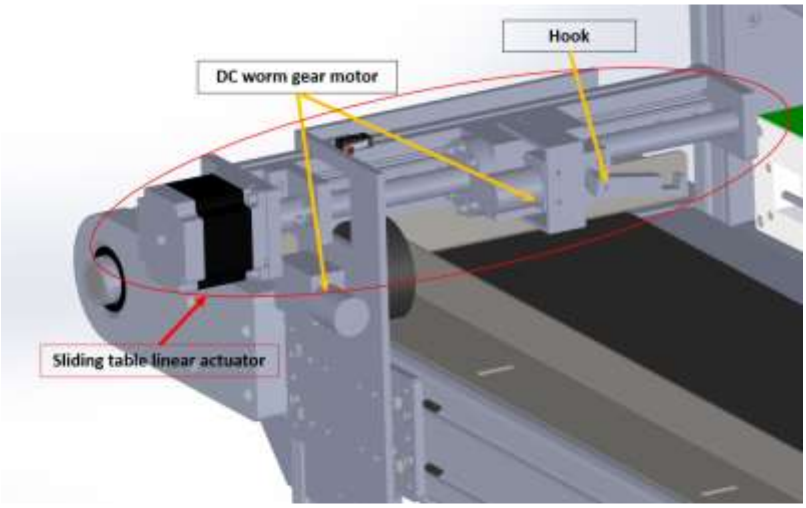

Figure 3.4: Battery Loading and Unloading Mechanism for the charging compartment.

3.3.3 Battery Storage

In this design, four independent battery storage compartments are used, with two on each side (left and right). Each independent battery storage compartment is constructed using different lengths of 4040 aluminium profiles, forming a rectangular shape measuring approximately 0.2 meters in length, 0.16 meters in width, and 0.155 meters in height. These compartments are separated from each other using acrylic panels. Initially, one side accommodates two fully charged batteries, while the other side is reserved for depleted batteries removed from the AMR. This design, combined with bidirectional conveyor belts, maximizes efficiency in transportation. When a fully charged battery is removed from one of the battery storage compartments, a depleted battery can simultaneously be transported to an idle battery storage compartment for recharging. These two activities can occur simultaneously without interfering with each other.

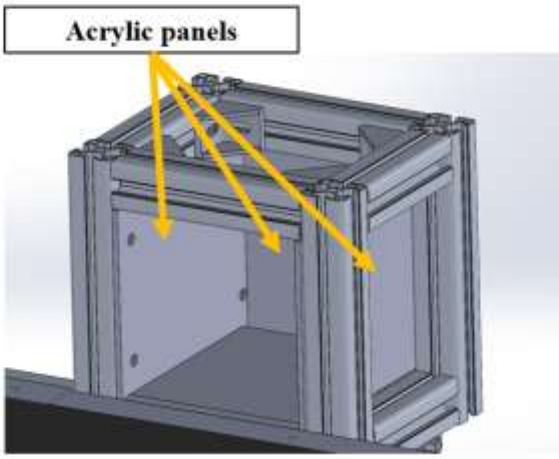

Figure 3.5: Independent Battery Storage Compartments.

Figure 3.6: Two Independent Battery Storage Compartments on Each Side.

3.4 Problems Encountered and Solutions for Automatic Battery Module Swapping Station

The first issue arises from using customized brackets to secure the entire sliding table linear actuator, resulting in uneven force distribution. As the sliding table of the actuator moves outward, the customized brackets deform significantly due to their insufficient surface area to evenly distribute the pressure. All force points concentrate on the screw holes and bending parts, amplifying the issue through a lever effect. Finite Element Analysis (FEA) provides insight into these issues, demonstrating the extent of deformation and uneven force distribution, as illustrated in Figure 3.7 and Figure 3.8.

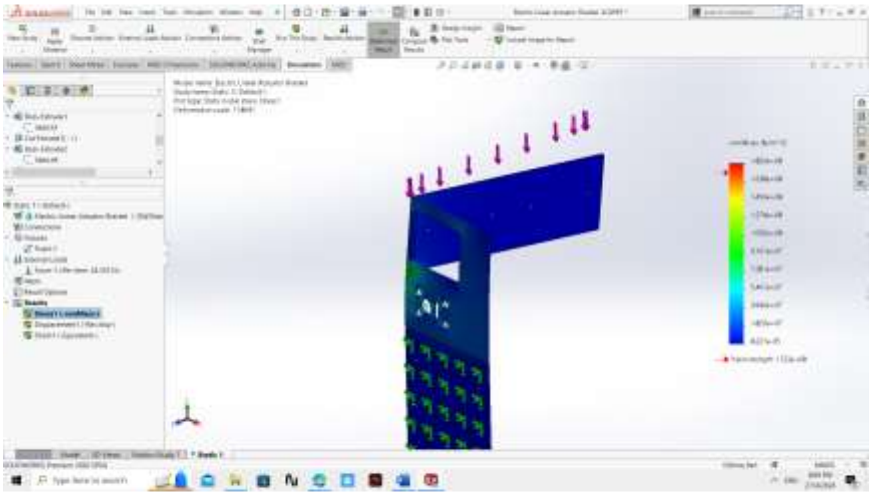

Figure 3.7: The Customized Bracket for FEA Stress Distribution Result.

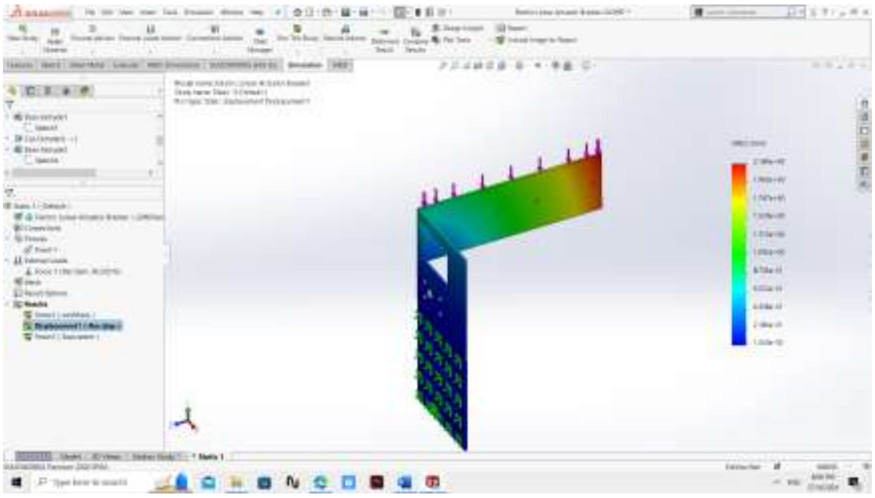

Figure 3.8: The Customized Bracket for FEA Displacement Result.

Additionally, during system operation, vibrations cannot be ignored as they impose additional stress on these components. While increasing the thickness of the customized brackets can mitigate the extent of sagging and enhance overall strength, but it leads to increased costs due to the necessity for more steel material and heightened construction complexity.

The solution to these issues involves rotating the placement position of the sliding table linear actuator by 90 degrees, allowing the rear portion of the actuator to lie horizontally on a gantry plate. This adjustment is necessary because the rear portion of the sliding table linear actuator, where the stepper motor is located, carries a significant portion of the weight. As the sliding table moves forward, it counteracts the force from the rear, maintaining balance. Additionally, the impact of vibrations can be reduced as the overall centre of gravity is significantly lowered. This modification eliminates the need for a customized bracket and ensures more even weight distribution, resulting in smoother movement and reduced structural strain. The Figure 3.9 demonstrates the new design concept.

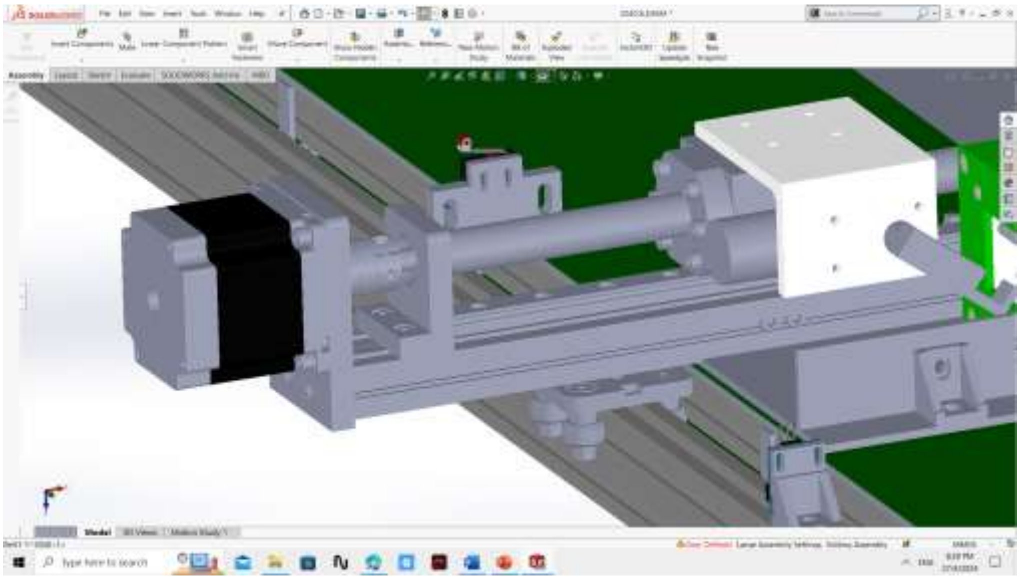

Figure 3.9: The Actuator Lies Horizontally on a Gantry Plate.

The second issue arises when the battery module is being dragged out from the battery compartment or exchange platform to the conveyor belt by the loading and unloading mechanism. This process often results in the battery pack tilting, making it challenging to smoothly insert it into the charging compartment and will cause the entire process to stop temporarily. The problem stems from the interaction between the hook of the loading and unloading mechanism and the handle of the battery module, which allows for some degree of movement, preventing the battery module from being inserted straight. This issue is illustrated in Figure 3.10.

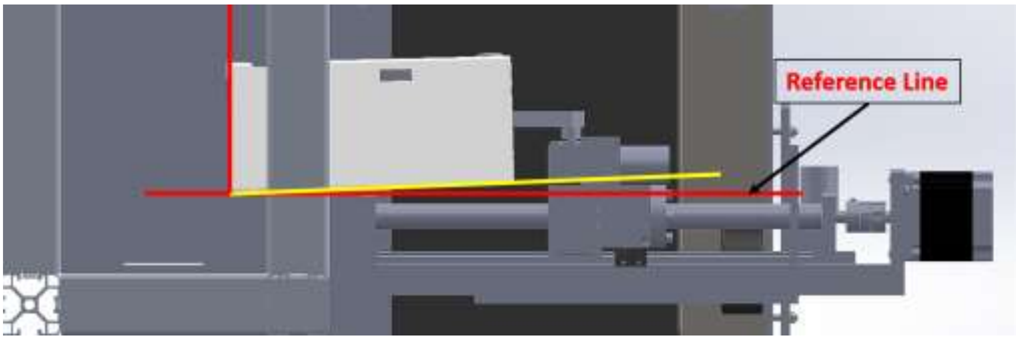

Figure 3.10: A Demonstration of the Battery Module Tilted During Insertion and Removal.

The solution to this problem involves introducing a new design feature: the battery carrier beneath the sliding table linear actuator. This additional feature creates a physical space to guide the battery module, ensuring precise alignment when removing and inserting it into the charging compartment. By connecting the motion of the battery carrier with that of the sliding table linear actuator to the conveyor belt, alignment is maintained throughout the process, further enhancing system performance. Even if the battery module is slightly angled during insertion, the enforced spatial constraints of the battery carrier prevent issues with inserting the battery module. The following Figure 3.11 illustrates how the battery module remains perfectly level with the reference line when the battery carrier is engaged.

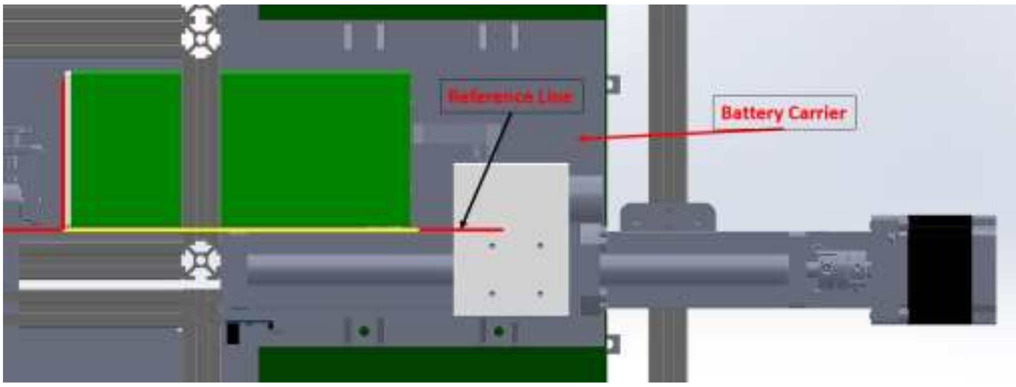

Figure 3.11: The Tilting Issue of the Battery Module Has Been Corrected.

These conceptual solutions, designed to address specific challenges in the prototype fabrication process, will be implemented during the construction phase. The effectiveness of these solutions in resolving the identified issues will be thoroughly evaluated and documented in Chapter 4.2.2 illuminating their practical applicability in real- world scenarios.

3.5 Mechanical Design (Second Version)

3.5.1 Overview Design for the second version

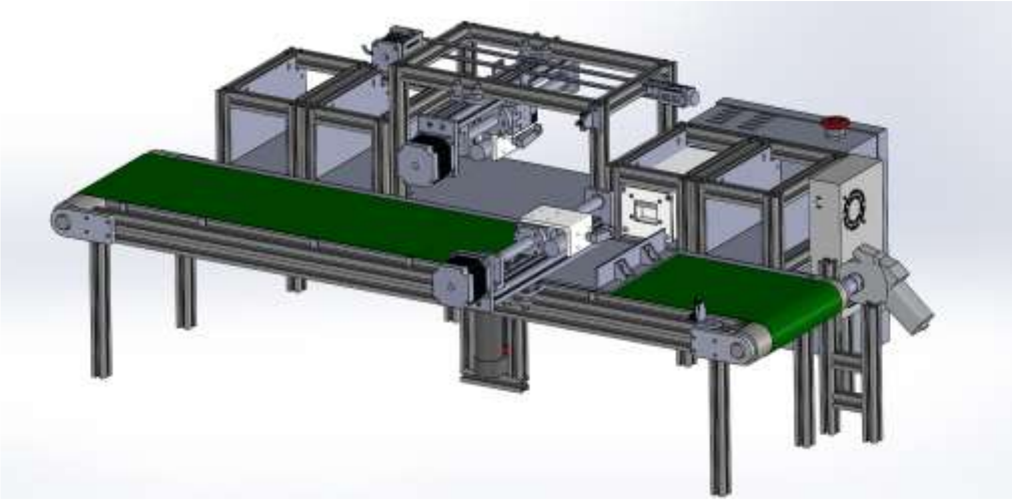

Figure 3.12: The Second Version Conception Design of the Overall Automatic Battery Swapping Station.

The second version is an optimized version of the first version that takes into account cost, functionality and solves some problems that may be encountered when building prototypes. However, most of the design from the first edition is still retained. It is worth noting that the cost of the first version is RM2680.96, while the cost of the second version is only RM1475.38, saving RM1205.58. The detailed bill of material is shown in Appendix A.

Overall, these adjustments strike a balance between cost reduction and maintaining essential functionality, resulting in an optimized second version for the automatic battery module swapping system. The modified automatic battery module swap system can also be divided into 3 sections as follows.

3.5.2 Bi-directional Belt Conveyor

In the second version of the bi-directional belt conveyor, several modifications have been implemented to enhance cost-effectiveness while maintaining essential functionality. Firstly, the length of the conveyor has been reduced from the original 1.8 meters to 1.1 meters, likely as a result of reassessing space requirements or refining the system layout. This reduction not only minimizes material costs but also contributes to a more compact overall footprint. Secondly, the original aluminium profiles of 4040 and 4080 have been substituted with smaller sizes of 2040 and 2020. This change optimizes structural support while further reducing material expenses. Lastly, the motor choice has been revised, with the original AC single-phase induction motor replaced by a power window motor. The use of AC single-phase induction motors in current prototypes is considered overkill. But it can be used later when it is needed for actual implementation. The current specifications of the power window are fully capable of providing sufficient torque to drive the battery and battery loading and unloading mechanism. This substitution is driven by cost considerations for prototype production, as power window motors are more readily available and cost-effective.

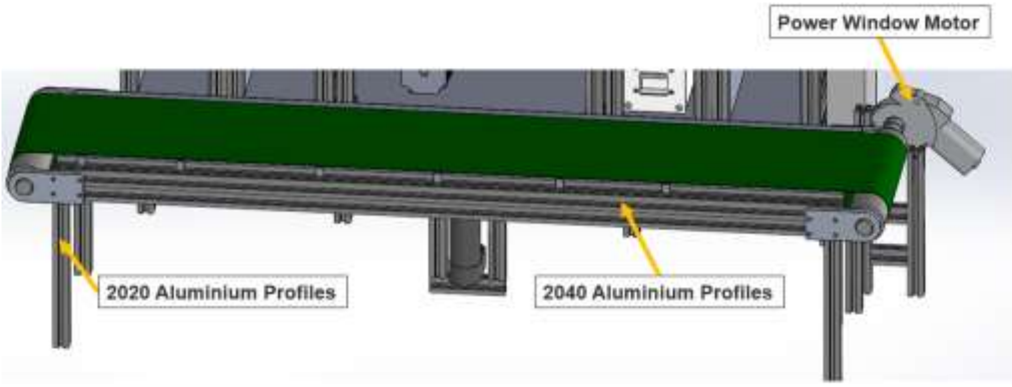

Figure 3.13: The Second Version of the Conceptual Design for the Bidirectional Belt Conveyor.

3.5.3 Battery Loading and Unloading Mechanism

3.5.3.1 Exchange Platform with A Battery Loading and Unloading Mechanism.

In the second version of the battery loading and unloading mechanism, several enhancements have been introduced to optimize its performance. Firstly, a limit switch has been incorporated into the mechanism to ensure precise positioning during startup. This limit switch, integrated with the DC worm gear motor and hook, enables the mechanism to accurately reset its position upon initialization, providing a consistent starting point for the loading and unloading process.

Secondly, to refine the lateral movement of the mechanism within the exchange platform, a u-shaped photoelectric sensor has been introduced. Positioned above the platform, this sensor serves as a reference point for initiating lateral movement. Coupled with the existing stepper motor and belt drive setup, the sensor enables precise and reliable positioning of the mechanism. As the stepper motor rotates counterclockwise, the mechanism shifts laterally until the u-shaped photoelectric sensor detects its alignment, ensuring accurate placement for battery exchange operations.

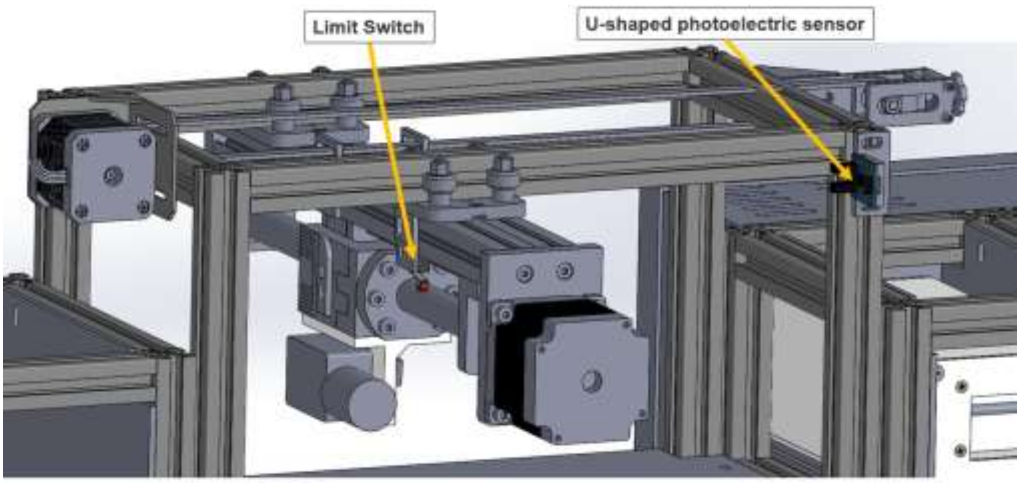

Figure 3.14: The Sensors is Equipped on the Exchange Platform.

Lastly, a limit switch has been added beneath the exchange platform to facilitate seamless integration with the electric cylinder linear actuator. This additional switch allows the actuator to lower the platform to ground level during startup, ensuring consistent positioning and alignment.

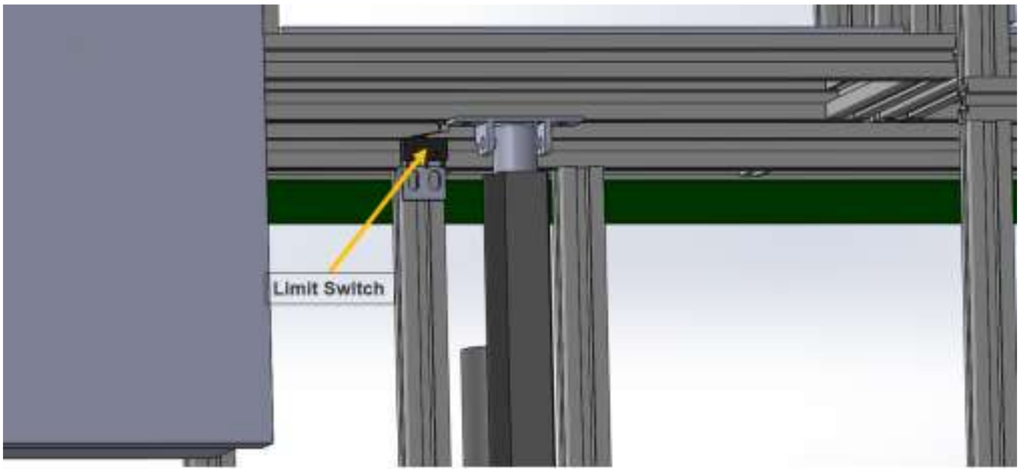

Figure 3.15: A Limit Switch Has Been Added Underneath the Exchange Platform.

