SOLAR PANELS CLEANING ROBOT

LING XIN WEI

UNIVERSITI TUNKU ABDUL RAHMAN

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

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

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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.

Signature : 

Name : LING XIN WEI

ID No. : 18UEB05730

Date : 25th April 2023

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"SOLAR PANELS CLEANING ROBOT"** was prepared by **LING XIN WEI** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Electrical and Electronic Engineering with Honours at Universiti Tunku Abdul Rahman.

Approved by,

Signature : ______________________

Supervisor : Dr. Chua Kein Huat

Date : 27th April 2023

Signature : ______________________

Co-Supervisor : ______________________

Date : ______________________

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ABSTRACT

The project aims to develop a solar panel cleaning robot that can clean a rooftop with over 100 solar panels arranged in an array. The accumulation of dust and debris on solar panels can significantly reduce their efficiency and decrease energy output. There are two types of solar panel cleaning robots in the market, namely the robot moving directly on the solar panels and the rail-guided robot. However, the first type is not suitable for solar panels arranged in multiple arrays with gaps, and the second type requires infrastructure expenses. This project introduces a solar panel cleaning robot with a moving frame and a cleaning robot that can move on the frame to clean the panels. This design avoids the weight of the robot on the surface of the solar panels and solves the gaps issue. The robot can remove stubborn dirt, such as bird droppings, and improve the efficiency and energy output of the solar panels, which is essential for meeting the increasing demand for renewable energy.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

Check_SP	Check the presence of solar panel.
CLBM	Cleaning Brush Motor
FWBL	Frame Wheel Back Left
FWBR	Frame Wheel Back Right
FWFL	Frame Wheel Front Left
FWFR	Frame Wheel Front Right
LAL	Linear Actuator Left
LAR	Linear Actuator Right
LAS	Linear Actuator Stopping
Ori Posi	Original Position
RWBL	Robot Wheel Back Left
RWBR	Robot Wheel Back Right
RWFL	Robot Wheel Front Left
RWFR	Robot Wheel Front Right
SP_No	Solar panel is absent.
SP_Yes	Solar panel is present.
SPCHECK	Solar Panel Checking

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Solar panels are now becoming a common infrastructure worldwide, including Malaysia. As the demand for renewable energy increases, solar panels have become an essential source of clean energy. The installation of solar panels is increasing from year to year (Vaka et al., 2020). Especially for industrial and commercial areas, they have a wide space for the installation of solar panels. A typical example is the installation of solar panels on the wide rooftop (Shi et al., 2022).

Just like most of the infrastructure and appliances, solar panels also require maintenance services to ensure their sustainability and performance. The cleaning service is required to remove the dirt, leaves, water marks, and bird drops on the surface of the solar panels (Deb and Brahmbhatt, 2018).

The primary purpose of the project is to develop a solar panel cleaning robot. The solar panel cleaning robot is targeted for the cleaning service of wide commercial building rooftop solar panels. A wide commercial building rooftop contains many solar panels. Traditional cleaning methods are not efficient, manpower intensive, high risks, and high costs (Bari et al., 2018). Therefore, an automatic smart system is suggested for the solar panel cleaning robot so that it could perform the cleaning task independently and effectively.

The development of the solar panel cleaning robot involves two parts, mainly the hardware construction and the software systems. The structural construction includes the structural design and electrical circuits design. The software system includes the basic tasks program and the smart systems development.

1.2 Importance of the Study

Solar power has become increasingly popular as a renewable energy source due to its environmental benefits and cost savings. The study conducted by Khalid et al. (2023) highlighted that solar panels could lose up to 50% of their efficiency due to dust, dirt, and debris accumulation. The authors stated that this reduction is a result of decreased solar radiation absorption and blocking of active surface area on the panels (Khalid et al., 2023). Therefore, the study of solar panel cleaning robots has become important to maintain the efficiency and cost-effectiveness of solar panels.

Solar panel cleaning robots had been found to be more efficient in cleaning solar panels than human cleaners. These robots can operate autonomously and are equipped with sensors that detect the presence of dust and debris. They can also clean solar panels without using excessive amounts of water or cleaning materials, reducing waste and environmental impact.