These sensors are implemented to provide a consistent starting point for the loading and unloading process and help eliminate potential misalignments or errors that can occur if the mechanism is activated from any position. It helps improve the overall accuracy and reliability of the system and is especially important in high-throughput operations where precise positioning is critical for seamless battery replacement.

3.5.3.2 The Mechanism of Battery Extraction and Placement into The Charging Compartment

In the second version of the battery loading and unloading mechanism for the charging compartment, significant changes have been introduced to enhance efficiency, reliability, and ease of maintenance. Firstly, the placement position of the sliding table linear actuator has been rotated 90 degrees, lying horizontally on a gantry plate. This adjustment eliminates the need for a customized bracket and distributes weight more evenly, resulting in smoother movement and reduced structural strain.

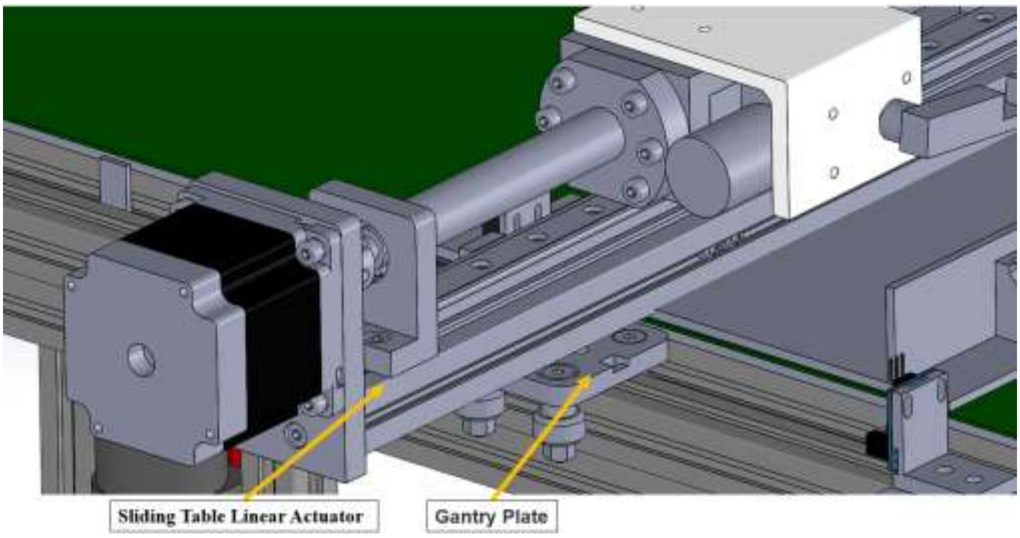

Figure 3.16: The Actuator Lies Horizontally on a Gantry Plate.

Furthermore, the mechanism's movement, originally driven by a separate DC worm gear motor, is now integrated with the conveyor system. This bundling of components reduces maintenance requirements and improves overall reliability, streamlining the system's operation.

In term of sensor technology has also been upgraded, with the addition of two u-shaped photoelectric sensors and a limit switch. The limit switch, integrated with the DC worm gear motor and hook, ensures consistent initialization and positioning for the loading and unloading process, enhancing operational stability. One u-shaped sensor refines lateral movement by serving as a reference point for alignment, while the other signals the conveyor when to stop, ensuring precise battery pack retrieval. The placement of L-shaped 3D printed parts in strategic positions determines the detection points of these sensors, optimizing system accuracy. The detection of the U-shaped photoelectric sensor was determined by placing the L-shaped 3D printed part in 6 different positions. For example, four of them are placed in front of each four battery compartments and two are placed in front of the switching platform.

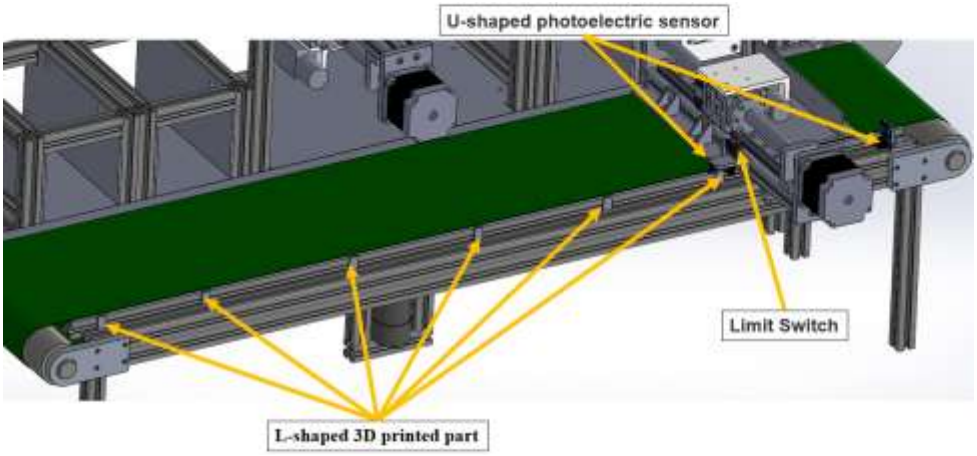

Figure 3.17: The Installation Positions of L-Shaped 3D Printed Parts and the Placement of Sensors.

Moreover, a new design feature has been introduced: the battery carrier under the sliding table linear actuator. This addition creates a physical space to guide the battery pack, ensuring precise alignment during extraction and placement into the charging compartment. By linking the movement of the battery carrier and sliding table linear actuator to the conveyor belt, alignment is maintained throughout the process, further enhancing system performance.

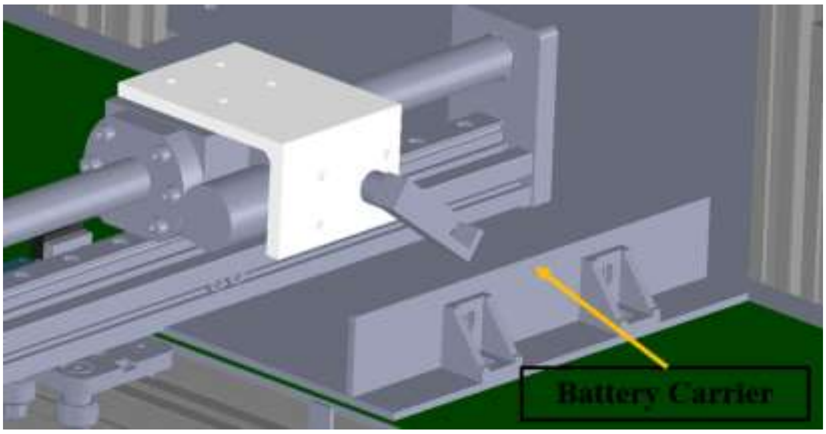

Figure 3.18: A Battery Carrier Is Installed Beneath the Actuator.

3.5.4 Battery Storage

In the second version of the Battery Storage system, the placement and overall design remain unchanged, with only minor adjustments to the dimensions. While the layout of the storage compartments remains consistent, the structural components have been updated from the original 4040 aluminium profiles to 2020 aluminium profiles.

The transition to 2020 aluminium profiles maintains the structural integrity of the compartments while reducing material costs and potentially decreasing the overall weight of the system. Despite the smaller profile size, the compartments retain their rectangular shape, measuring 0.20 meters in length, 0.135 meters in width, and 0.125 meters in height. In order to accommodate the dimensions of the prototype's battery pack, a more suitable storage space is created.

3.6 Electrical Circuit Diagram

The electrical circuit diagram for the automatic battery module swapping system comprises six main parts: Power, Microcontroller, Sensors, DC Motor (Low Current), DC Motor (High Current), and Stepper Motor. The Power part includes essential components such as a 12V power supply, a 20A DC circuit breaker, and emergency buttons for safety. The microcontroller part utilizes an Arduino Mega and push buttons to initiate and stop system processes. Sensors, including limit switches and FC-33 photoelectric sensors, provide feedback for precise system operation. DC motor (Low Current) control is facilitated by two L298N motor drivers, managing various DC motors. The DC motor (High Current) section employs a QF-M05S motor driver and relay modules to control high-power DC motors, such as the conveyor system. Stepper motors are controlled by TB6600 stepper motor drivers, with specific functions including battery module loading/unloading and lateral shifting.

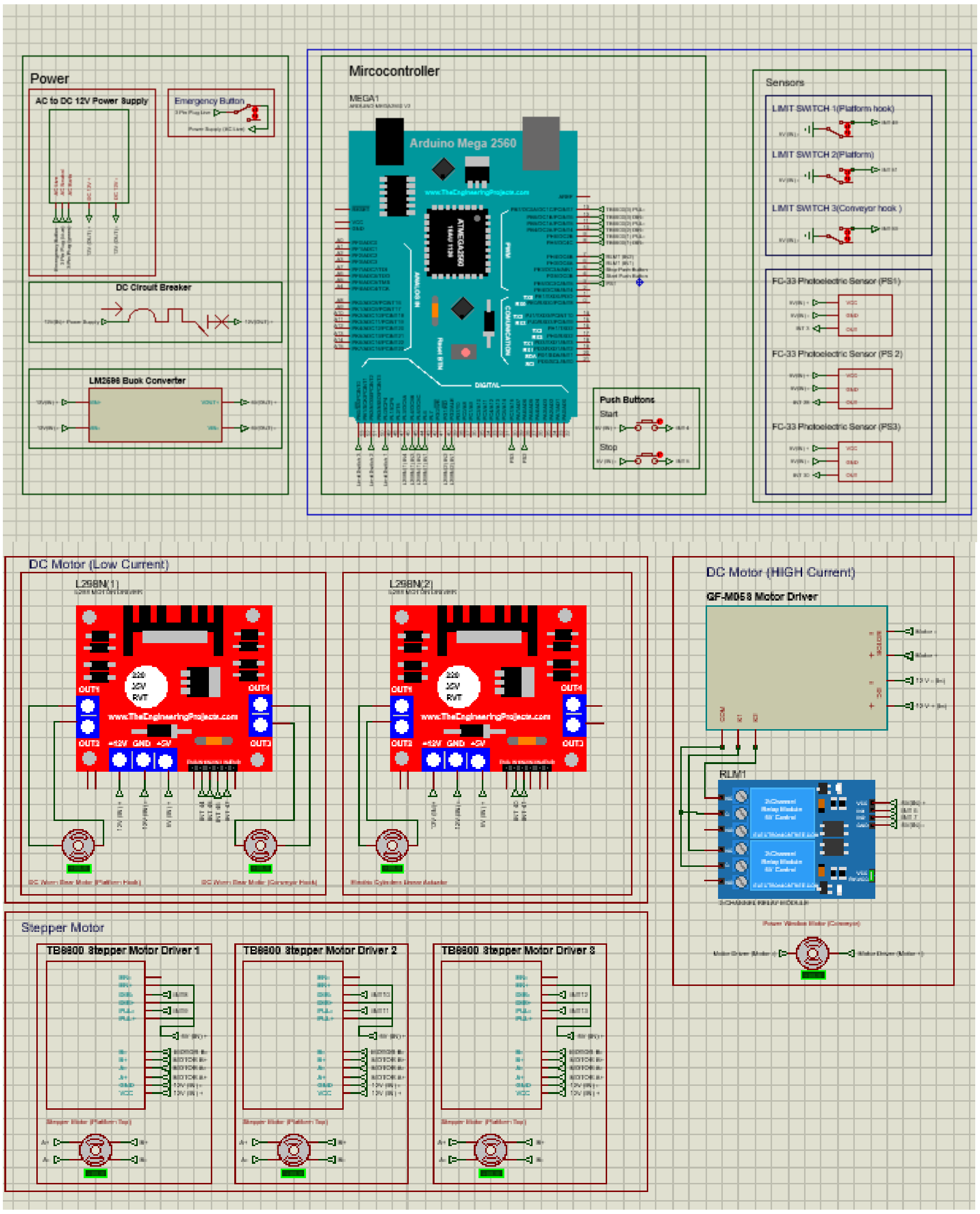

Figure 3.19: An Overview of the Circuit Diagram for the Automatic Battery Swapping Station System.

3.6.1 Power Supply

The power supply part serves as the backbone of the system, providing essential electrical supply and safety features. The 12V power supply acts as the primary power source for the system's operation. The 20A DC circuit breaker ensures protection against overcurrent situations, safeguarding the system from potential damage. Emergency buttons serve as safety mechanisms, allowing operators to quickly halt system operations in case of emergencies.

The LM2596 buck converter regulates the voltage from 12V to 5V, ensuring compatibility with components requiring lower voltage levels.

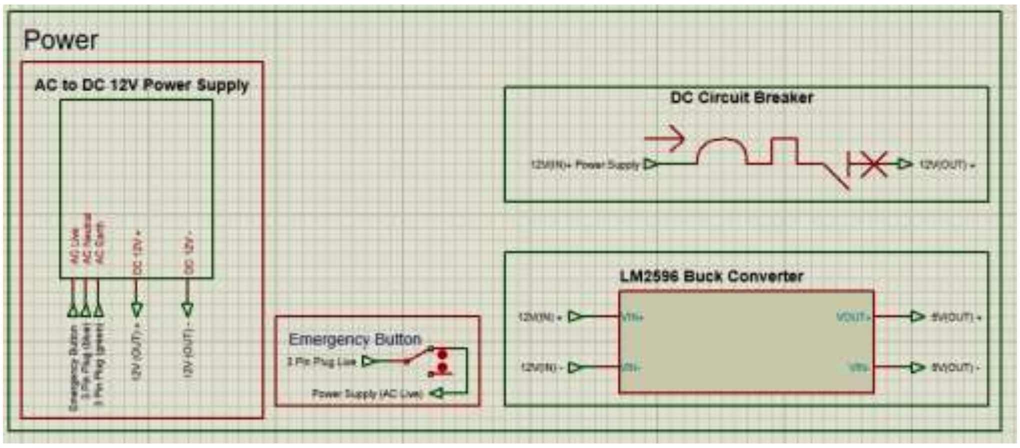

Figure 3.20: The Circuit Diagram for the Power Management of the System.

3.6.2 Microcontroller

The microcontroller part utilizes an Arduino Mega to control system processes. Push buttons provide user interface functionality, enabling operators to start and stop system operations as needed.

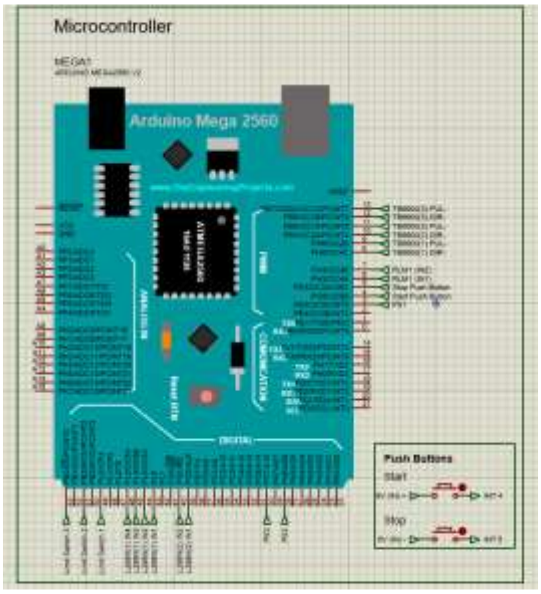

Figure 3.21: The Circuit Diagram for the Microcontroller of the System.

3.6.3 Sensors

Sensors play a crucial role in providing feedback and ensuring precise system operation. Limit switches are used to detect physical limits or positions of mechanical components, providing accurate positioning information. FC-33 photoelectric sensors utilize light beams to detect the presence or absence of objects, enabling automated detection and control within the system.

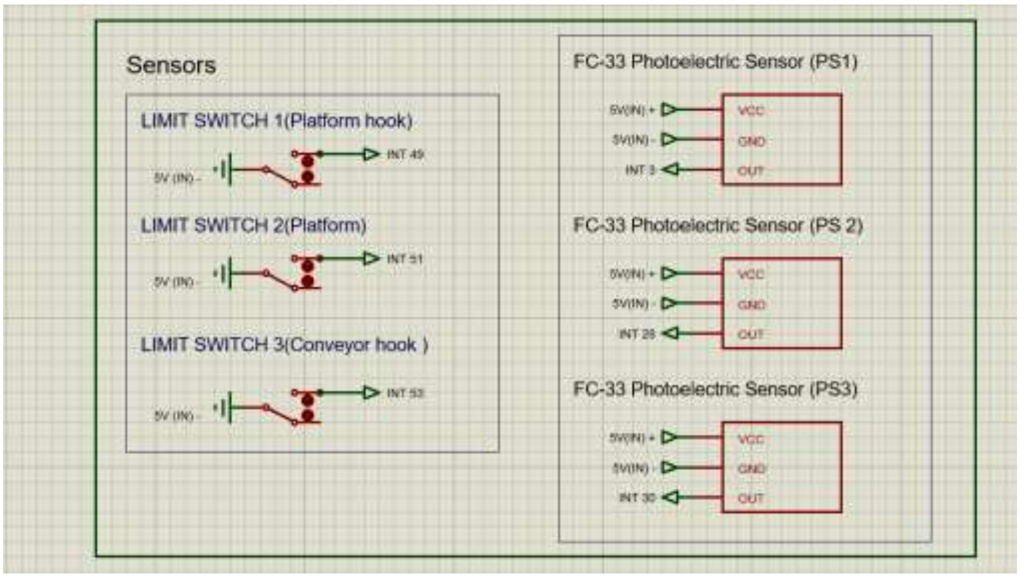

Figure 3.22: The Circuit Diagram for the Sesnors of the System.

3.6.4 DC Motor (Low Current)

This part focuses on controlling low-current DC motors responsible for various mechanical movements within the system. Two L298N motor drivers are employed. One driver manages the platform and conveyor hooks. While the other controls the platform angle via electric cylinders linear actuators.

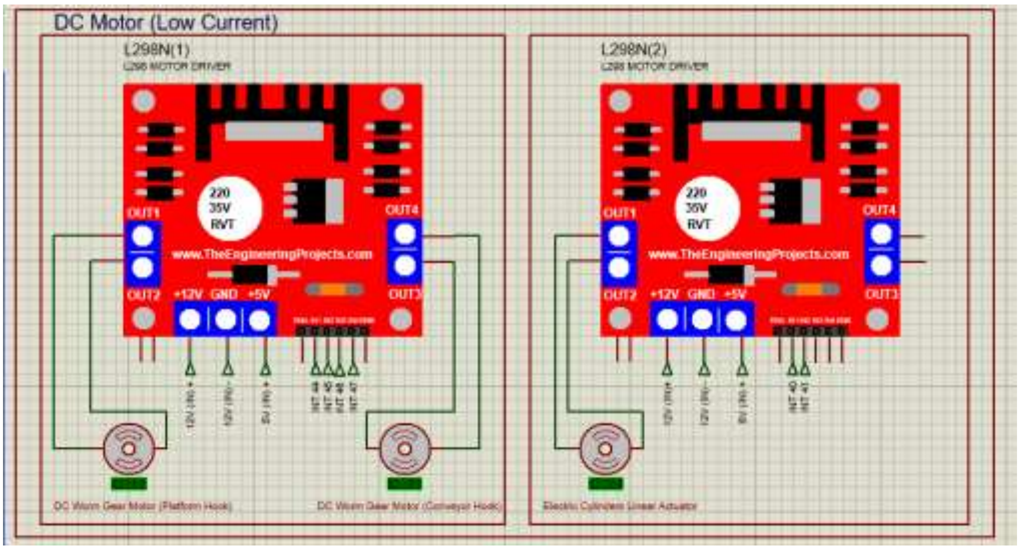

Figure 3.23: The Circuit Diagram for the DC Motor (Low Current) of the System.

3.6.5 Stepper Motor

Stepper motors are controlled by TB6600 stepper motor drivers, with each driver dedicated to a specific function. They manage tasks such as loading/unloading battery modules between compartments and lateral shifting. The TB 6600 Stepper motor driver is used to control NEMA 17 stepper motors are used for precise movement control.

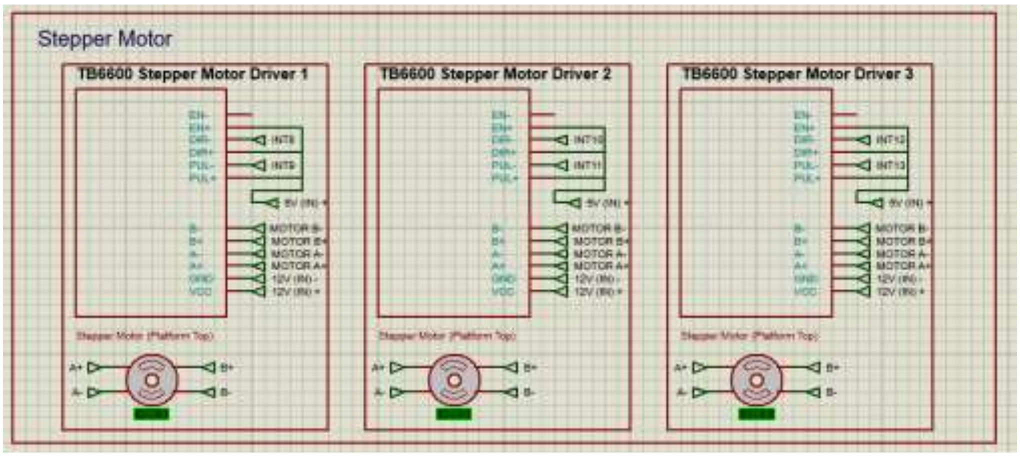

Figure 3.24: The Circuit Diagram for the Stepper Motor of the System.

3.6.6 DC Motor (High Current)

The DC Motor (High Current) section handles the control of high-power DC motors, particularly those driving the bi-directional conveyor system. A QF-

M05S Motor Driver, along with relay modules, is utilized for the control and direction management of these motors. Relay modules receive signals from the Arduino Mega and trigger the QF-M05S Motor Driver to control motor direction, start, and stop functions effectively.

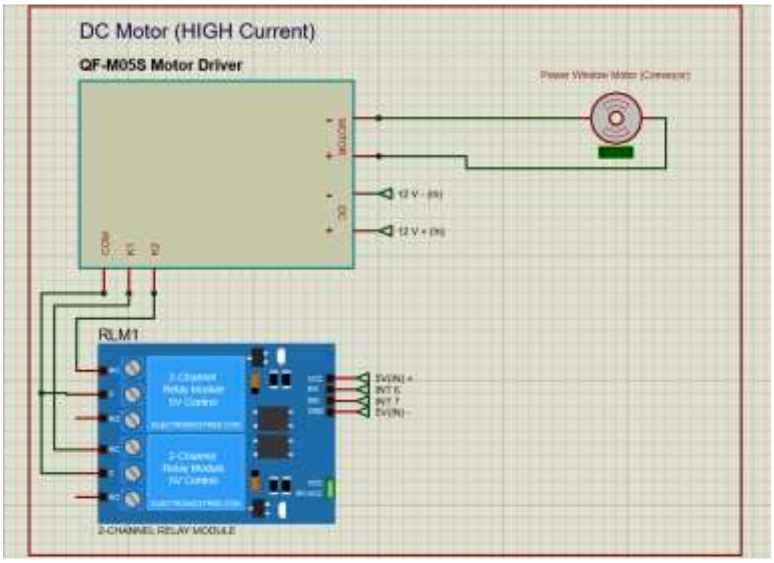

Figure 3.25: The Circuit Diagram for the DC Motor (High Current) of the System.

3.7 Lithium-Ion Battery Module Enclosure *Additional Work Done

In this section, the prototype design methodology involves adopting components from various commercial products. After conducting a thorough analysis of the literature review and existing commercial products, the pros and cons of each product have been collected. These insights are used to identify the most suitable design elements for the current project. By amalgamating the best features from different designs, a comprehensive battery enclosure design is formed.

Simultaneously, the layout of the circuit for hot swapping and the hardware requirements for IoT integration need to be considered. This ensures optimal flexibility and safety during the testing phase. Therefore, the design process prioritizes accommodating the necessary circuitry for hot swapping and the hardware components essential for IoT functionalities. This integrated approach enhances the overall flexibility and security of the prototype design.

3.7.1.1 Battery Enclosure Design

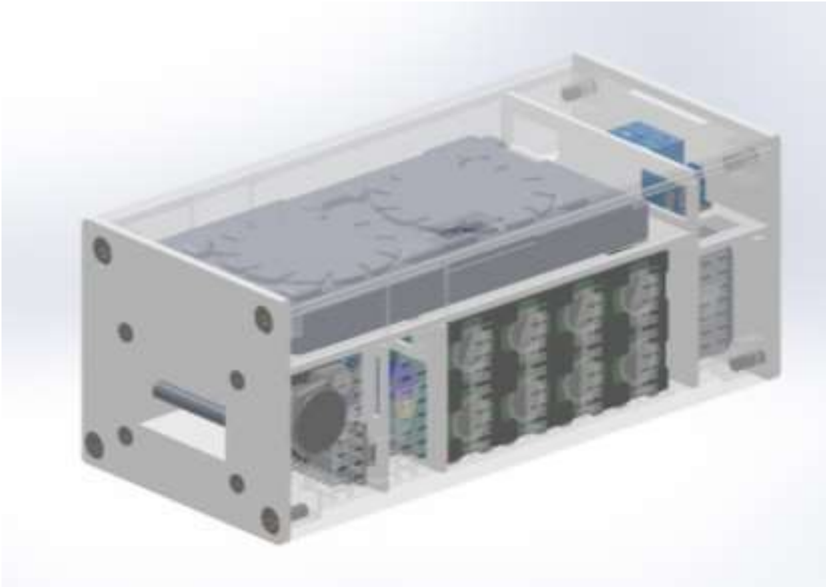

Figure 3.26: The Conception Design of the Overall Battery Enclosure Design.

The battery enclosure is designed in a cuboidal shape with filleted edges, measuring approximately 179.5mm x 81mm x 71mm. This specific design concept was chosen for its simplicity, offering a clean overall appearance to the enclosure. However, the inclusion of filleted edges holds significant importance for safety considerations. Filleted edges play a crucial role in contribute to the longevity of materials used in the enclosure. By distributing stress more evenly throughout the material and avoiding sharp corners that are prone to damage or wear, filleted edges help to minimize the possibility of cracks, chips, or other forms of damage. Additionally, filleted edges can also reduce friction between moving parts in certain situations. By providing a gentle transition rather than a sharp corner, they promote smoother operation and potentially extend the lifespan of components within the enclosure and through the results of FEA, it is concluded that the filled edge only deformed by 0.00003342mm (Material: ABS) when subjected to a force of 10N as shown in Figure 3.27. Overall, the incorporation of filleted edges not only enhances safety but also contributes to the durability and functionality of the battery enclosure design.

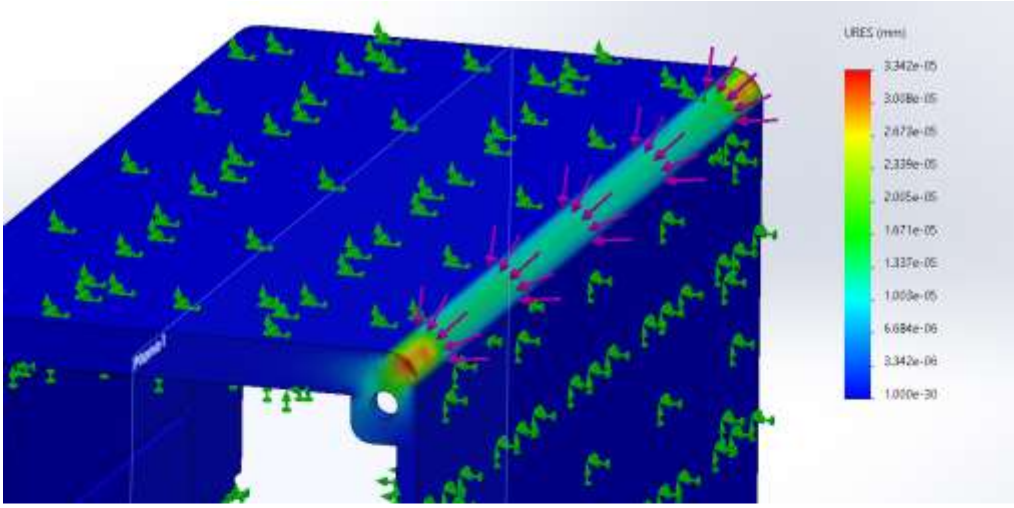

Figure 3.27: The Results of Finite Element Analysis.

3.7.2 Internal layout of the battery module

The battery module adopted compartment design to separate the communication module, Battery Management System (BMS) and battery module as shown in Figure 3.28. Using a compartmentalized design within the battery module offers several benefits. Firstly, it isolates components such as the communication module, BMS, and the battery itself, minimizing the risk of interference or damage between them. This isolation enhances safety by containing any potential malfunctions or thermal events within their designated compartments, thus reducing the risk of cascading failures. Additionally, compartmentalization facilitates easier access to individual components for maintenance or replacement, streamlining maintenance procedures and minimizing downtime. Lastly, by tailoring each compartment to meet the specific requirements of its contained component, such as providing adequate cooling or electromagnetic shielding, overall performance and reliability of the battery module are optimized. Therefore, the use of compartmentalization is a practical and effective design choice for integrating diverse components into a cohesive lithium-ion battery system.

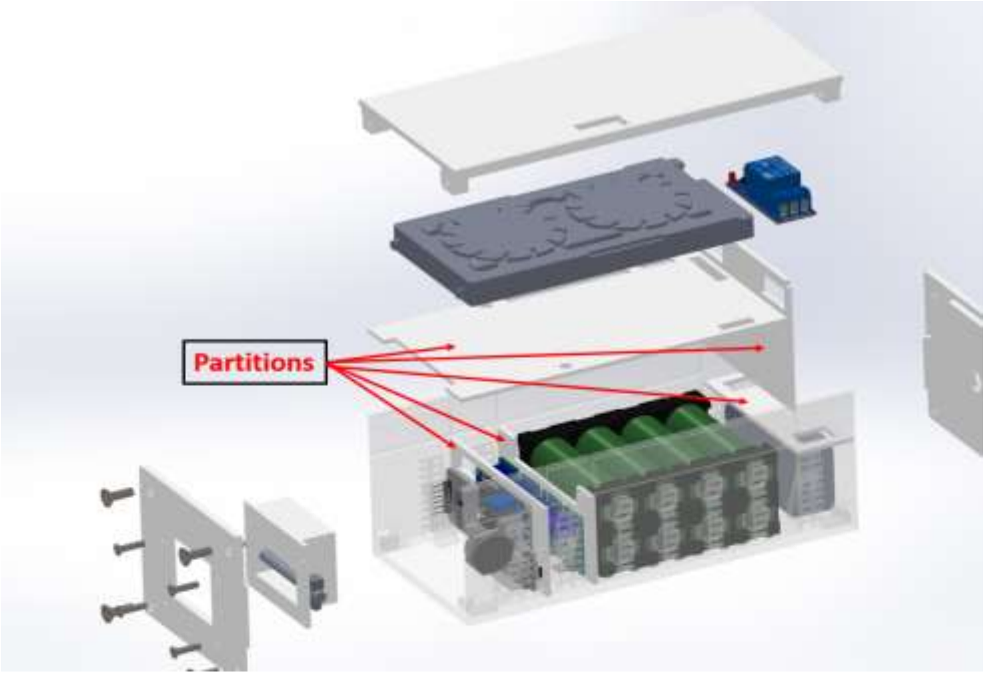

Figure 3.28: The Exploded View Showing Internal Layout.

3.7.3 Handle Design

In this design, the battery handle is concealed within the entire enclosure, ensuring that it is not exposed externally. Instead of protruding outside the enclosure, the handle's entire structure remains hidden within its confines. This approach offers several advantages. Firstly, it reduces the risk of damage to the handle during transportation or handling, as it remains protected within the enclosure. Additionally, by keeping the handle internal, the overall footprint of the battery module is minimized, optimizing space utilization and potentially allowing for easier integration into various applications or systems. Furthermore, this design is based on the need for a battery-swapping station. The hook of the battery replacement station needs to be able to reach the battery handle, so it is designed in a round shape. By hiding the battery handle inside the casing, the hook can easily reach the battery handle, making it easier to replace the battery. This design not only meets the functional requirements of the battery replacement station but also preserves the overall aesthetics of the casing. Overall, this design takes into account both functionality and aesthetics and provides convenience for battery replacement.

In addition, the handle case can be separated from the battery enclosure simply by removing four screws. The reason for this design choice is primarily for application during the prototype phase. This is because the hook used in the battery swapping station must match both the handle and handle case. Therefore, having a detachable design allows for experimentation with different handle and handle case designs without the need to produce an entirely new battery enclosure. This approach effectively reduces waste and lowers energy consumption.

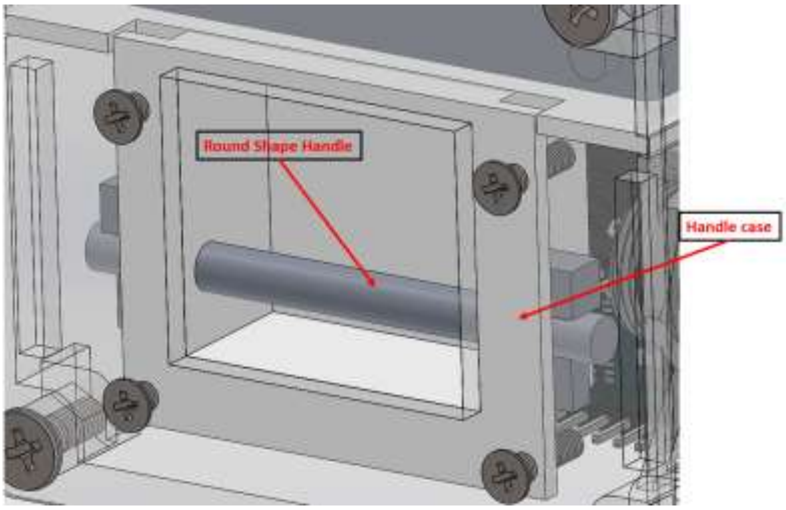

Figure 3.29: The Conception Design of the Round Shape Handle.

3.7.4 External layout of the battery module

The exterior layout of the battery enclosure is designed with two holes for easier testing and calibration during the prototype phase. Because all electronic components are placed within a sealed enclosure, re-encoding would require disassembly, which is time-consuming. Therefore, these openings allow testing and calibration personnel to easily communicate with the microprocessor inside by using physical wires to obtain data. Additionally, there is a button beside the battery enclosure to facilitate testing of the battery hot-swap circuit system. The hole behind the battery enclosure is the location of the battery connector, which is used to connect the charging system and the AMR to provide and receive energy.

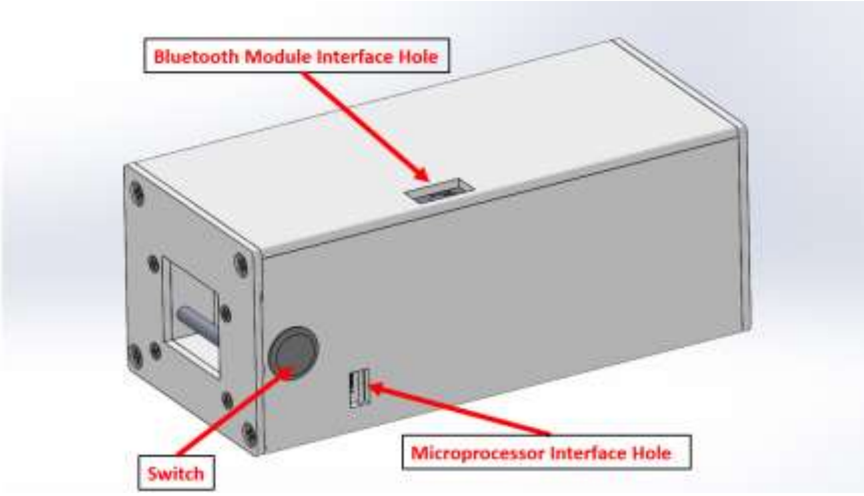

Figure 3.30: The Front External Layout of the Battery Module.

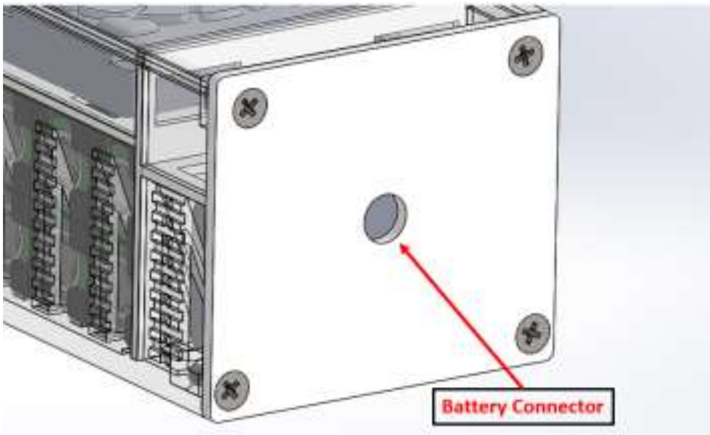

Figure 3.31: The Rear External Layout of the Battery Module.

3.8 Problems encountered and solutions for Lithium-Ion Battery Module

The fabrication of Lithium-Ion battery module presents challenges, particularly when attempting to 3D print the entire housing in one pass. The likelihood of collapse increases significantly due to the size and height of the battery module's casing. Utilizing 3D slicing software reveals that printing the integrated housing of the battery module would be time-consuming as shown in Figure 3.32, as it requires setting support structures at a high level to mitigate the risk of collapse, leading to material wastage. Additionally, the printing process may be susceptible to various external factors, such as power outages, resulting in the scrapping of partially completed prints. These are risks that need to be considered.

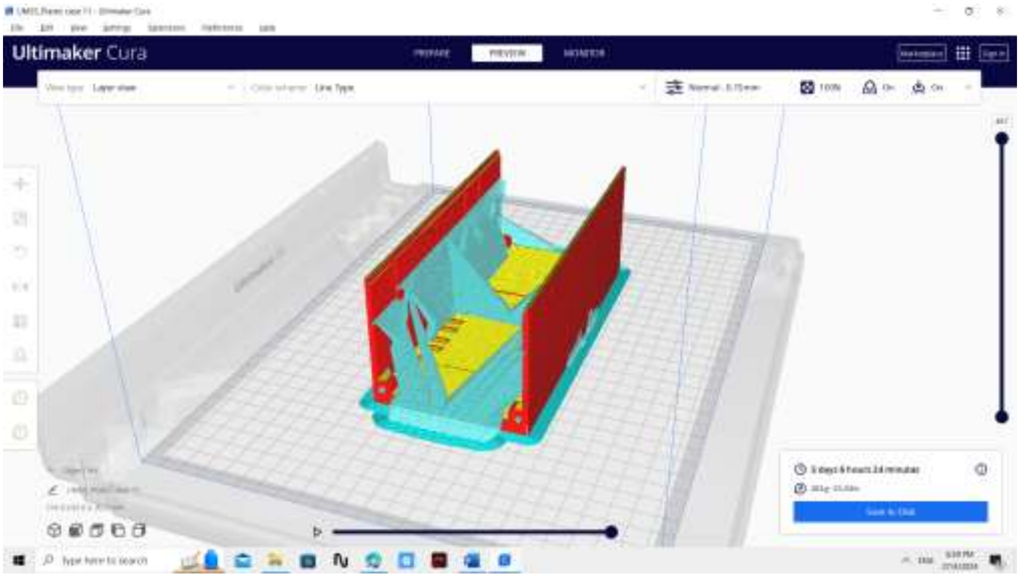

Figure 3.32: The 3D Slicing Software Displays the Entire Housing in One Pass.

The solution to this issue involves splitting the battery module's casing in half for printing, significantly reducing the risks mentioned earlier. The casing is divided into two parts: the battery case left and the battery case right. Each of these halves is designed with seven small holes at their respective connection points. Seven 5cm welding rods are inserted into corresponding holes in either the left or right battery case, and then the other half of the battery case is joined by gently tapping it into place. This method effectively combines the two halves of the battery case without compromising the strength of the integrated print. As shown in Figure 3.33, this approach greatly reduces the printing time.

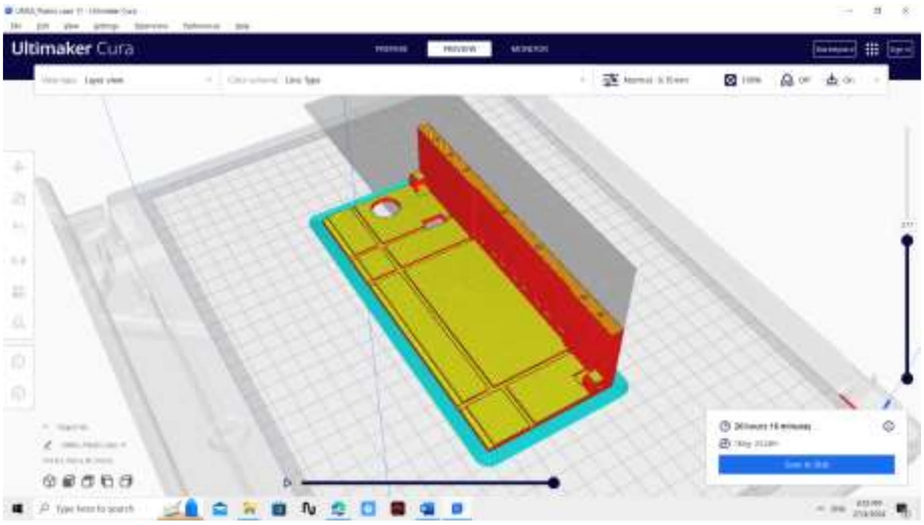

Figure 3.33: The Casing of the Battery Module Is Divided into Two Parts for Printing.

3.9 Hardware and Electronics Components Selection

3.9.1 Mechanical

3.9.1.1 Aluminium Profile

The utilization of aluminium profiles in constructing the primary battery swapping station is driven by several compelling factors. One of the factors is the aluminium profiles possess lightweight yet high-strength properties, making them an ideal choice for crafting various structural elements within the station. Furthermore, these profiles are highly modular, facilitating easy assembly, disassembly, and reconfiguration. This adaptability proves advantageous, allowing for the station's design to flexibly accommodate varying battery sizes and operational requirements. Additionally, aluminium's non-conductive nature is beneficial in applications where electrical components are present, effectively mitigating the risk of electrical interference or hazards within the battery swapping station.

3.9.1.2 Conveyor Belt

PVC (polyvinyl chloride) conveyor belts are utilized to transfer battery packs from (AMR) to charging stations and vice versa because PVC conveyor belts are durable and resilient. It can withstand heavy loads, repeated use and changing environmental conditions. In our application, this ensures that the conveyor belt can reliably transport battery packs over time without wear and tear, while minimizing the risk of bumps or vibrations during transport. This is especially important for delicate battery packs that require gentle handling to prevent any damage or failure.

3.9.1.3 Acrylic

The use of acrylic as a cover for the battery pack at the charging station is a well-considered choice for several crucial reasons. Firstly, acrylic's transparency allows for easy visual inspection of the battery pack, eliminating the need to remove the cover and facilitating real-time monitoring of the battery's condition and positioning during charging. Secondly, it serves as a protective barrier, safeguarding the battery from dust, debris, and potential contaminants that could compromise its performance or safety. Lastly, acrylic's non-conductive nature and excellent electrical insulation properties enhance safety during charging, reducing the risk of electrical interference or short circuits that might occur with conductive materials.

3.9.1.4 3D Printed Parts

The incorporation of 3D printed parts enables the creation of custom-designed parts tailored to precise specifications. This customization ensures that the coupling, dc worm gear motor and sensor brackets precisely fit the unique requirements of the battery swapping station, optimizing their functionality. 3D printing enables the creation of intricate and complex geometries that would pose significant challenges or even be unattainable using conventional manufacturing techniques. This flexibility in design can lead to more efficient and space-saving components. In cases where the production volume of specific components is relatively low, 3D printing can be a cost-effective solution. It eliminates the need for expensive Mold or tooling, making it economically viable for small-batch production.

3.9.2 Electrical

3.9.2.1 Linear Actuator – Electric Cylinders and Sliding Table

The utilization of electric linear actuator cylinders to adjust the angle of the platform. This can ensure that the hook on the platform shares the same angle as the slanted battery in the AMR, thereby simplifying the process of securely transferring the battery onto the platform. The electric linear actuator cylinders offer precise and controlled adjustments to the platform's angle, ensuring that it precisely matches the slant of the battery in the AMR. This precision is critical for achieving a seamless and secure battery transfer process. Also, it can be customized to provide specific ranges of motion to accommodate batteries of various sizes and weights.