The use of solar panel cleaning robots resulted in significant cost savings compared to traditional cleaning methods in large-scale solar power plants (Patil, Bagi and Wagh, 2018a). In addition to improving efficiency, the use of solar panel cleaning robots can also reduce maintenance costs. Traditional solar panel cleaning methods can be costly, time-consuming, and require skilled labour. However, using robots eliminates the need for human labour, minimising costs and time spent on maintenance.

Riawan et al. (2018) conducted a study on the design of a solar panel cleaning robot for rooftop PV systems, emphasising the safety benefits of using robots for solar panel cleaning. The authors stated that cleaning solar panels on roofs can be dangerous, especially for workers who were not trained to work at heights. By using robots, the need for human workers to climb onto roofs is eliminated, reducing the risk of accidents and injuries. Solar panel cleaning robots can operate in adverse weather conditions, ensuring that cleaning is done even during harsh weather. The authors' design of a solar panel cleaning robot features a range of sensors and an automated cleaning system, further enhancing the safety and efficiency benefits of using robots for solar panel cleaning (Riawan et al., 2018).

The study of solar panel cleaning robots is also important in promoting sustainability. By improving the efficiency of solar panels and reducing maintenance costs, solar panel cleaning robots can help make solar power more sustainable and accessible to more people. Solar power has the potential to be a game-changer in the renewable energy industry, and the use of solar panel cleaning robots can help realise this potential.

In conclusion, the study of solar panel cleaning robots is important in improving the efficiency, reducing maintenance costs, improving safety, and promoting sustainability of solar power. With the growing demand for renewable energy sources, the use of solar panel cleaning robots can help to make solar power more efficient, cost-effective, and accessible to more people.

1.3 Problem Statement

The accumulation of dirt on solar photovoltaic (PV) panels, including dust, bird droppings, and water marks, can significantly reduce the performance and efficiency of the panels, leading to the generation of hot spots and fire hazards. Routine cleaning of PV panels is necessary to improve the energy output of solar PV systems and prevent damage (Maghami et al., 2016). Dust accumulation can often be removed by rainwater, but blockages caused by leaves must be eliminated to prevent unnecessary reduction of sunlight exposure. However, the most significant challenge arises from bird droppings, which are highly stubborn and aggressive types of soiling that can cause hot spots and permanent damage to the solar panels if not cleaned promptly and thoroughly (Singh Chaudhary and Chaturvedi, 2017). Hence, the development of an effective solar panel cleaning robot is essential to maintain the efficiency and longevity of solar PV systems.

Several studies had emphasised the importance of regular cleaning and maintenance of solar PV panels to optimise their performance and minimise the risk of damage. Moreover, recent research has focused on the development of automated cleaning systems, including robotic technologies, to enhance the efficiency and effectiveness of the cleaning process. These systems employ various techniques, such as water jet cleaning, brush cleaning, and air cleaning, to remove the accumulated dirt and debris from the solar panels' surface. Additionally, some of these systems utilise artificial intelligence and machine learning algorithms to improve their accuracy and precision in detecting and cleaning the dirt on the solar panels (Almalki et al., 2022).

In conclusion, the soiling loss caused by dirt, bird droppings, and other debris is a significant challenge that affects the performance and efficiency of solar PV systems. Therefore, developing an automated solar panel cleaning robot is crucial to maintain the longevity and efficiency of the system. The utilisation of advanced technologies, such as artificial intelligence and machine learning, can further enhance the effectiveness and accuracy of the cleaning process.

1.4 Aim and Objectives

The aim of this project is to develop a solar panel cleaning robot. The objectives of this research are as follows:

1. To investigate the existing methods of cleaning the solar panels
2. To develop a robot for cleaning the solar panels
3. To evaluate the performance of the robot developed

1.5 Scope and Limitation of the Study

The project covers various engineering fields. From the design of the hardware to the software systems, the knowledge required are the mechanical structure, mechanical motions, power conversion, electrical machines, electronic circuit design, microcontroller application, and high-level programming. By considering the overall performance of the robot, it was found that some limitations of the project were encountered.

Firstly, the solar panels on the industrial rooftop were undertaken by different contractors. Different installation methods were practised. For example, the array arrangement, height of the solar panels from ground, spacing between the arrays, availability of water and power supply on the rooftop, the walking surface of the rooftop, and the size of each solar panel. Therefore, by the end of this project, a prototype of the solar panels cleaning robot will be constructed with specific dimensions.