On the other than, the incorporation of a sliding table linear actuator to facilitate the movement of the hooks for the purpose of extracting and inserting the battery pack into the charging station, as well as transferring it between the conveyor and the AMR. The Sliding Table Linear Actuators provide precise and controlled linear motion, ensuring the hooks can accurately approach and engage with the battery pack. This precision is essential to prevent any misalignment or damage during the extraction and insertion process. These actuators offer smooth and stable linear movement, which is crucial for delicate battery handling. It minimizes jerky motions and reduces the risk of shocks or vibrations that could harm the battery. It also can be customized to offer a specific stroke length, accommodating various battery pack sizes and ensuring the hooks properly engage them.

3.9.2.2 Motor – Stepper, DC Worm Gear, and Power Window Motors

The application of a stepper motor is to drive the belt to drive the gantry plate. The reason for using the stepper motor is that it is known for its excellent precision and control of position and movement. They operate by moving in distinct, precise steps, which enables to achieve accurate and repeatable positioning of the belt. This precision is vital in ensuring that the battery pack is correctly aligned and securely hooked in place. Their operation in an open-loop control system eliminates the need for feedback sensors to determine their position. This streamlined control system simplifies the overall setup, reduces complexity, and lowers costs. Additionally, Stepper motors possess the unique capability to maintain their position even when not actively in motion. This attribute proves highly advantageous when the gantry plate must remain stationary while other operations are in progress.

On the other hand, the utilization of a DC Worm Gear motor in our application, specifically for the purpose of hooking the battery pack. DC

Worm Gear motors offer precise control over the rotation of the output shaft. This precision is essential when hooking the battery pack to ensure accurate and secure attachment. One of the standout features of worm gear systems is their self-locking property. This means that when the motor is not actively turning, the output shaft remains stationary and does not drive backwards. This is particularly advantageous for maintaining a secure hold on the battery pack, preventing accidental disengagement.

Lastly, the decision to utilize a power window motor for driving the conveyor was driven by several factors aimed at optimizing performance and minimizing costs. Primarily, the choice was influenced by the motor's cost-effectiveness, as power window motors are widely available and affordable due to their mass production for automotive applications. This aligns well with the project's budget constraints, allowing for efficient resource allocation without compromising on quality. Additionally, the motor's availability from various suppliers ensures timely procurement, reducing lead times and streamlining the production process. Despite not being specifically designed for conveyor applications, power window motors offer sufficient torque and rotational capabilities to effectively drive the conveyor, making them a suitable choice for the system's needs. Furthermore, their standardized mounting brackets and electrical connections facilitate easy integration into the conveyor system, simplifying assembly and deployment.

3.9.2.3 Sensor – U shaped photoelectric sensor and limit switch

The incorporation of limit switches and photoelectric sensors is aimed at enhancing functionality, accuracy, and safety. Limit switches are essential for establishing precise starting and stopping points for various mechanical components within the system, ensuring consistent alignment and preventing misalignment issues during battery exchange operations. Also, the switch has a simple structure; it is certainly impeccable in terms of durability. On the other hand, photoelectric sensors play a vital role in detecting the presence, absence, or position of objects within the system. Strategically placed u-shaped photoelectric sensors in the Battery Loading and Unloading Mechanism detect the alignment of the mechanism and conveyor, allowing for precise positioning of components and ensuring smooth and accurate battery exchange processes.

3.9.2.4 Microcontroller

The Arduino Mega was chosen as the system microcontroller for the automatic battery module swapping system due to its robust processing power, extensive input/output (I/O) capabilities, and broad compatibility with existing resources and community support. With its ATmega2560 microcontroller, the Arduino Mega offers sufficient computational capacity to manage the complex tasks involved in controlling various system components and processes. Its ample array of digital and analogy I/O pins enables seamless interfacing with sensors, actuators, and peripheral devices, allowing for flexible system expansion and integration. Additionally, the Arduino platform's widespread popularity and large community provide access to a wealth of libraries, code examples, and tutorials, facilitating rapid development and troubleshooting. Despite its advanced features, the Arduino Mega remains cost-effective, making it an attractive option for projects with budget constraints. Furthermore, its user-friendly development environment, featuring a simple IDE and programming language, ensures ease of use and facilitates efficient prototyping and testing of the system design.

3.9.2.5 DC Breaker – 12V Overcharge automatic circuit breaker for Car Audio Marine

The selection of a 12V Overcharge automatic circuit breaker was made based on its specific suitability for the project's requirements. Designed to handle 12V DC voltage levels commonly found in automotive, this type of circuit breaker ensures optimal compatibility and performance within the system. Its current rating is likely chosen to match the expected load and operational demands of the system, providing effective protection against overcurrent conditions without being undersized. Additionally, features such as weatherproof construction and home reset capabilities make it well-suited for outdoor or automotive installations, allowing for easy resetting after a trip.

3.9.2.6 Buck converter – DC Step Down LM2596 (Adjustable) 2596 Display Buck Converter

The incorporation of a DC Step Down LM2596 (Adjustable) 2596 Display Buck Converter to reduce the voltage from 12V to 5V Designed specifically for DC voltage conversion, the LM2596 Buck Converter offers precise adjustment capabilities, allowing for accurate tuning to the required 5V output voltage level. Its compact size and integration-friendly design make it a practical choice for space-constrained environments, facilitating easy incorporation into the system's electronics. The converter's adjustability provides flexibility to accommodate variations in input voltage levels and load conditions, ensuring stability and reliability across diverse operating scenarios. Also, the Display can know the voltage changes at any time. For example, it can be easily observed when encountering a short circuit.

3.9.2.7 Motor Driver – L298N (Low Current) and QF-M05S (High Current)

The adoption of the L298N motor driver for managing three 12V DC motors. Its capacity for simultaneous control of multiple motors enables synchronized movement crucial for the smooth operation. Moreover, the motor driver's ability to govern both direction and speed grants precise control over motorized mechanisms, facilitating accurate and efficient swapping processes. Equipped with built-in protective features like overcurrent and thermal protection, the L298N shields both motors and the driver from potential damage, enhancing overall system reliability and durability. Additionally, its straightforward integration into the system's electronics, coupled with its compatibility with standard microcontrollers and logic signals, simplifies the design and implementation process.

On the other than, the QF-M05S motor driver offers handling high-current motors in driver the power window motor. With a compact size of 7x4x3cm, it suitable for use with 12V input voltage. Available in options with continuous output currents of 30A or 40A, this motor driver ensures reliable performance even under heavy loads. Its single-phase design and compatibility with DC motors featuring two wires make it versatile for various applications. With a maximum applicable motor capacity of 400W, the QF-M05S motor driver offers ample power for driving motorized components in the swapping system. Additionally, the motor driver's compatibility with standard microcontrollers and logic signals simplifies integration into the system's electronics, facilitating seamless control by just using a relay to control the motor direction.

3.10 Software Selection

3.10.1 Arduino IDE

The Arduino Integrated Development Environment (IDE) software will be serving as the core platform for programming and controlling various components. Arduino IDE is renowned for its user-friendly interface and robust capabilities, making it an ideal choice for implementing and managing the project's electronic and control systems. Its flexibility, community support, and real-time capabilities position it as an essential tool in the development of the Automatic Battery Module Swap System for AMRs.

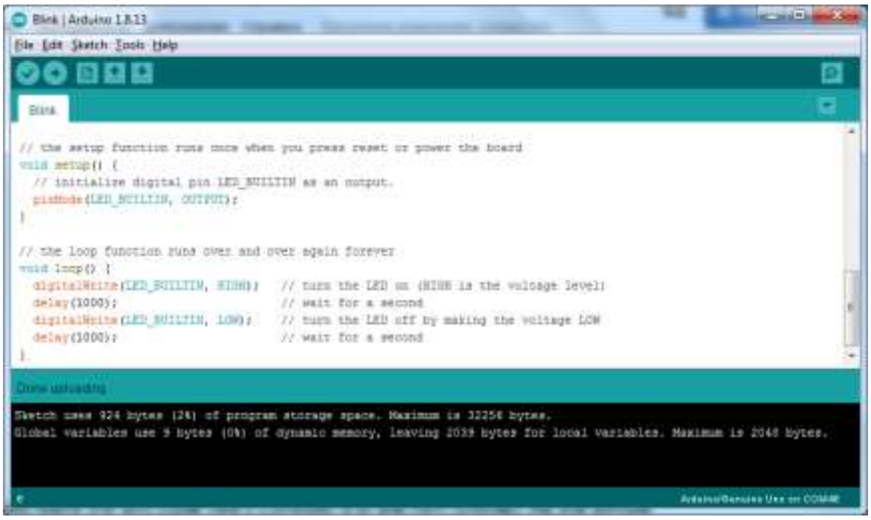

Figure 3.34: Arduino Code Examples.

3.10.2 Programmable Logic Controller

Other software that can be chosen in this project is Programmable Logic Controller (PLC) software, which is a key aspect of automation system control and management. PLCs are specialized digital computers designed to control a variety of electromechanical processes and machinery, making them ideal for overseeing the complex operations of AMR battery swap stations. The flexibility of PLC programming will enable fine-tuning and customization of the system. to meet specific requirements and adapt the behaviour of different battery sizes and types.

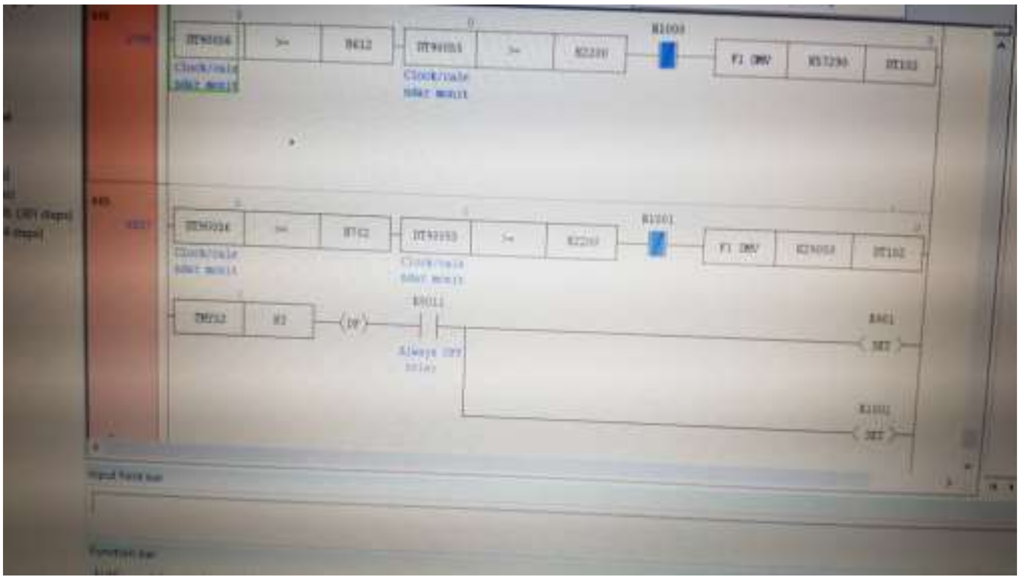

Figure 3.35: PLC Ladder Diagram Examples.

3.11 Sequence of Flow

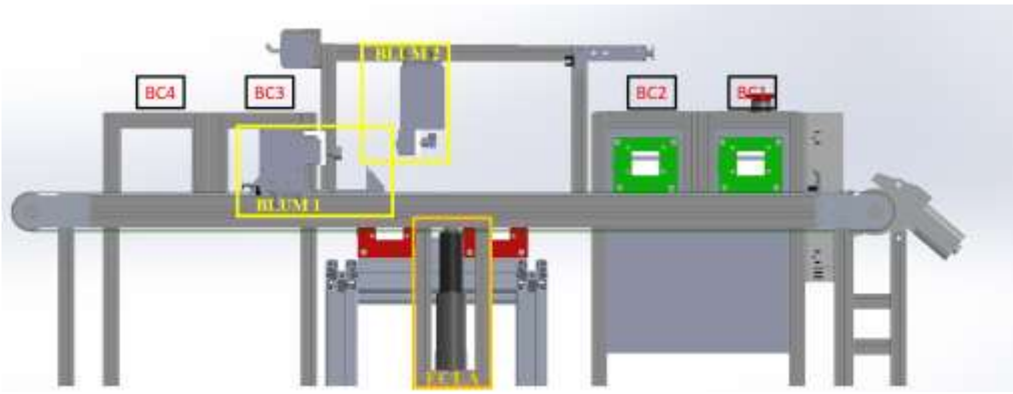

Figure 3.36: The System with Position Labelled.

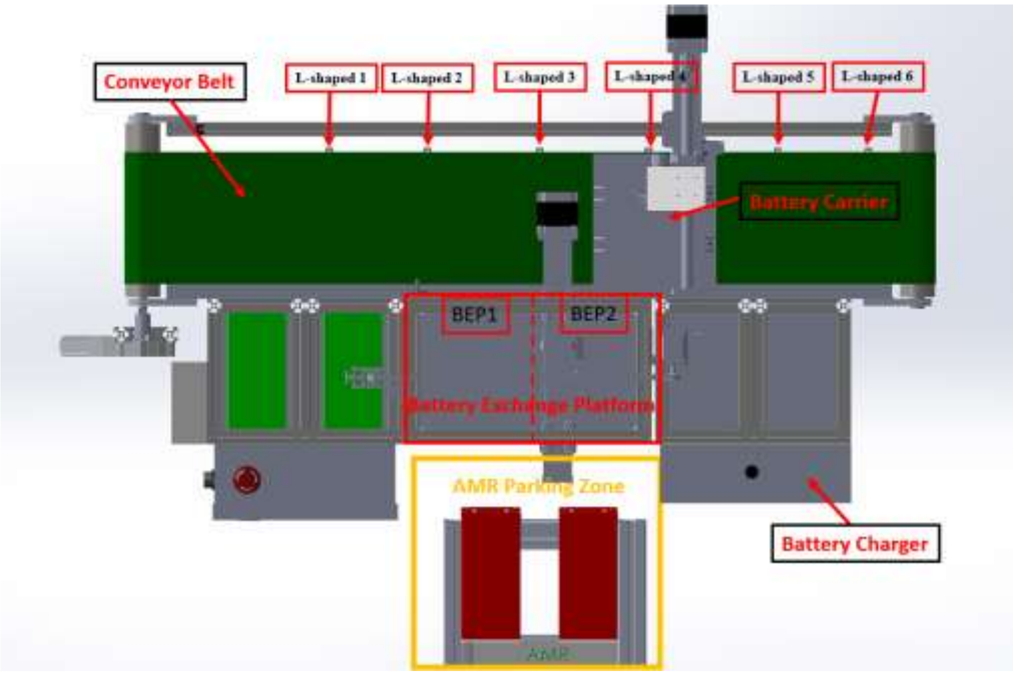

Figure 3.37: The System with Position Labelled 2.

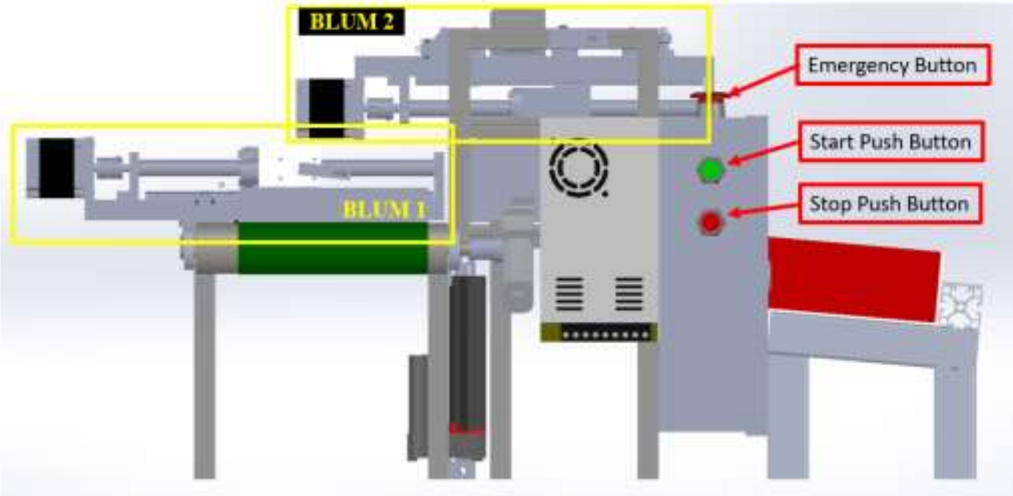

Figure 3.38: The System with Position Labelled 3.

Initially, there will be fully charged batteries in the battery compartments of Battery Compartment 1 (BC1) and BC2, and the AMR will park in front of the Battery Exchange Platform (BEP) and wait for battery replacement. When the user presses the start push button, each mechanism, such as Battery Loading and Unloading Mechanism 1 (BLUM 1), BLUM 2, and the battery exchange platform, will return to their respective home positions. When these mechanisms return to their respective home positions, they will each be detected by their respective sensors, which will then send signals to the master microcontroller.

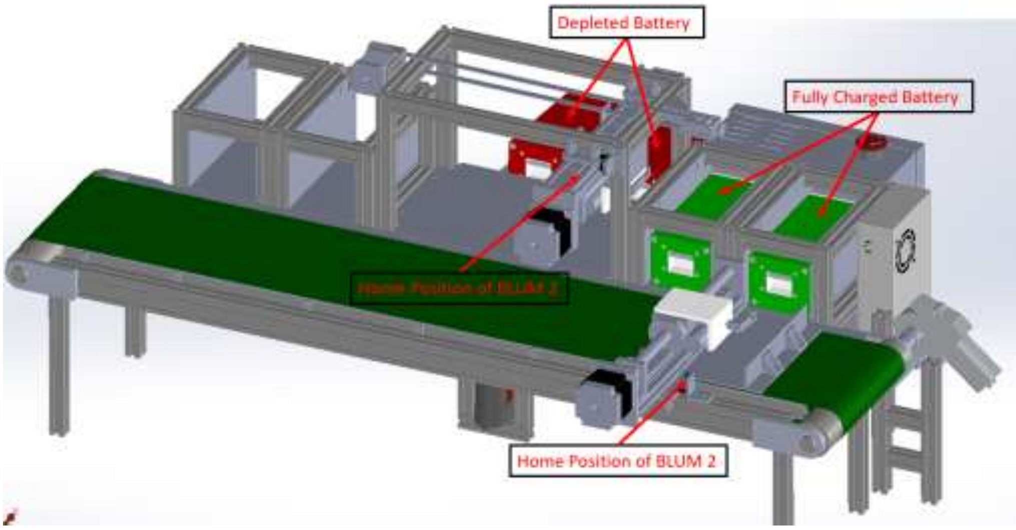

Figure 3.39: The Initial Configuration of the System.

Next, the entire process begins with the battery exchange platform's platform tilting and aligning with the batteries inside the AMR, achieved by employing an Electric Cylinder Linear Actuator (ECLA) positioned below. Subsequently, BLUM2 moves to the position of BEP1, aligning with the first battery in the AMR through lateral movement using a belt drive. Then, the stepper motor in BLUM2 rotates, moving the sliding table forward with the DC worm gear motor with hook until it reaches the depleted battery of the AMR. Afterwards, the DC worm gear motor rotates 90 degrees, and the hook attached to it latches onto the handle of the depleted battery in the AMR.

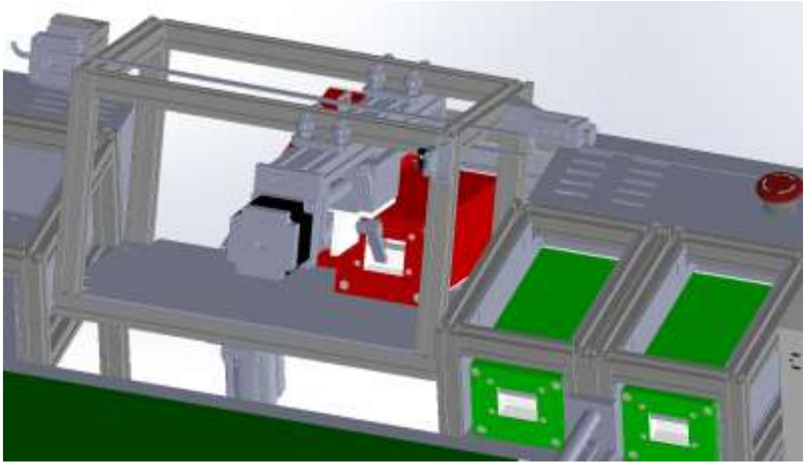

Figure 3.40: The Battery Exchange Platform Aligns with the AMR and Latches the Handle of the Depleted Battery Pack.

After latching, the stepper motor of BLUM2 rotates in the opposite direction, moving the sliding table backward while carrying the depleted battery to the exchange platform, until the limit switch on BLUM2 is triggered by the sliding table. Meanwhile, the ECLA below will start to descend so that the battery exchange platform and the belt conveyor are at the same level. Then, the hook of the DC worm gear motor will rotate back 90 degrees to disengage the handle of the depleted battery, and then BLUM2 will move to BEP 2. At the same time, BLUM1 moves from the starting point to the position of BEP1 of the exchange platform to wait for the arrival of the battery.

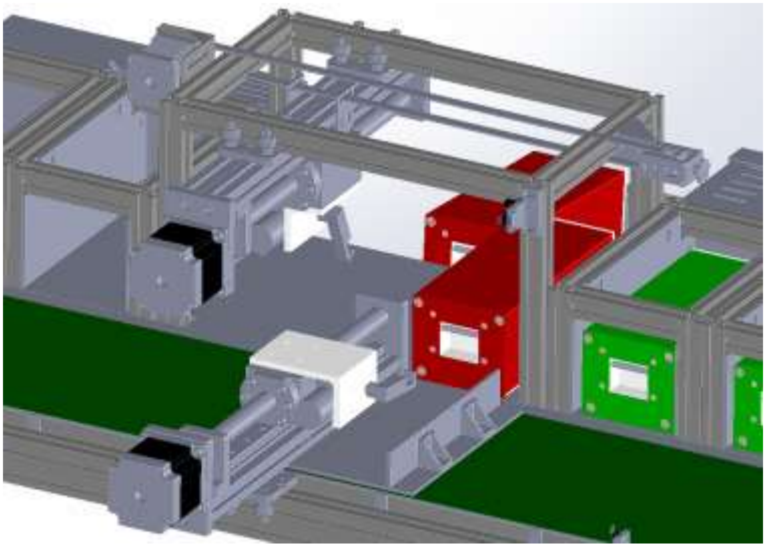

Figure 3.41: The Sliding Table of BLUM 1 Is Moving Towards the Depleted Battery.

When the depleted battery reaches BEP1, the stepper motor of the BLUM1 rotates and moves its sliding table forward with the DC worm gear motor and hook until it reaches the depleted battery in BEP1. Afterwards, the DC worm gear motor rotates 90 degrees, and the hook attached to it latches onto the handle of the depleted battery. Once latched, the stepper motor of BLUM1 rotates in the opposite direction, moving the sliding table backward while dragging the depleted battery to the battery carrier.

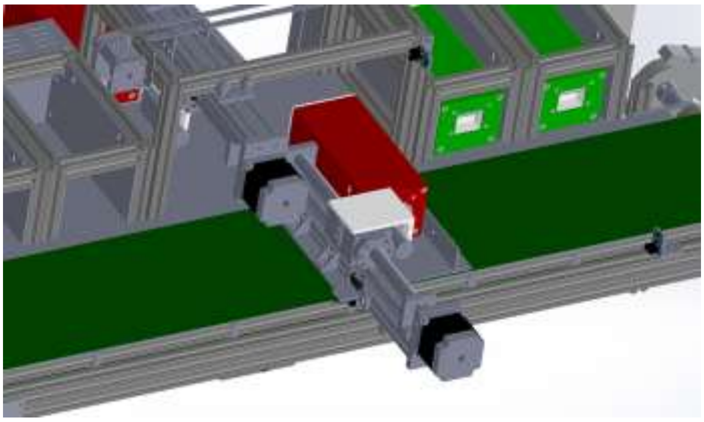

Figure 3.42: The BLUM 1 Is Dragging the Depleted Battery into the Battery Carrier.

After that, the conveyor brings BLUM1 with the depleted battery to the left, sending the depleted battery into BC3 for charging. When BLUM1 and the depleted battery reach BC3, BLUM1 will use the same method as before: the stepper motor of BLUM1 rotates and moves its sliding table forward with the DC worm gear motor to push the depleted battery into BC3. Next, the conveyor brings BLUM1 to BC1, where BLUM1 retrieves the fully charged battery and places it onto the battery carrier.

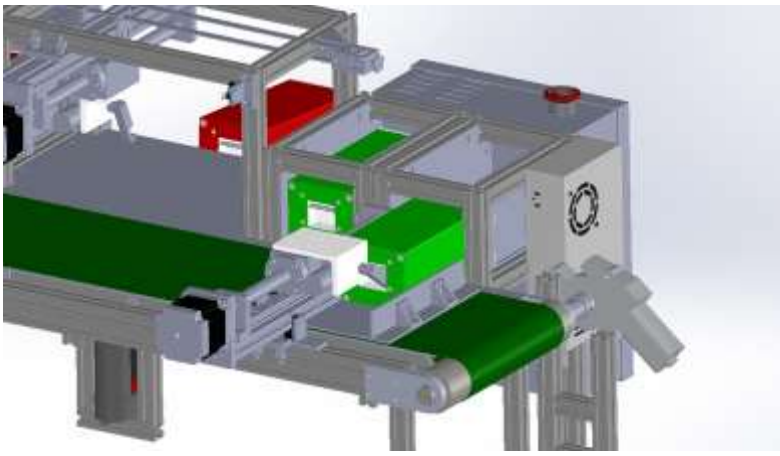

Figure 3.43: The BLUM 1 Is Dragging the Fully charged Battery from the BC1.

Then, the conveyor moves to the left while carrying BLUM1 and the fully charged battery. The fully charged battery is transported to BEP1. Subsequently, BLUM1 sends the fully charged battery into BEP1. Upon arrival inside BEP1, BLUM2 moves back from BEP2 to BEP1, and the hook of BLUM2 latches onto the handle of the fully charged battery. Working in conjunction with the ECLA below, BLUM2 sends the fully charged battery back into the AMR.

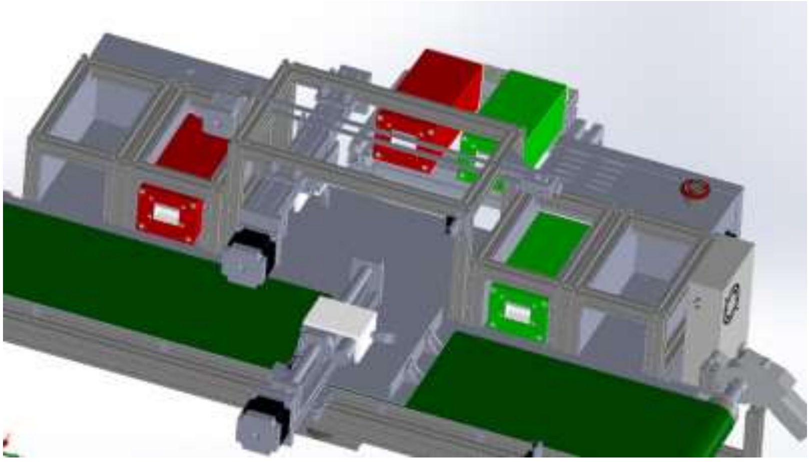

Figure 3.44: The Battery for the AMR Has Been Successfully Replaced.

3.12 Programming

The programming methodology adopted here leans towards a hardcoded structure, which means that specific actions and sequences are predefined within the code. However, this doesn't imply a rigid system; instead, the program dynamically adjusts its behaviour based on real-time sensor inputs.

For instance, it continuously monitors signals from limit switches and photoelectric sensors to precisely track the positions of critical components like the battery exchange platform. Upon detecting certain conditions or events, such as reaching a designated position or encountering an obstacle, the program initiates predefined actions to ensure the smooth operation of the system. These actions may include moving components to their designated home positions, activating motors, or triggering other mechanisms as needed. This blend of hardcoded logic and sensor-driven adaptability allows for precise control and reliable performance in various operational scenarios. The source code will be presented in the appendix for further reference.

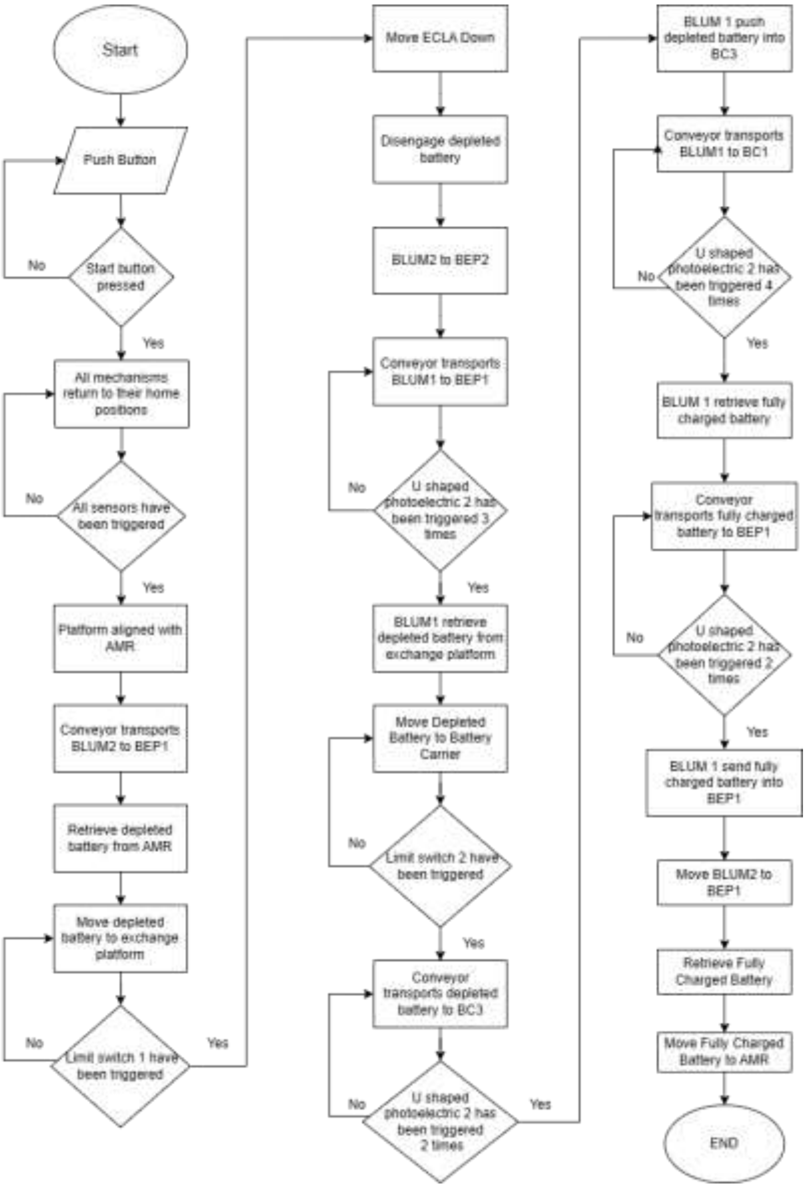

Figure 3.45: The Process Flow of the System.

3.13 Test and Validation of System

3.13.1 Automatic Battery Swapping Station

Testing and validation procedures for the battery swapping station are crucial to ensure the system's functionality, efficiency, reliability, and resilience to environmental conditions. To commence, functional testing encompasses the comprehensive examination of the entire system, including the conveyor system, platform adjustment, and battery loading/unloading mechanisms. Detailed test cases are developed to evaluate the battery swapping process thoroughly, and these tests verify that each component and mechanism executes its designated tasks accurately. Any discrepancies or malfunctions observed during these tests are carefully recorded.

Load testing focuses on assessing the battery swapping station's capacity and its ability to handle specific battery sizes, weights, and quantities. Various load scenarios are simulated to examine the station's performance under different load conditions, and special attention is paid to signs of strain or unusual behaviours during these tests. The station's maximum capacity is also evaluated to ensure it can safely manage the highest anticipated loads without compromising safety or efficiency.

Efficiency testing calculates the time required for the battery swapping station to complete a full battery swap cycle and compares it to the time saved compared to manual battery replacement. Benchmarks for efficiency are established, and tests are conducted to assess whether the station meets predefined efficiency objectives. This testing phase helps identify opportunities for optimizing the station's performance.

Reliability testing involves subjecting the battery swapping station to real-world operating conditions for extended periods. Components are observed for any signs of wear, overheating, or other issues that could compromise their reliability. All observed incidents or anomalies are documented to evaluate the overall reliability of the station and pinpoint areas requiring improvements or modifications.

3.13.2 Lithium-Ion Battery Module Enclosure

Following the development of the prototype, comprehensive testing and validation procedures were executed to ensure the functionality, reliability, and safety of the system. The methodologies employed and the outcomes observed during the testing phase are elaborated below.

The structural integrity of the battery enclosure design was assessed through physical testing and analysis. Various stress tests were conducted to evaluate the enclosure's ability to withstand mechanical forces and impact testing and compare it with the FEA result. The prototype enclosure was subjected to controlled impact tests to simulate real-world scenarios such as accidental drops or collisions. Visual inspections and measurements were conducted to assess any structural damage or deformation.

Functional testing was carried out to validate the performance and functionality of the system components. Each subsystem, including the battery module, communication module, was tested individually and in conjunction with the overall system.

Battery Module Testing: The battery module underwent charging, discharging, and capacity testing to validate its energy storage capabilities and operational efficiency. Performance metrics such as charge/discharge rates, voltage stability, and energy capacity were measured and analysed.

Handle Mechanism Testing: The concealed handle mechanism was subjected to repeated opening and closing cycles to assess its durability and reliability. Also, the battery enclosure handle needs to match the battery swapping station's hook.

3.14 Equipment Needed for Fabrication

The equipment needed for fabrication includes:

- **3D printer** which is used to turn the complex and customized designs into three dimensional objects such as bearing housing, linear actuator bracket and etc.
- **Laser machine** which is used to precisely cut and perforate the acrylic plate.
- **Metal cutting machine** which is used for cutting aluminium profile.

- **Drilling machine** which is used for drilling aluminium profiles and sheet metal.
- **Bending machine** which is used to bend metal sheets to achieve the desired angle.
- **Milling machine** which offers a precise means of machining aluminium profiles, achieving precise dimensions, and high-quality surface finishes.

3.15 Summary

Methodology and work plan section of this project outlines a comprehensive approach for developing the automatic battery module swap system and battery enclosure. It begins with careful planning, involving stakeholders and setting clear objectives, with milestones spanning two semesters to track progress. The core mechanical components undergo precise design, and hardware choices are explained with a bill of material for cost estimation. Software selection, particularly the Arduino or PLC software, is discussed for system control. A flowchart guides system operation, while rigorous testing ensures functionality, efficiency, and reliability, meeting predefined benchmarks. A list of necessary equipment streamlines procurement. Overall, this section presents a systematic approach to creating an efficient battery-swapping solution for AMRs.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The primary objective of this chapter is to provide a detailed examination and analysis of the results obtained from the implementation and testing of the Automatic Battery Module Swapping Station and Lithium-Ion Battery Module. This chapter discusses the hardware and electrical aspects of the system, outlining the fabrication processes, assembly procedures, and problem-solving approaches undertaken during the project. The subsequent sections delve into the testing phases, evaluating the performance of individual subsystems, semi-integrated components, and the unified system. The findings presented herein offer insights into the system's functionality, effectiveness, and compliance with the predetermined objectives outlined in the study.

4.2 Fabrication Process

4.2.1 Automatic Battery Module Swapping Station

4.2.1.1 Hardware fabrication

The initial step involved constructing the framework structure. Following the dimensions specified in the design, aluminium profiles were utilized to build the main frame, exchange platform, and battery compartment. The pre-purchased aluminium profiles were first cut to specific sizes using a vertical band saw machine. Subsequently, the cut aluminium profiles underwent a milling process to refine their dimensions further, ensuring precision in the construction process.

Next, the acrylic plates were precisely cut to the specified dimensions using a laser machine. These acrylic plates served various purposes within the system, including forming the base of the exchange platform, the base of the battery compartments, and the side panels for both the left and right sides. Additionally, they were utilized for the base of the conveyor. These components, being composed of aluminium profiles, necessitated the creation of cut-outs or voids within the acrylic plates to accommodate the structural elements and ensure proper alignment and assembly.

Figure 4.1: The Laser Machine Is Cutting the Acrylic Plate.

The next manufacturing process involved utilizing a 3D printer to build each component according to the instructions provided in the STL files. Depending on the complexity and size of each part, the printing process varied in duration. In addition to the components mentioned earlier, the sensor brackets, DC worm gear motor brackets, couplings, and hooks for this project were also manufactured using 3D printing technology. These brackets and fittings, utilizing 3D printing, allowed for the creation of custom-designed brackets and fittings tailored to the specific requirements of the project. Once printing was complete, each component was carefully removed from the build platform of the printer. Any support structures or excess material introduced during the printing process were removed, and the parts were inspected for any defects or imperfections.

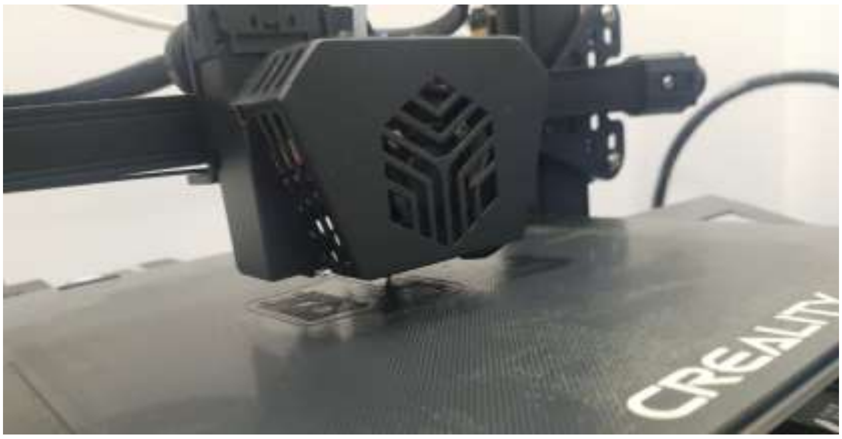

Figure 4.2: The 3D Printer Is Printing the Sensor Bracket.

4.2.1.2 Components Assembly

Entering the assembly phase, it was divided into three main parts: the battery compartment, the exchange platform, and the conveyor system. The first step involved constructing four battery compartments using pre-cut aluminium profiles and acrylic plates. These compartments were assembled using gussets, T-slots, and M5 bolts. The dimensions of the assembled battery compartments were L x 200mm, W x 13.5mm, H x 12.5mm. After completing the assembly of the battery compartments, the assembly of the exchange platform and conveyor followed. They were connected using the same method as the battery compartments, utilizing gussets, T-slots, and M5 bolts.

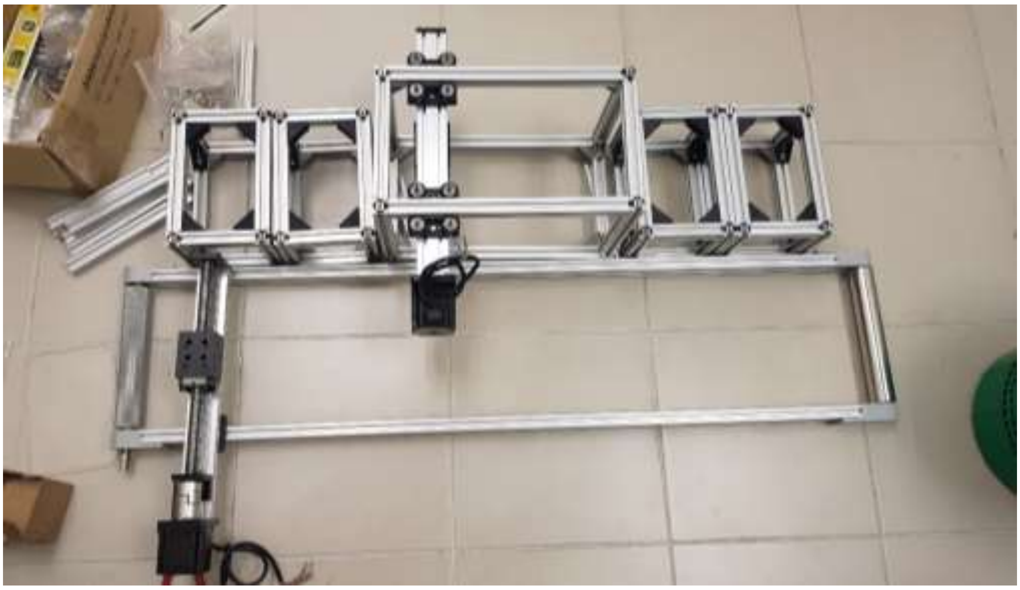

Figure 4.3: The Main Structure Is Constructed Using Aluminium Profiles.

Once the main structure was fully assembled, the focus shifted to installing various components. These components included critical elements such as the conveyor belt for transporting batteries, the exchange platform responsible for levelling the battery loading and unloading mechanism with the battery module in the AMR, the gantry plate providing support and stability for other mechanisms, the battery loading and unloading mechanism responsible for handling battery exchange operations, as well as the motors and sensors essential for system functionality. The Figure 4.4 also illustrated the installation of the belt drive system above the exchange platform, encompassing components such as the tensioner, gantry plate, stepper motor, and battery loading and unloading mechanism, along with the conveyor belt and battery loading and unloading mechanism at the rear.

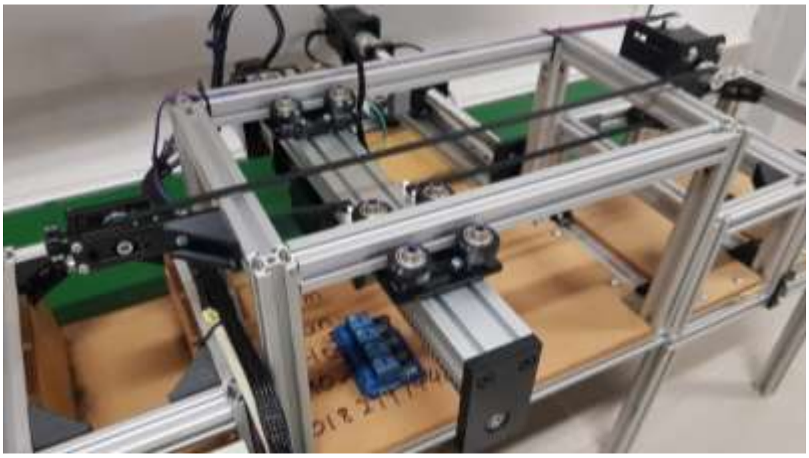

Figure 4.4: The Belt Drive System Is Installed on Top of the Exchange Platform.

Before installation, electronic components underwent thorough testing to ensure their functionality and compatibility with the system. Detailed explanations of these testing procedures were provided in the subsequent Chapter 4.2.1.3.

During the installation process, each component was carefully positioned and secured onto the main structure according to the system's design specifications. This meticulous process ensured proper alignment and functionality of the entire system. Some components, particularly those requiring precise positioning or specific attachment points, were affixed using brackets that had been previously fabricated using 3D printing technology. These brackets provided secure mounting solutions and ensured the components were properly integrated into the overall system architecture.

For instance, the electric cylinder linear actuator installed beneath the exchange platform was secured to the main structure using 3D-printed brackets. Additionally, to achieve the desired angle of the exchange platform, a customized design was employed at the connection point between the electric cylinder linear actuator and the platform. This customized design was implemented using 3D-printed brackets, ensuring the platform was positioned at the required angle while also capable of withstanding a certain amount of pressure as show in Figure 4.5.

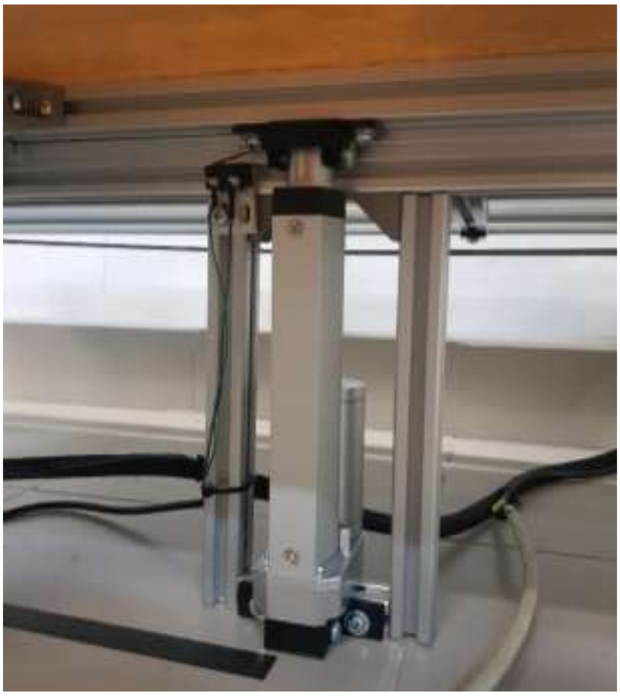

Figure 4.5: The 3D-Printed Brackets Are Mounted on the Electric Cylinder Linear Actuator.