A specific location of the solar panels site was taken into consideration as an example. The rail of the robot was customised to fit into the panel size and the array arrangement on the reference location. Hence, the rail of the robot could only fit into the specific location. The dimension of the rail needed to be reconstructed with a new dimension if the robot is going to perform its service in other sites.

The scope of this project is to develop an automatic solar panel cleaning robot which can perform routine cleaning for a specific testing environment. A simple testing environment is constructed for the project practical testing and debugging. At the end of this project, there will be two products which are the moving frame and the cleaning robot. The moving frame carries the cleaning robot to the desired cleaning position. The cleaning robot performs the cleaning tasks.

1.6 Contribution of the Study

This project introduced a novel idea for cleaning solar panels using a moving frame. The proposed design eliminates the need for expensive rail construction and reduces the risk of damaging the solar panels.

By incorporating a moving frame, the cleaning robot can move independently without the need for rails, saving costs and improving flexibility. The robot's movement on the moving frame also avoids direct contact with the surface of the solar panels, eliminating the risk of damage from the robot wheels. Additionally, the weight of the cleaning robot is not directly exerted onto the solar panels, further reducing the chance of damage.

Overall, the study's findings contributed to the development of a cost-effective and efficient solar panel cleaning robot that can help increase the performance and lifespan of solar panels. The innovative design of the robot has the potential to reduce maintenance costs and increase the efficiency of solar power generation, making it a valuable contribution to the field of sustainable energy.

1.7 Outline of the Report

Chapter 1 of the report serves as an introduction to the project and provides a clear and concise overview of the solar panel cleaning robot. The chapter outlined the importance of the study and the problem statement, followed by the aims and objectives of the project. Additionally, the scope and limitations of the study were discussed, and the contribution of the study was highlighted.

This chapter set the foundation for the rest of the report by establishing the context and purpose of the research, and by providing a clear understanding of the project's goals and objectives.

Chapter 2 of the report, the literature review, provided an overview of the importance of solar panels and their maintenance. It reviewed the current solar panel cleaning techniques, their challenges, and the state of the art in robotics for solar panel cleaning. The chapter also discussed the limitations of existing solutions and design considerations for solar panel cleaning robots. Control systems and sensors, power and energy management, and the environmental impact and sustainability of solar panel cleaning robots were also analysed. Finally, a comparative analysis of existing solar panel cleaning robots was presented, followed by a conclusion that highlighted the research gaps and future directions for this field. Overall, this chapter provided valuable insights into the current state of solar panel cleaning technology and its potential for future development.

Chapter 3 of the report showcased the planning and organisation that was employed to achieve the project's milestones. The chapter provided comprehensive details of the design process, including the creation of AutoCAD drawings, electronic circuit design, and flow charts of Arduino codes. By providing detailed information on the design process and the tools and techniques used, this chapter helped readers to understand the flow of the project and replicate it if necessary. Overall, Chapter 3 is an essential component of the report that demonstrates the meticulous planning and execution required to achieve the project's goals.

Chapter 4 of the report presented the results of the project prototype. The chapter provided an in-depth analysis of the robot's features and functions, highlighting its strengths and limitations. Discussions were made on the purposes of the design and how well the prototype met the project's aims and objectives. The results were presented in a clear and organised manner. This chapter demonstrated the successful implementation of the design and the achievement of the project's goals. Overall, Chapter 4 is a crucial component of the report that provides valuable insights into the effectiveness of the solar panel cleaning robot prototype.

Chapter 5 of the report presented a comprehensive conclusion of the project's achievements, highlighting the successful implementation of the solar panel cleaning robot prototype. The chapter summarised the key findings and discussed their implications. Additionally, suggestions for future work were provided, identifying areas for further improvement and development of the solar panel cleaning robot. The recommendations were based on the insights gained from the project's limitations and the potential for further research and innovation in this field. Overall, Chapter 5 serves as a critical component of the report by offering valuable insights into the potential for future work in solar panel cleaning robot technology.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The global focus on renewable energy has led to the rapid growth of the solar energy industry in recent years. Solar panels are the primary components of solar energy systems, and their efficiency is critical to the success of solar power generation. However, the accumulation of dirt, dust, and other debris on solar panels can significantly reduce their performance by causing shading and hot spots.