4.2.1.3 Electrical Wiring

Transitioning to the electrical phase, the first step entails extending all the wires of the electronic components to ensure they reach the control box. This involves soldering the wires to achieve the required length. After soldering, heat shrink tubing is applied to insulate the connections, protecting them from external factors. Additionally, the wires outside the control box are encased in PET expandable braided wire, offering robust protection against cuts and abrasions. These measures are crucial for ensuring the safety and integrity of the electrical connections.

The next step involved arranging all the electronic components of the control system inside the control box. This arrangement required careful consideration of wire routing and heat dissipation, among other factors. Once arranged, the positions of the fixed electronic components were marked on the control box for drilling holes. After drilling, PCB stands were used to secure the electronic components inside and elevate them above the surface, creating space for other components. Subsequently, the intricate wiring process began. Finally, the last step was to connect the power supply. The Figure 4.7 shows the completed wiring in the control box.

Figure 4.6: The Electronic Components of the Control System Are Arranged Inside the Control Box.

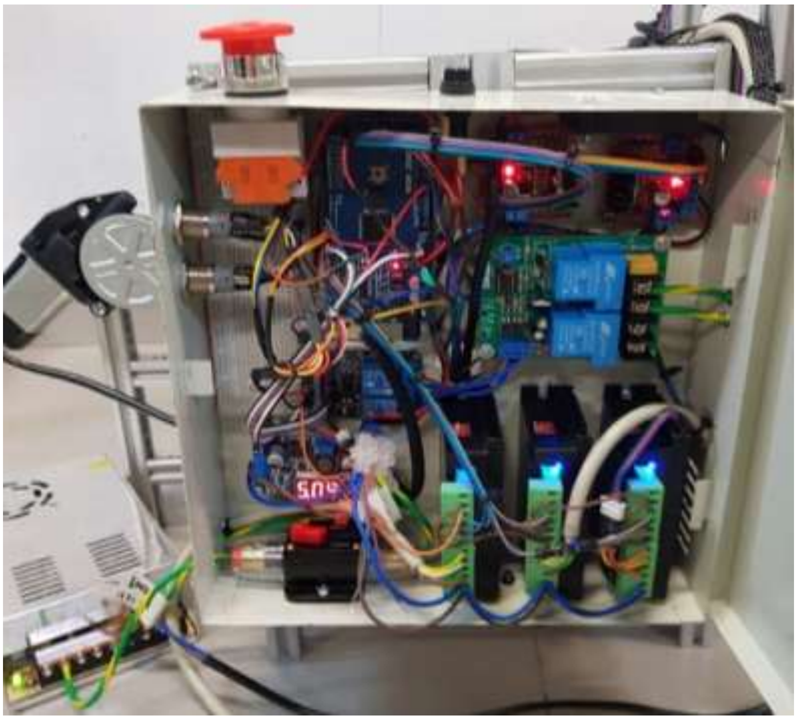

Figure 4.7: All Electronic Components and Wiring in the Control Box Have Been Completed.

The following Figure 4.8 displays the entire automated battery swapping station in its entirety.

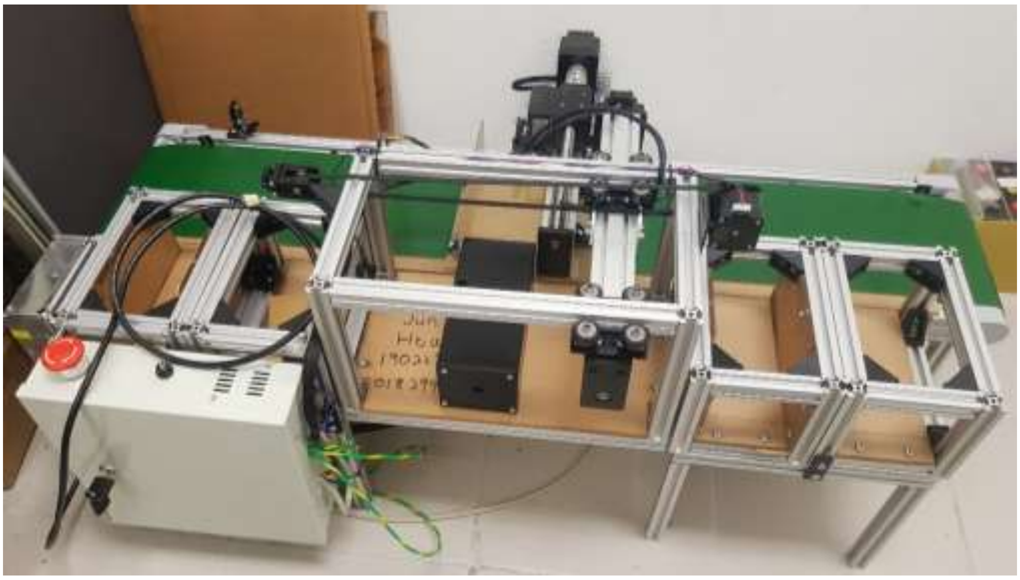

Figure 4.8: The Battery Module Automatic Exchange Station Prototype Has Been Assembled.

4.2.2 Solution Implemented in Prototype

The first worth noting that the issue of uneven force distribution in the sliding table linear actuator has been successfully resolved. Chapter 3.4 of the documentation provides detailed insights into the problem and outlines the proposed solution. Indeed, the installation of the sliding table linear actuator in a horizontal position, as depicted in Figure 4.9, has proven effective in resolving the issue. This orientation allows for a more balanced distribution of forces along the length of the sliding table, mitigating the uneven force distribution that was previously observed. By laying the actuator flat, gravitational forces act uniformly across its structure, reducing the risk of mechanical strain or distortion. The results of these tests confirmed that the solution successfully addressed the issue of uneven force distribution in the sliding table linear actuator.

Figure 4.9: The Actuator Is Placed Horizontally on the Gantry Plate.

The second noteworthy aspect pertains to a challenge highlighted in Chapter 3.4 also regarding the possibility of misalignment during the loading and unloading of battery modules. This misalignment could cause the modules to get stuck and fail to enter the battery compartment smoothly. To tackle this issue, a solution was proposed in Chapter 3.4 and subsequently implemented in practice. This solution, depicted in Figure 4.10, has substantially mitigated the problem. By integrating adjustments and enhancements into the system's design and mechanisms, the alignment precision during the loading and unloading processes has been greatly improved. Consequently, the risk of modules becoming obstructed or misaligned has been significantly reduced, contributing to smoother and more reliable operation overall.

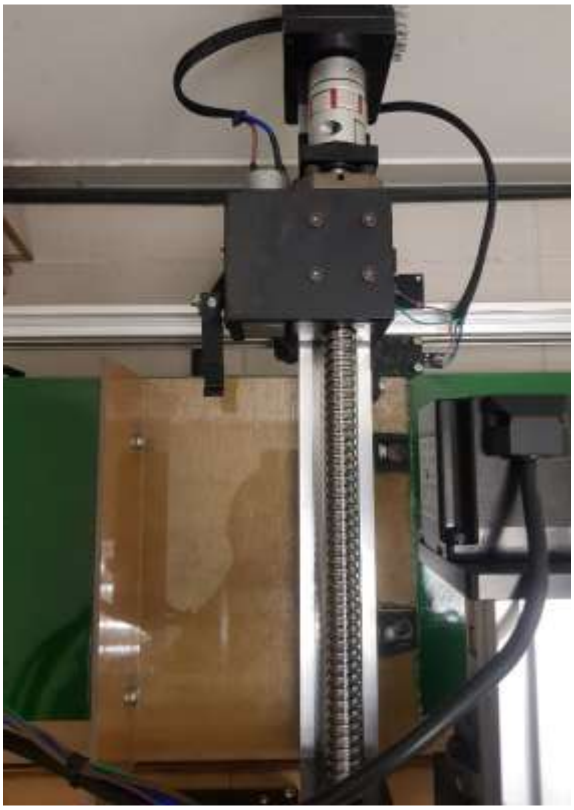

Figure 4.10: The Battery Carrier Is Positioned Beneath the Actuator.

During the implementation of the above problems and solutions, rigorous testing and validation procedures were carried out to verify its effectiveness. Real-world testing scenarios were simulated and were carefully monitored to assess the system's behaviour under various conditions. The mechanism now operates with improved stability and reliability, enhancing the overall functionality of the battery module swapping system.

4.2.3 Lithium-Ion Battery Module

4.2.3.1 Hardware fabrication

The entire lithium-ion battery module prototype was comprised of 11 3D-printed parts. These parts included the voltage regulator plate, relay plate, left battery case, right battery case, top lid, controller plate, front cover, back cover, BMS plate, handle case, and balancer plate. All of these components were designed using 3D CAD drawing software, specifically SolidWorks. Once the designs were finalized, they were converted into STL format.

The fabrication process began with the STL files being transferred to a 3D printer. The 3D printer utilized additive manufacturing techniques to build each component following the instructions provided by the STL files. Depending on the complexity and size of each part, the printing process took varying amounts of time. After the printing was complete, the individual components were carefully removed from the printer's build platform. Any support structures or excess material introduced during the printing process were removed, and the parts were inspected for any defects or imperfections.

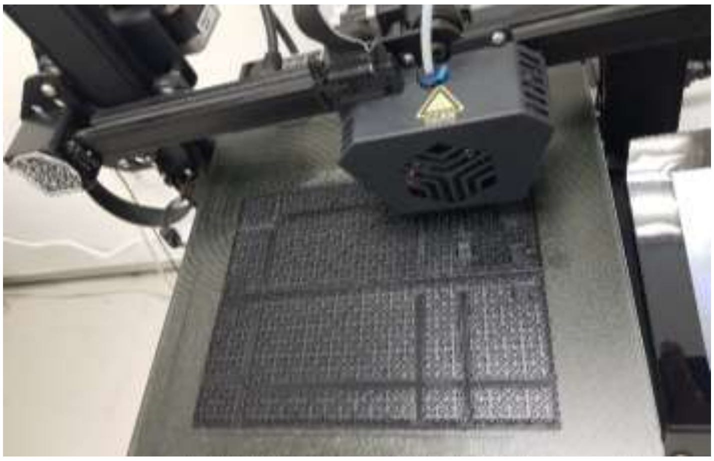

Figure 4.11: The 3D Printer Is Printing the Left and Right Battery Cases.

Figure 4.12: All the 3D parts have been successfully printed.

4.2.3.2 Components Assembly

Before printing the battery case, a challenge was encountered due to the size limitations of the 3D printer, which prevented the entire battery case from being printed in one piece, as explained in Chapter 3.8. To address this issue, the solution proposed in Chapter 3.8 was implemented. This involved printing the left and right battery cases separately. Subsequently, seven 5cm welding rods were inserted into corresponding holes in either the left or right battery case. Then, the other half of the battery case was joined by gently tapping it into place. This method effectively combined the two halves of the battery case.

This solution proved to be effective and was validated through strength and pressure testing, as detailed in Chapter 4.3.2.1. The strength and pressure testing of the battery case are explained in detail in Chapter 4.3.2.1of the report.

Figure 4.13: The Left and Right Battery Cases Have Been Combined Using Welding Rods.

After combining the left and right battery cases and ensuring their alignment, the next step involved placing M4 nuts into the four corners of the assembled battery case and the four corners of the top lid. These nuts served as anchor points for fastening the battery case and top lid together. Using strong adhesive, the M4 nuts were securely affixed to their respective corners of the battery case and top lid.

This process ensured that the battery case and top lid could be firmly attached to each other, providing structural integrity to the overall battery module. It also facilitated easy assembly and disassembly of the battery module during maintenance or component replacement.

Figure 4.14: The M4 Nuts Are Fixed at The Corners of The Assembled Battery Case Using Strong Adhesive.

Next, a 7cm M4 screw was inserted through the pre-drilled hole in the handle case to serve as the handle, and M4 nuts were used to secure it in place. Then, the assembled handle case was attached to the front cover using four M3 screws and nuts, as depicted in Figure 4.15.

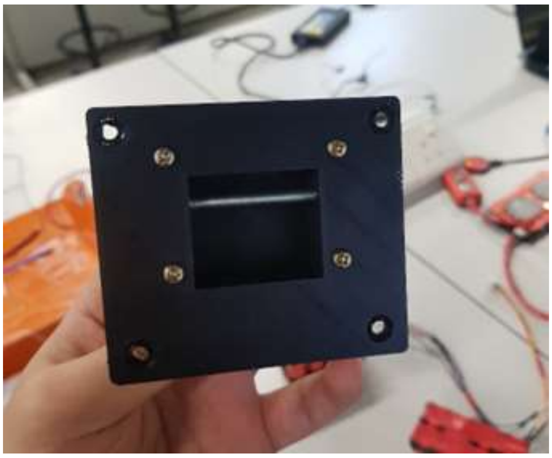

Figure 4.15: The Handle Case is Secured to The Front Cover.

4.2.3.3 Electrical Wiring

Following the assembly of the battery case components, the integration of electronic elements commenced. This phase requires meticulous planning to ensure optimal placement and routing of wiring within the confined space of the battery case.

Each electronic component was carefully positioned according to a predefined sequence, taking into account factors such as accessibility and thermal management. The sequence of component installation was optimized to facilitate ease of access for future maintenance or troubleshooting. Components that required frequent inspection or adjustment were strategically placed for convenient accessibility without compromising the overall integrity of the system.

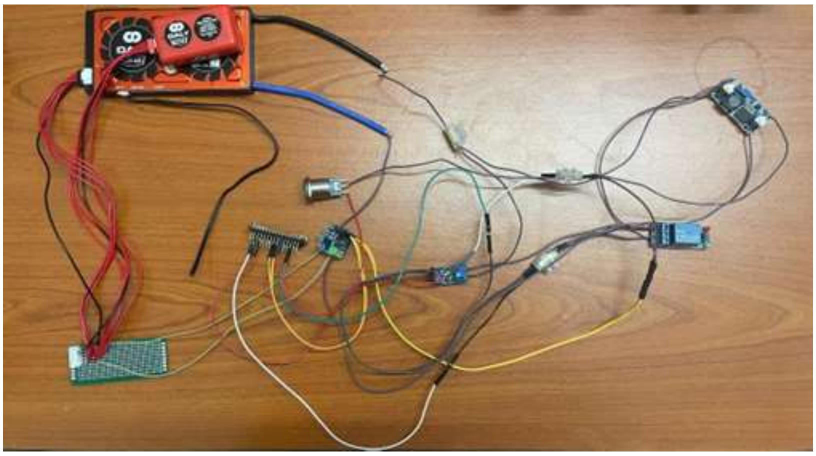

Figure 4.16: The Entire Battery Circuit.

Figure 4.17: The Entire Battery Circuit Is Installed Inside the Battery Enclosure.

Finally, the top lid was placed over the assembled battery case, and the back cover and front cover were attached. Using eight M4 10mm screws, the top lid and battery case were secured together by fastening them to the nuts previously fixed in the four corners. With this step, the assembly of the entire Lithium-Ion Battery Module was completed as shown in Figure 4.18.

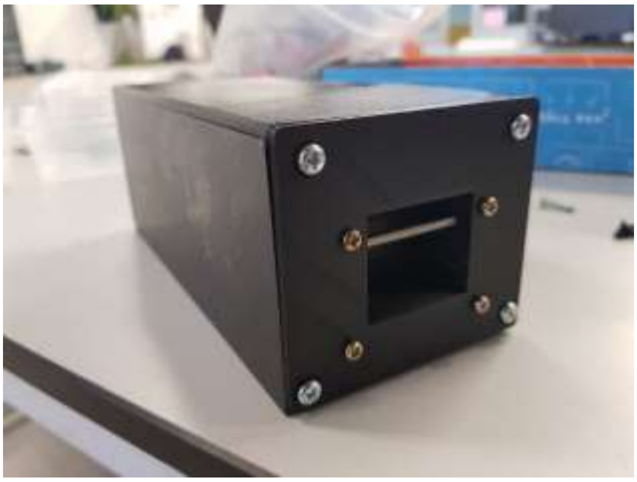

Figure 4.18: The Battery Module Has Been Assembled.

4.3 Result

4.3.1 Battery Swapping Station

The testing of the Battery Swapping Station will be divided into three main parts. The first part involves individual system testing, which includes three main systems: the Bi-directional Belt Conveyor, the Exchange Platform with Battery Loading and Unloading Mechanism, and the Battery Storage. In this phase of testing, each of the three main systems will undergo specific functionality tests to assess whether they meet all the objectives of this study.

The second part is semi-integrated testing, where two systems are combined to conduct tests. For example, compatibility tests between the Battery Loading and Unloading Mechanism and the Battery Storage will be performed in this phase.

The third part involves integrating all the systems into a complete system. This comprehensive testing phase assesses the overall functionality and performance of the Battery Swapping Station as a unified system.

4.3.1.1 Individual System Testing

Bi-directional Belt Conveyor

After constructing the prototype, the next step is to conduct testing to achieve the project objectives. The first test involves the load-bearing test of the Bidirectional Belt Conveyor. The test employs two Valve Regulated Lead-Acid batteries, each weighing 10kg, as shown in Figure 4.19. The batteries are placed on the Bidirectional Belt Conveyor, separated by a distance, to ensure comprehensive coverage of the weight testing across different sections of the conveyor as shown in Figure 4.20 and ensure fairness in the testing process.

Figure 4.19: The Battery Weighs 10kg, as Displayed on the Weight Scale.

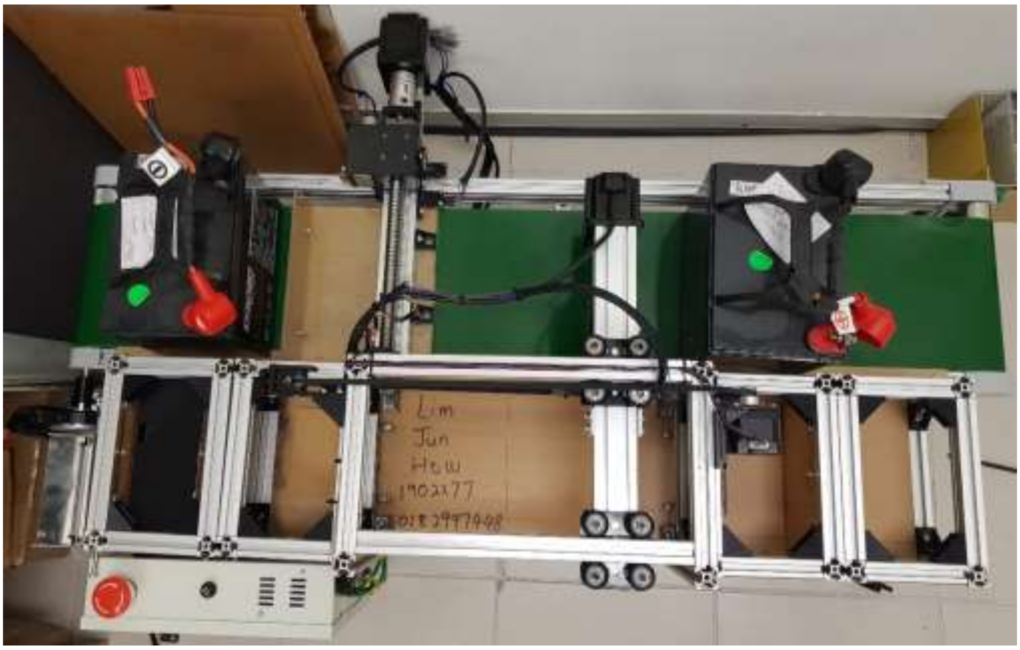

Figure 4.20: The Batteries Are Placed on the Bidirectional Belt Conveyor, Separated by a Distance.

Subsequently, the conveyor motor is triggered to rotate left for 3 seconds and then right for 3 seconds, simultaneously transporting the Valve Regulated Lead-Acid batteries to their respective locations. This entire cycle is repeated continuously for 10 minutes to ensure the durability and load-bearing capacity of the Bidirectional Belt Conveyor. During the testing, data such as motor performance, conveyor speed, and any signs of strain or malfunction are carefully monitored and recorded.

After 10 minutes of testing, a total of 100 cycles were completed. Following a prolonged observation period of 10 minutes, there was no noticeable degradation in the conveyor's speed. Additionally, using an infrared thermometer to detect the temperature of the driver powering the conveyor motor revealed no overheating issues. However, there was a slight increase in temperature, rising from 31.6°C to 37.4°C. After that, observing the fixed points of the conveyor's main structure, only minor loosening of bolts was detected. This issue was promptly addressed by installing spring washers between the bolts and the main structure to absorb vibrations generated during conveyor operation.

The results of this experiment demonstrate that the first objective of the study, which aimed to design a horizontally moving conveyor belt capable of bearing the weight of at least two sets of batteries (each battery pack weighing 3kg) and transporting them simultaneously to their respective places, has been achieved. Moreover, the weight target set by the original objective has been exceeded by 6.67 times, which means the load-bearing safety factor of the conveyor is 6.67 times.

Exchange Platform with Battery Loading and Unloading Mechanism

The upcoming test aims to evaluate the functionality of the exchange platform with loading and unloading mechanism under different tilt angles, simulating real-world scenarios encountered during battery exchange operations in an AMR environment. By subjecting the platform to tilting angles ranging from 0 to 15 degrees and assess its ability to accommodate battery packs efficiently despite varying orientations within the AMR.

During the test, the exchange platform will be adjusted incrementally to each specified angle, replicating the dynamic conditions experienced during AMR operation. Meanwhile, the battery loading and unloading mechanism positioned above the platform will be tasked with smoothly transferring a 3kg battery pack onto the exchange platform at each tilt angle. At each angle, the test will be repeated three times to ensure the reliability and consistency of the results.

Based on the testing results, the Exchange Platform with Battery Loading and Unloading Mechanism demonstrated a 100% success rate across all tested angles, including 0 degrees, 5 degrees, 10 degrees, 12 degrees, and 15 degrees, after three repeated trials at each angle. No breakdowns or failures were observed during the testing process, indicating the robustness and reliability of the system under various incline conditions. The following Figure 4.21, Figure 4.22, Figure 4.23, Figure 4.24 and Figure 4.25 depict the process of dragging a 3kg battery pack across the exchange platform at incline angles of 0, 5, 10, 12, and 15 degrees.

The second objective of this study, which aims to develop a mechanism capable of loading and unloading batteries from the AMR while adjusting the tilt angle to accommodate the battery's tilt, has been successfully achieved as confirmed by this test.

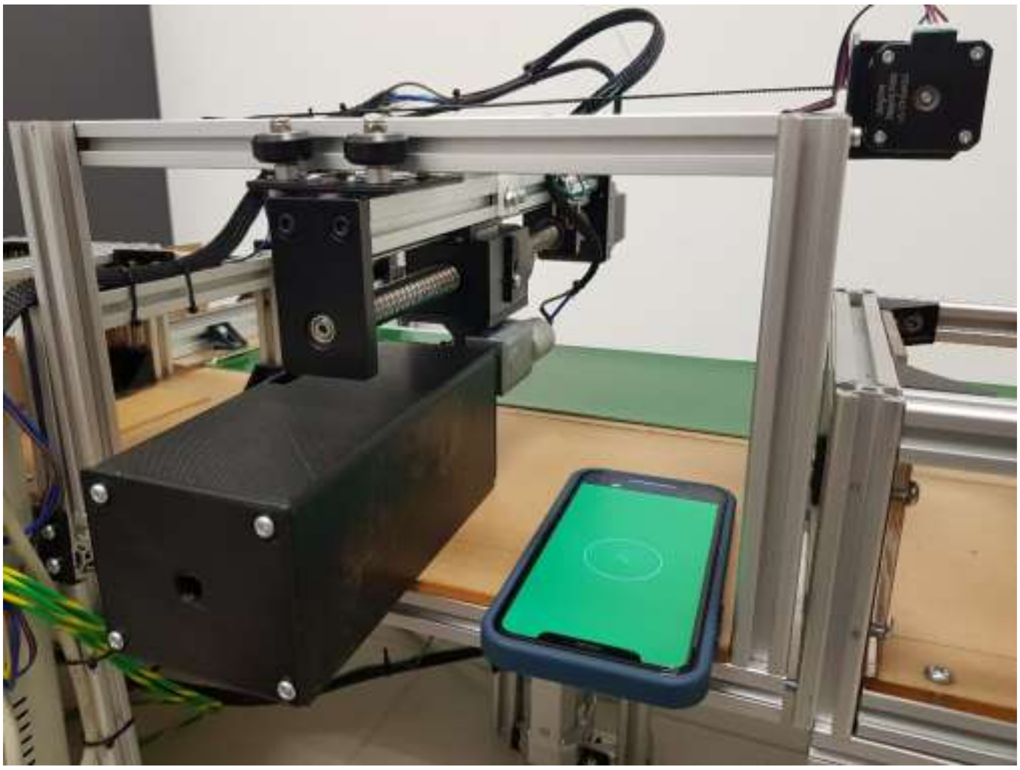

Figure 4.21: The Exchange Platform Is Being Tested at 0 Degrees.

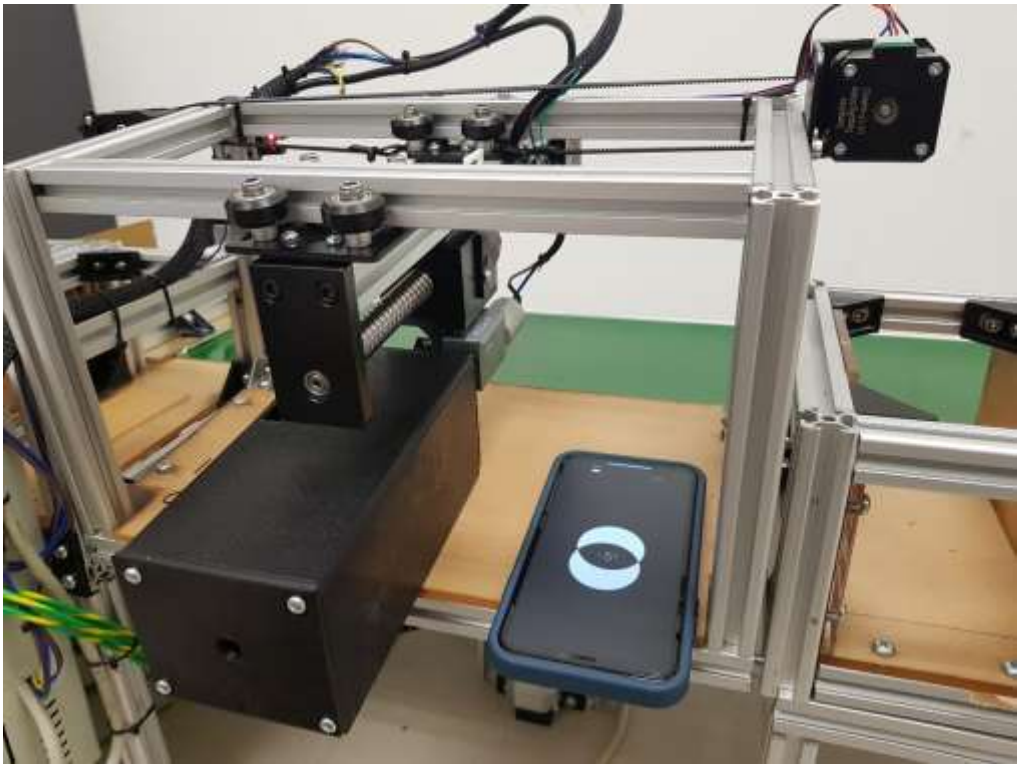

Figure 4.22: The Exchange Platform Is Being Tested at 5 Degrees.

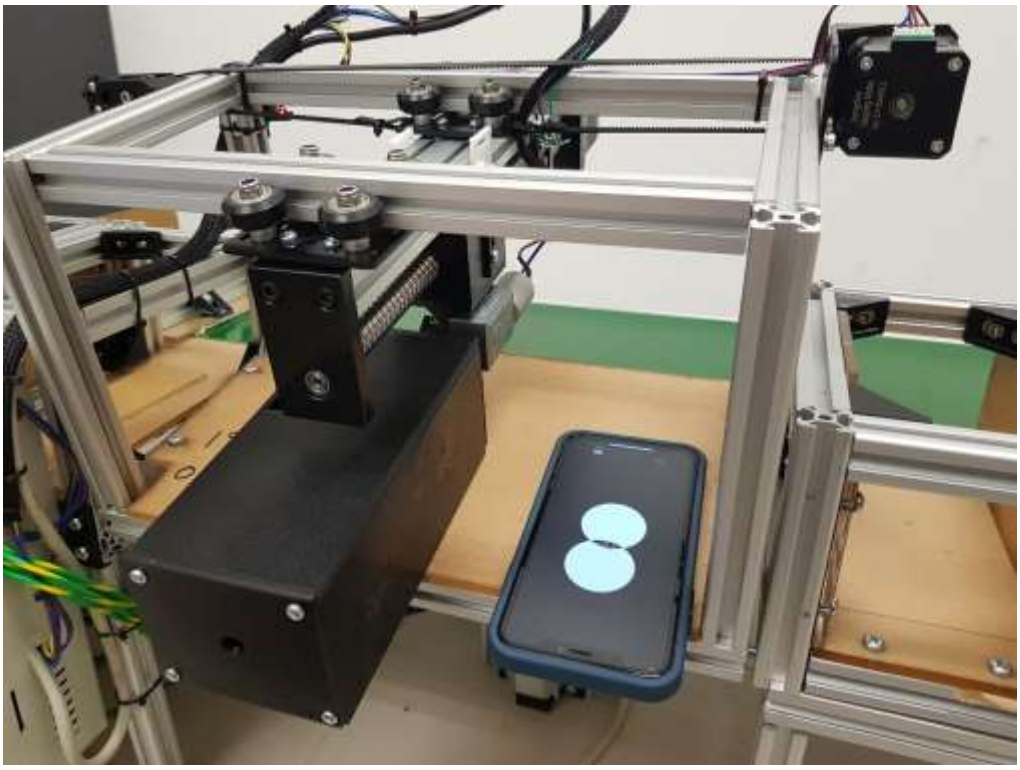

Figure 4.23: The Exchange Platform Is Being Tested at 10 Degrees.

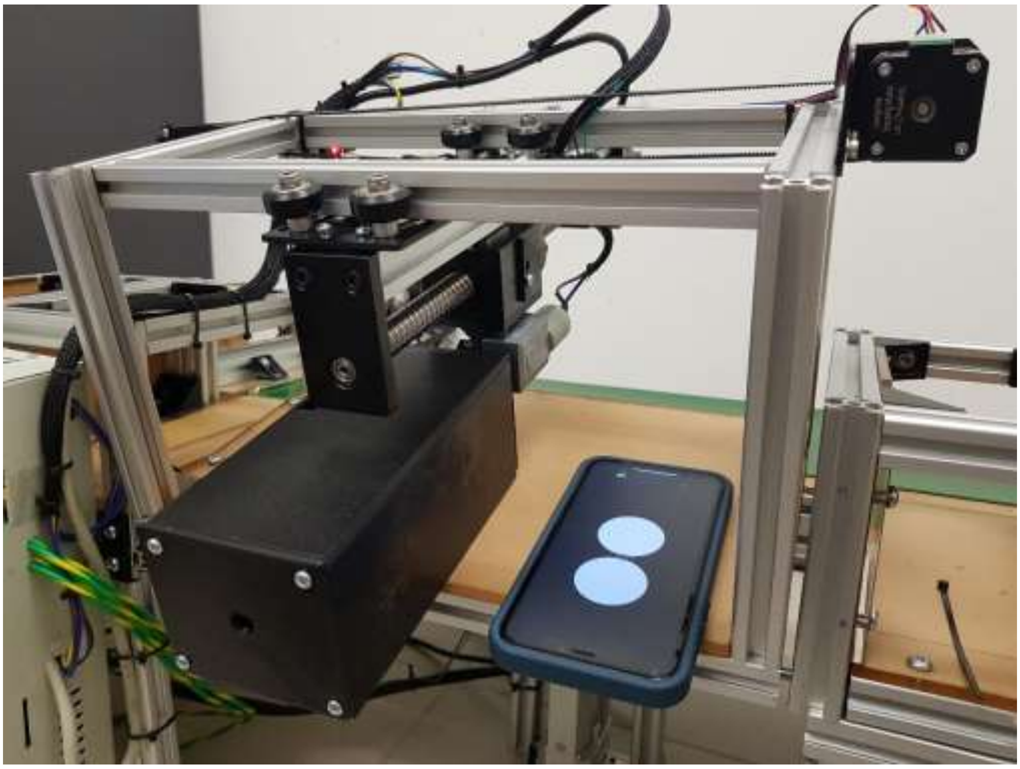

Figure 4.24: The Exchange Platform Is Being Tested at 10 Degrees.

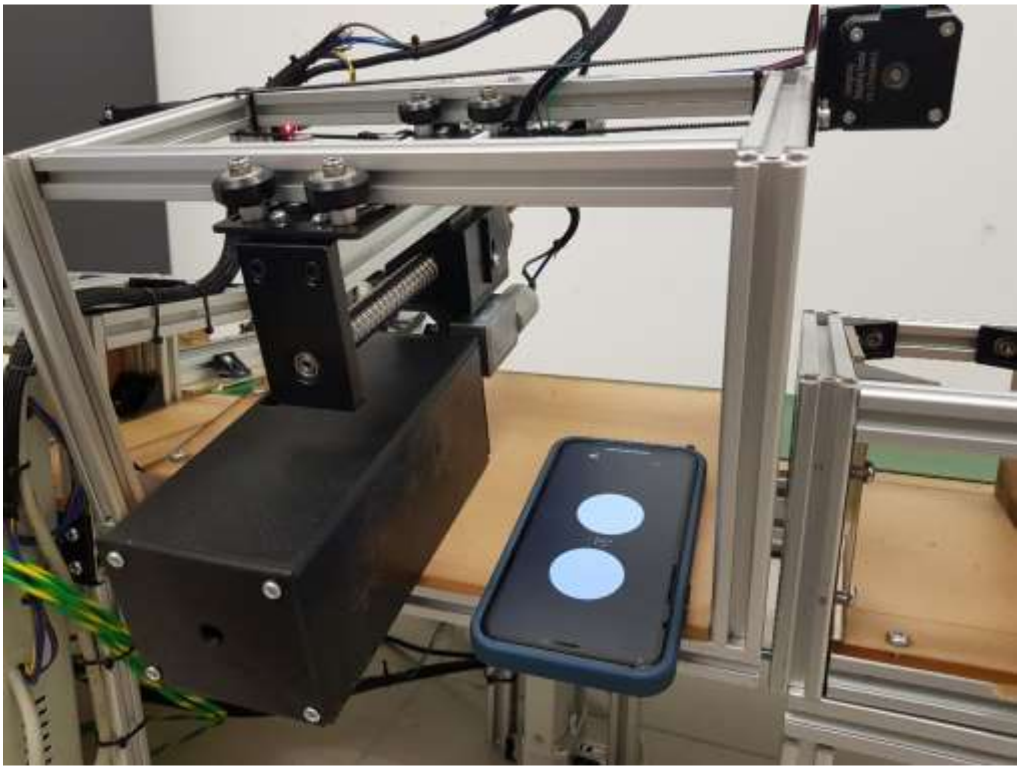

Figure 4.25: The Exchange Platform Is Being Tested at 15 Degrees.

Battery Storage

In this testing phase, the focus is on assessing the compatibility and load-bearing capacity of the battery compartment. Each battery module prototype is carefully inserted into the designated battery compartment to evaluate its fit and alignment within the space as shown in Figure 4.26. Additionally, the prototype's ability to support the weight of a 3kg battery is examined to ensure it can withstand the intended load without deformation or structural compromise. Through this testing process, any potential issues regarding fitment or weight-bearing capabilities can be identified and addressed accordingly to ensure the successful integration of the battery module into the system.

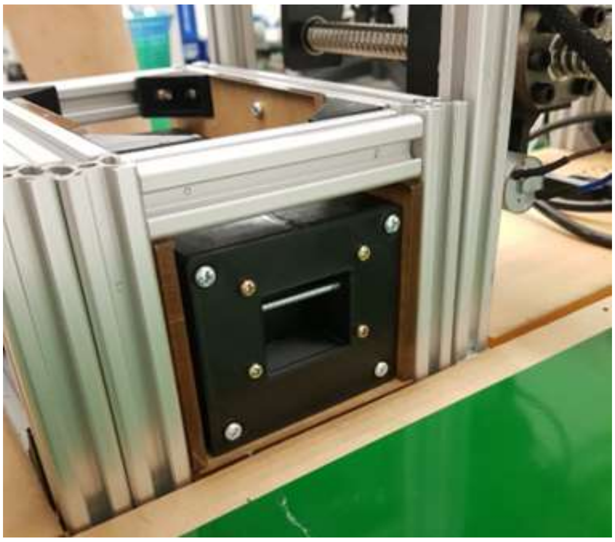

Figure 4.26: The Battery Module Prototype Fits Perfectly into the Battery Compartment.

4.3.1.2 Semi-Integrated Testing

Battery Extract and Return Testing

In this phase, compatibility tests between the Battery Loading and Unloading Mechanism with the battery carrier and the Battery Storage will be conducted. This test assesses the compatibility and functionality of the Battery Loading and Unloading Mechanism with the battery carrier and the battery storage. Additionally, this test aims to validate whether the battery carrier design, as discussed in Chapter 3.4, effectively addresses the intended problem.

During the test, batteries will be moved from the battery compartment onto the battery carrier and then returned to the battery compartment repeatedly for a total of 10 cycles. This process will evaluate the seamless interaction between the Battery Loading and Unloading Mechanism, the battery carrier, and the Battery Storage, ensuring smooth and efficient battery swapping operations.

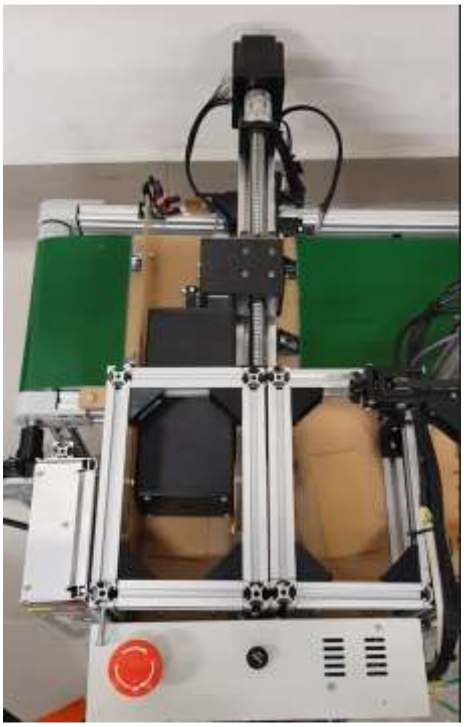

Figure 4.27: The Battery Pack Is Repeatedly Tested by Dragging and Inserting It into the Battery Carrier.

After 10 rounds of testing, the system achieved an impressive success rate of 90%. There was one instance of test failure due to a slight tilting issue with the battery pack. This issue will be addressed in the recommendations outlined in Chapter 5.2. However, it's worth noting that the tilting problem has been significantly reduced after implementing the battery carrier concept in the prototype, validating the effectiveness of the concept discussed in Chapter 3.4.

4.3.1.3 Unified System Testing

This section integrated all systems into a single comprehensive unit. This comprehensive testing phase evaluated the overall functionality and performance of the battery swapping station as a unified system. The entire testing process followed the sequence of flow outlined in Chapter 3.7. After testing, the results indicated that the entire process took 6 minutes and 33 seconds, comprising five test runs. Four of these five tests were successful, resulting in an 80% success rate.

4.3.2 Lithium-Ion Battery Module

4.3.2.1 Enclosure Stress Test

Firstly, mechanical stress testing was conducted on the battery enclosure, and the results were compared with those obtained from Finite Element Analysis (FEA). A pressure of 5 kilograms was applied to the top and side surfaces of the battery enclosure. In the real-world pressure test, two 2.5-kilogram weights were used to apply pressure, and precise measurements were taken using an electronic scale accurate to two decimal points, as shown in Figure 4.28. Subsequently, deformation testing was performed using vernier callipers.

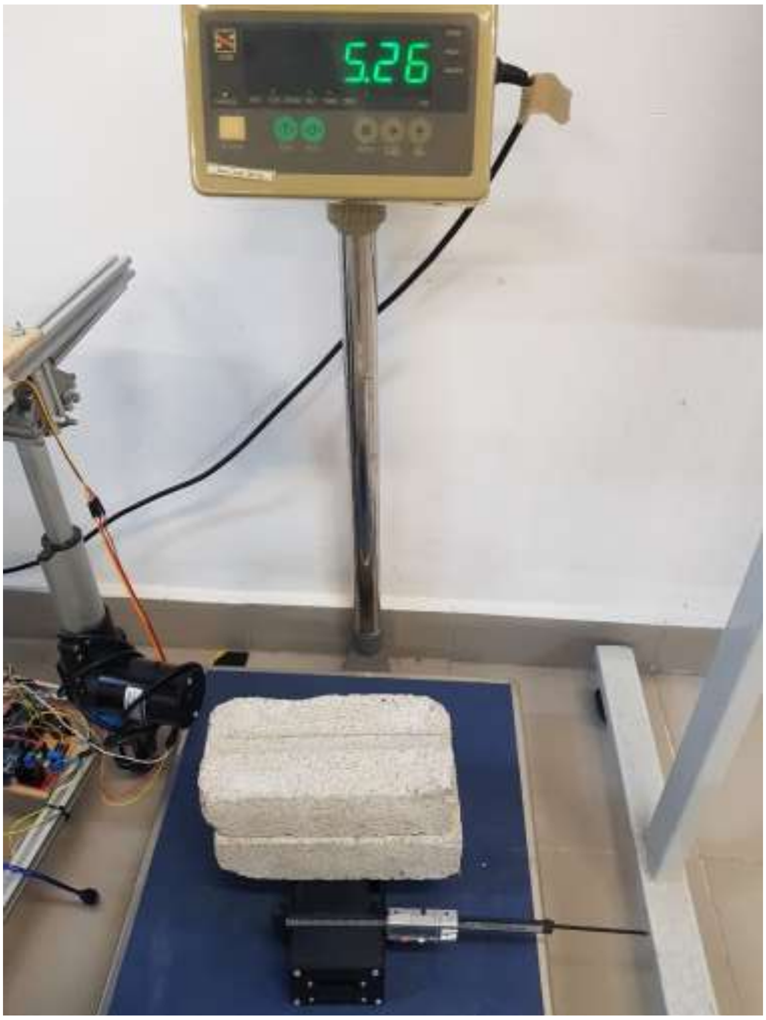

Figure 4.28: The Setup of the Stress Test.

From Figure 4.29 and Figure 4.30, it can be observed that when no mechanical forces were applied to the enclosure and it was in an undistorted state, the measurement of the top surface was 81.70mm, and the measurement of the side surface was 73.00mm. After applying a pressure of 5 kilograms, the measurement of the top surface increased slightly to 81.80mm, while the measurement of the side surface remained the same at 73mm, as shown in Figure 4.31 and Figure 4.32. This indicates that after applying a pressure of 5 kilograms, there was only a deformation of 0.10mm on the top surface and no deformation on the side surface.

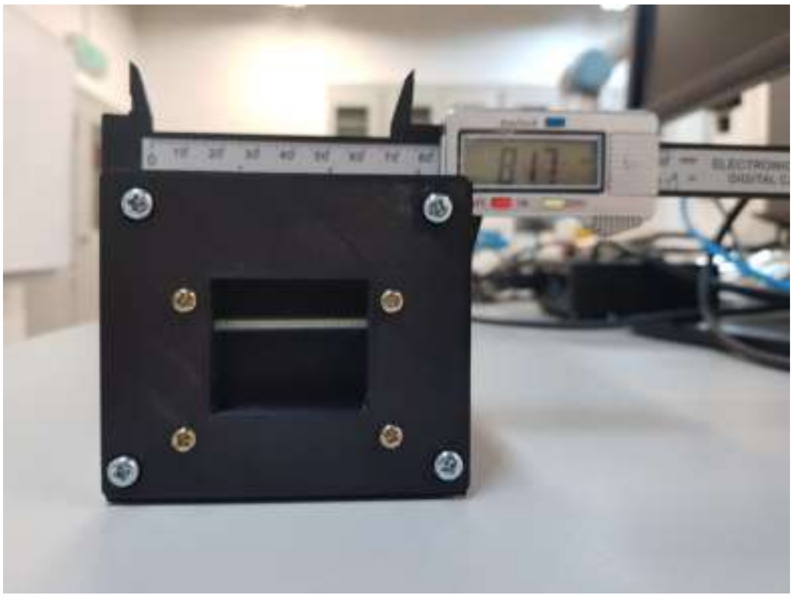

Figure 4.29: The Dimensions of the Battery Enclosure Top Before the Experiment.

Figure 4.30: The Dimensions of the Battery Enclosure Side Before the Experiment.

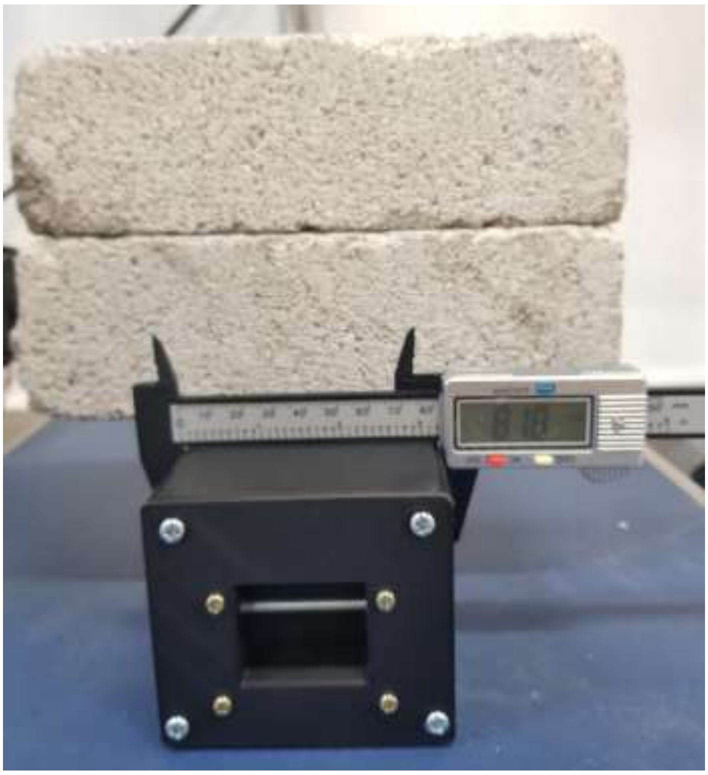

Figure 4.31: The Dimensions of the Battery Enclosure Top After the Experiment.

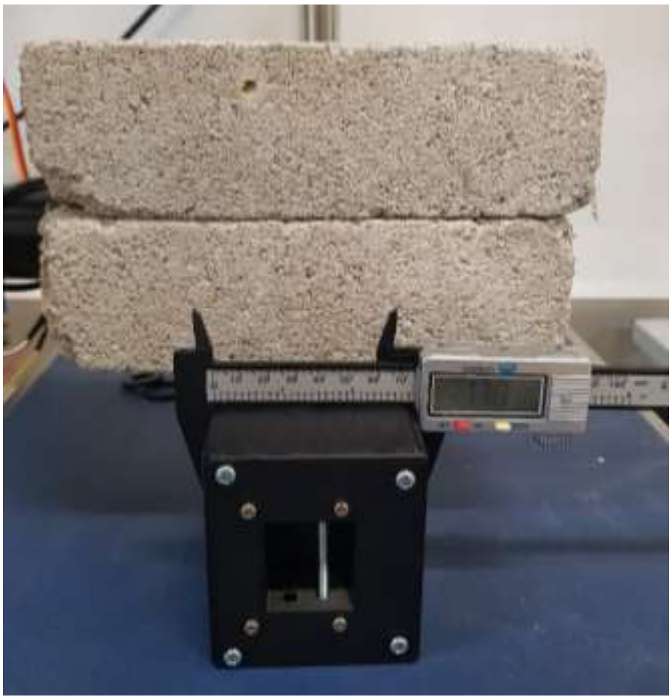

Figure 4.32: The Dimensions of the Battery Enclosure Side After the Experiment.

The results of the FEA simulation of the pressure test showed that the maximum displacement of the top surface was 0.1264mm, while the maximum displacement of the side surface was 0.02862mm. Table 4.1 and table 4.2 summarizes the testing results.

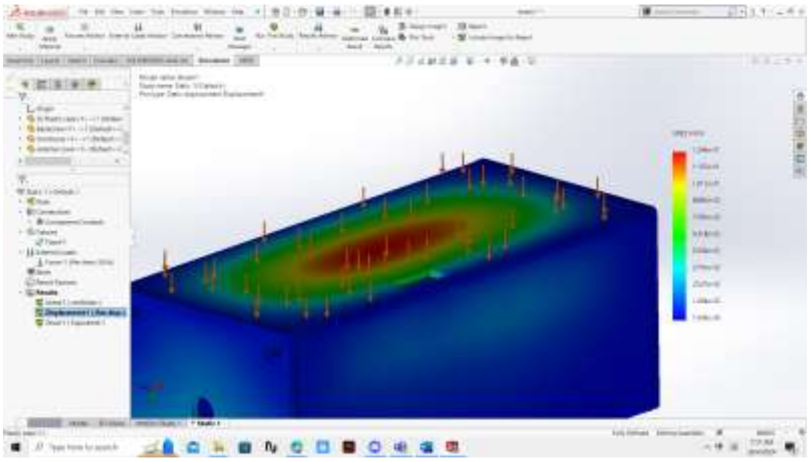

Figure 4.33: The FEA Stress Test Results When Applying 50N to the Battery Enclosure Top.

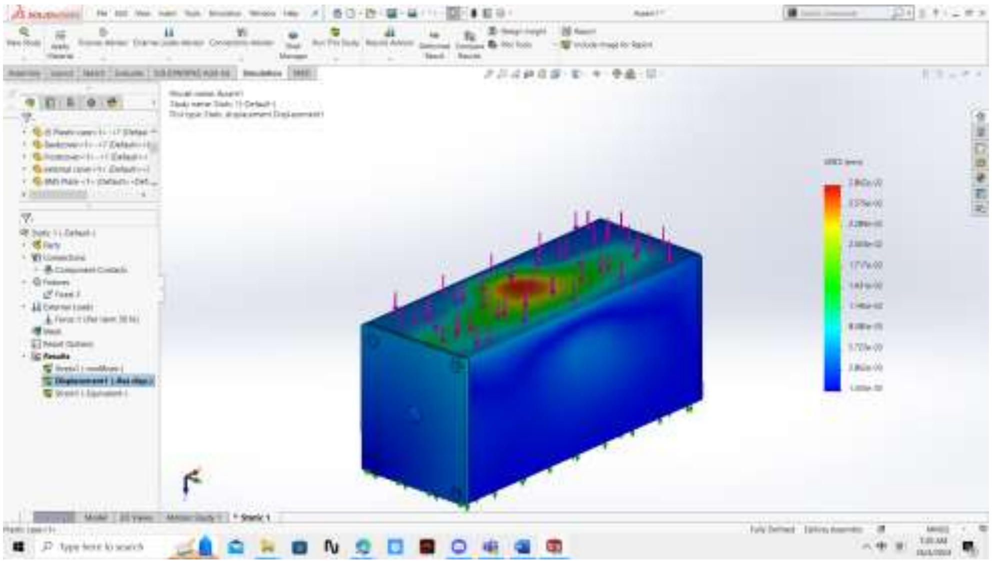

Figure 4.34: The FEA Stress Test Results When Applying 50N to the Battery Enclosure Side.

Table 4.1: The Stress Test Results of the Battery Enclosure Top.

	Top surface displacement, mm (Before applying load)	**Top surface displacement, mm (After applying load)**	**Displacement different, mm**
Prototype	81.70	81.80	0.10
FEA	81.0000	81.1264	0.1264

Table 4.2: The Stress Test Results of the Battery Enclosure Side.

	Side surface displacement, mm (Before applying load)	**Side surface displacement, mm (After applying load)**	**Displacement different, mm**
Prototype	73.00	73.00	0.00
FEA	71.0000	71.02862	0.02862

4.3.2.2 Handle Load Testing

The next test conducted was the Handler load testing, which involved placing a heavy iron plate weighing 3.28kg inside the battery enclosure. Subsequently, a digital hanging weight scale was hooked onto the handler of the battery enclosure, suspending it in the air for a continuous duration of 30 seconds. This experiment was repeated three times to ensure accuracy. The setup for the testing is depicted in Figure 4.35.

Figure 4.35: The Handle of The Battery Undergoes a Test With A Load Of 3.65 Kilograms.

After the experiment concluded, a visual inspection of the handler of the battery enclosure was conducted. It was observed that the battery enclosure did not undergo any deformation, and all connection points remained intact. This observation demonstrates that the handler is capable of withstanding the dragging force exerted during battery swapping station operations. Additionally, it indicates that the handler has a safety factor of three times the dragging force, as the weight of the entire assembled battery module is only close to 1 kilogram. Moreover, the hook of battery swapping stations can also be matched with the handle of the battery module as shown in Figure 4.36.

Figure 4.36: The Battery Handle and Hook Compatibility Test.

4.3.2.3 Functional and Battery Module Testing

After the assembly of the battery module, Liaw Yee Wei, the student tasked with constructing the circuit, will assume responsibility for conducting a series of comprehensive tests. These tests are vital for validating the functionality and performance of the battery system.

The testing verifies the communication between the computer and the microcontroller embedded within the battery module. This entails confirming that data can be reliably exchanged between the microcontroller and external devices. The capability of the system to retrieve crucial information, such as battery status, voltage levels, and temperature readings. This data retrieval process is essential for monitoring the health and performance of the battery module, enabling proactive maintenance and troubleshooting as needed.

Additionally, the testing also needs to evaluate the effectiveness of the hot-swapping feature, which allows for the seamless replacement of batteries during operation. The following Figure 4.37, Figure 4.38, Figure 4.39, and Figure 4.40 serves as evidence that the circuit is operational within the battery module and is capable of communication with internal electronic components, as well as retrieving critical information.

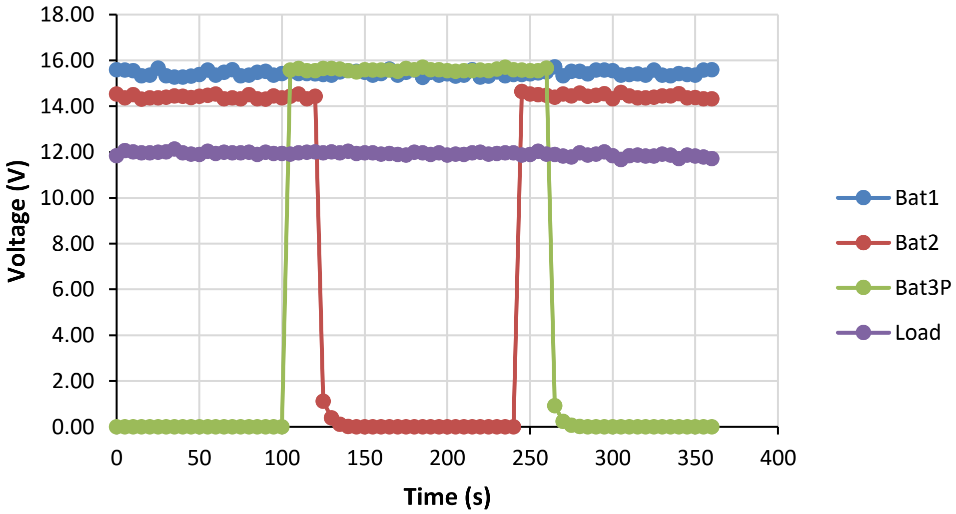

Figure 4.37: The Battery Circuit Output Voltage Graph.

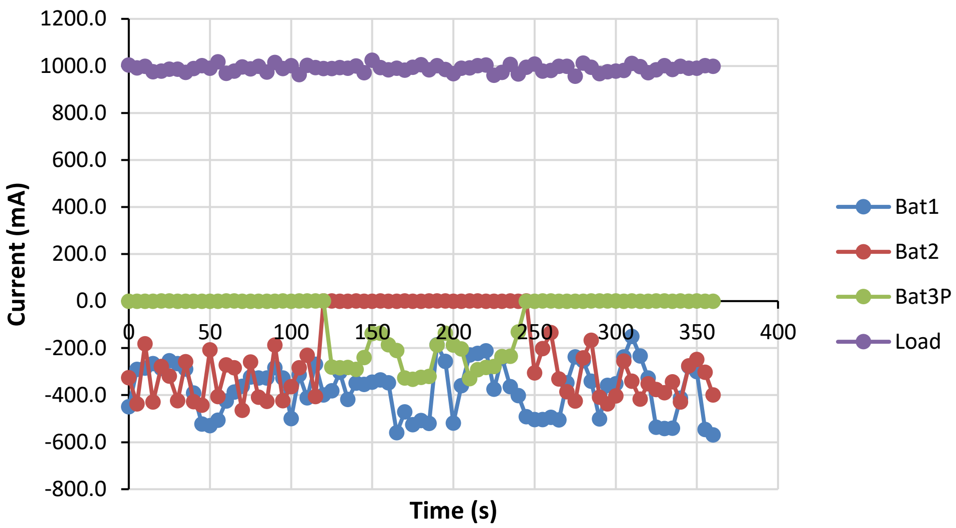

Figure 4.38: The Battery Circuit Output Current Graph.

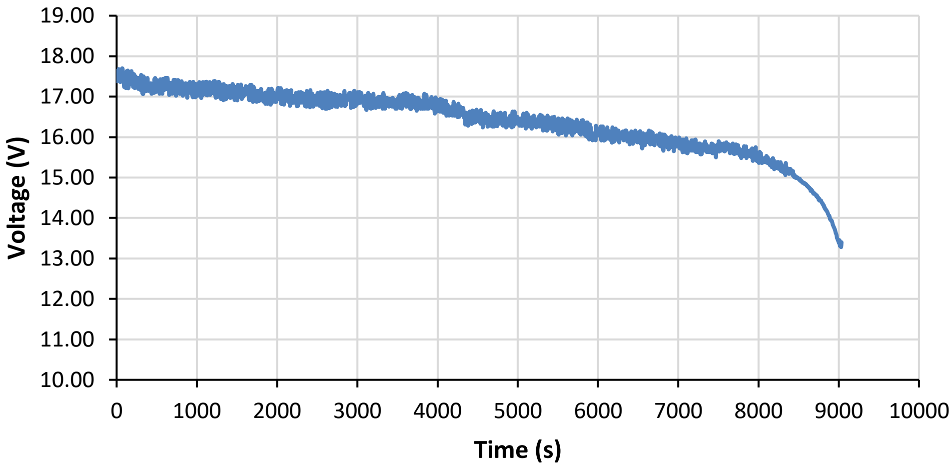

Figure 4.39: The Battery Discharge Voltage Graph.

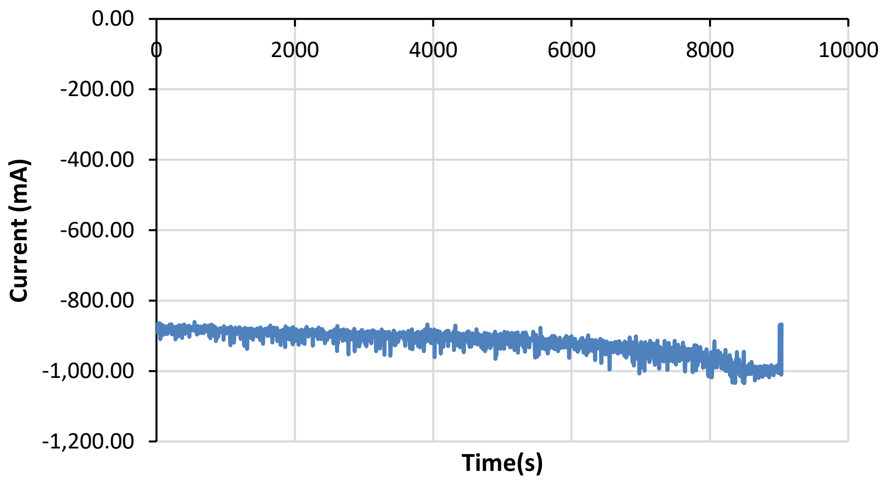

Figure 4.40: The Battery Discharge Current Graph.

4.4 Summary

This chapter presents a detailed examination of the outcomes stemming from the implementation and testing of the Automatic Battery Module Swapping Station and Lithium-Ion Battery Module. The successful completion of semi-integrated and unified system testing showcases the seamless operation of the entire battery swapping station with the results indicated that the entire process took 6 minutes and 33 seconds, comprising five test runs. Four of these five tests were successful, resulting in an 80% success rate. For example, the battery capacity of a DF automation Titan series AMR is 64 Ah, and it requires 3 hours to charge. Compared to the results of this prototype, the speed of changing the battery is much faster than the time needed for charging, with an efficiency 30 times greater. Furthermore, comprehensive testing of the Lithium-Ion Battery Module confirms its structural integrity and functional capabilities, ensuring effective communication and hot-swapping functionality. Overall, the chapter provides valuable insights into the project's achievements, paving the way for further improvements and future developments in battery swapping technology.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, the study of developing the Automatic Battery Module Swapping Station and Lithium-Ion Battery Module has been a resounding success, validated through a series of rigorous tests. These tests were meticulously designed to assess the performance, functionality, and reliability of the systems under various conditions. The culmination of this effort signifies the achievement of all objectives outlined in this study.

The Automatic Battery Module Swapping Station, designed with precision and attention to detail, has demonstrated exceptional performance throughout the testing phases. From the fabrication of hardware components to the meticulous assembly process, every step has contributed to the station's robustness and efficiency. Challenges encountered during the project were met with innovative problem-solving strategies, ensuring seamless operation and reliability.

Similarly, the development of the Lithium-Ion Battery Module has been marked by meticulous design and rigorous testing. The integration of electronic components, coupled with mechanical stress testing, has validated the module's structural integrity and functional capabilities. Through comprehensive testing, the module has proven its ability to communicate effectively with external devices and facilitate seamless hot-swapping functionality.

Importantly, the successful development and testing of both systems have led to the fulfilment of all objectives set forth in this study. From designing a horizontally moving conveyor belt to developing a mechanism for adjusting the tilt angle during battery exchange operations, each objective has been met with dedication and precision. The outcomes of this study underscore the effectiveness of the proposed solutions in addressing real-world challenges in battery swapping technology.

In essence, the successful culmination of this project signifies a significant milestone in the advancement of battery swapping technology. The systems developed not only meet the specified requirements but also pave the way for further innovation and refinement in this field.

5.2 Recommendations for future work

Replace the current microcontrollers with PLCs because Arduino Mega cannot perform tasks or processes simultaneously, leading to most of the time being wasted waiting for another process to finish. If PLCs are used, the time can be shortened to within 4 minutes, and PLCs are designed for reliability and durability in harsh industrial environments, providing real-time operation and precise timing critical for industrial automation.

On the other hand, predictive maintenance and fault diagnosis can be introduced along with the system by leveraging machine learning algorithms and predictive analytics techniques to develop models for identifying potential battery failures or degradation before they occur. Integrate fault diagnosis algorithms within the battery swapping station to automatically detect and diagnose issues with battery modules, enabling proactive maintenance and minimizing downtime.

Besides that, the scalability and adaptability of the prototype can be enhanced by exploring avenues to accommodate varying battery sizes, shapes, and specifications, catering to the diverse needs of different applications and industries. Investigate modular design approaches that allow for easy customization and expansion of the battery swapping station to meet evolving requirements and technological advancements.

Moreover, the design of the battery carrier can be improved as the current design has some minor flaws. During the transportation of batteries, the battery carrier may experience movement, causing the battery pack to not align parallelly with the battery compartment. This issue can be addressed by adding flexible wheel guides to the battery carrier. When transporting the battery pack on the battery carrier, the flexible wheel guides apply pressure to the battery enclosure to reduce movement and provide guidance when removing and inserting the battery.

Lastly, the mechanical safety of the system can be improved by installing mechanical safety interlocks, light curtains, and guards on moving parts and access points within the battery swapping station to prevent accidental contact and injuries during operation.

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APPENDICES

Appendix A: Bill of Materials

No.	Item Name	Description	Quantity	Price per Unit, RM	Sub Total, RM
1.	3D Printing Material	Material = PLA	500g	0.055	27.5
2.	Acrylic Panel	Thickness 3mm, A4size	12	7.5	90.00
3.	TB6600 Driver		3	23.3	69.9
4.	Arduino Mega		1	54.9	54.9
5.	Aluminium Profile	2020-12meter, 2040-2meter	12+2	162.1	162.1
6.	Power Window Motor		1	34	34
7.	2040 CNC conveyor belt complete set		1	91.84	91.84
8.	DC motor driver	12V,20A	1	17.04	17.04
9.	Power Supply	12V,30A	1	42.99	42.99
10.	Breadboard		1	3.90	3.90
11.	Limit Switch		3	1.60	4.80
12.	Conveyor Belt	200x2250mm	1	80	80
13.	On/Off Push Button		2	6.35	12.70
14.	FC-33 photoelectric sensor		3	4.5	13.5
15.	DC Worm Gear motor	12v 40RPM	2	35.50	71
16.	Sliding Table Linear Actuator	200mm	2	149.03	298.06
17.	Electric Cylinders Linear Actuator	10mm,1500N	1	86	86
18.	Gantry Set		2	40.28	80.56
19.	Aluminium Profile Gusset	4040	60	1.159	69.54
20.	CNC 3D Printer High Quality GT2 6mm Timing Belt	1m	1	3.95	3.95
21.	L298N 2A DC Motor		2	4.99	9.98
22.	Wire	0.75mm,2 core	10	0.76	7.6
23.	DC Circuit Breaker	20A	1	19.95	19.95
24.	2 channel Relay Module	5V	1	4.73	4.73

25.	Nema 17 Stepper motor		1	20	20
26.	LSE Metal Distribution Empty Box	10" x 12" x 6"	1	65	65
27.	2020 synchronous belt tensioner	2020 short	1	33.84	33.84
				Total	1475.38

Appendix B: Engineering Drawings

https://drive.google.com/file/d/1LkJla0g6oWeOB9vY4ogwBrHW6LOGXC_4
/view?usp=drive_link

Appendix C: Source Code

https://drive.google.com/file/d/1MpAQjaW7nKw2s4EkSn0IS0ZXaekSkrQo/view?usp=drive_link