Manual cleaning methods, such as using water and brushes, are commonly used to clean solar panels. However, manual cleaning can be time-consuming, labour-intensive, low efficiency, and potentially dangerous. Automated cleaning technologies, such as solar panel cleaning robots, offer a more efficient and sustainable solution for maintaining the optimal performance of solar panels (Jaiganesh et al., 2022).

This literature review aims to explore the existing research on solar panel cleaning robots, their design, functionality, and potential benefits. The review will analyse the advantages and disadvantages of different types of solar panel cleaning robots, such as mobile robots and fixed robotic arms, and compare their performance to traditional manual cleaning methods. Additionally, the review will examine the different cleaning techniques used by these robots, such as water-based cleaning and dry cleaning, and evaluate their effectiveness.

Moreover, the review will analyse the current gaps in the literature and suggest areas for future research to enhance the development of sustainable and efficient solar panel cleaning technologies. This review will provide a foundation for the design and development of solar panel cleaning robots and contribute to the development of a more sustainable and efficient method of solar panel maintenance.

2.2 Solar Panel Cleaning Techniques: Current Methods and Challenges

There are several methods of solar panel cleaning that are currently being used. Manual labour cleaning, water cleaning, and brush cleaning are three common methods used to clean solar panels. Manual labour cleaning involves wiping off dirt and dust from the surface of the solar panel using a cloth or sponge. Water cleaning, on the other hand, involves spraying water onto the surface of the solar panel to remove loose dirt and debris. Brush cleaning uses a soft-bristled brush to scrub the surface of the solar panel, effectively removing stubborn stains and build-up. The choice of cleaning method will depend on the size of the solar panel, the type and amount of dirt or debris present, and the resources available for cleaning. It is important to follow manufacturer guidelines for cleaning solar panels to avoid damage to the panels or voiding of the warranty.

Manual cleaning is a traditional method of cleaning solar panels, which involves using water, soap, and squeegees to clean the panels. This method is time-consuming and labour-intensive, as workers need to climb onto the roofs of buildings to reach the solar panels. Moreover, it can be hazardous for workers to perform this task, as it involves working at heights and on slippery surfaces (Dewlaney and Hallowell, 2012). The process is also highly dependent on the skill and experience of the workers, which can lead to inconsistent cleaning results. Therefore, the manual cleaning method has several challenges that need to be addressed to make it more efficient and safer.

Another water cleaning method for solar panels is the use of a simple hose and spray nozzle. In this method, clean water is sprayed onto the surface of the panels to remove dirt and debris. This method is relatively easy and inexpensive, and it can be done by anyone with access to a water source. However, the effectiveness of this method can be limited, especially in areas with hard water or high mineral content. Hard water can leave mineral deposits on the solar panels, which can reduce their efficiency (Patil, Bagi and Wagh, 2018b). Additionally, using water that is too hot can cause thermal shock to the panels, leading to damage or reduced efficiency over time. The use of low-pressure water jets is effective in removing dust and debris from solar panels. However, it is important to note that water quality can vary depending on location, and the use of low-quality water for cleaning can lead to mineral deposits and other issues. In general, the water cleaning method can be a cost-effective and efficient way to clean solar panels. However, it is important to consider the quality of the water being used and the potential for mineral deposits to accumulate on the panels.

In high-pressure water jets method, high-pressure water is sprayed onto the surface of the solar panels to remove dirt and debris. The pressure of the water can be adjusted to ensure that it does not damage the panels (Syafiq et al., 2018). Compared to manual cleaning, the use of high-pressure water jets is more efficient as it requires less labour and time. However, it is still dependent on the availability of clean water and can be limited in areas with water scarcity. Moreover, if the water used for cleaning is not clean, it can leave mineral deposits on the solar panels, which can reduce their efficiency. Overall, while the use of high-pressure water jets can be an effective method for cleaning solar panels, it is important to consider the availability and quality of water resources in the area before adopting this method.

Deionized water is water that has been purified by removing all minerals and impurities. This method involves spraying deionized water onto the surface of the solar panels to remove dirt and debris. The advantage of using deionized water is that it does not leave any mineral deposits on the solar panels, which can reduce their efficiency over time. However, the challenge with this method is the availability and cost of deionized water. In addition, it is still important to ensure that the quality of the water used for cleaning is high, as even small amounts of impurities can lead to water marks on the solar panels. Water marks can create shaded areas on the surface of the panels, which can reduce their efficiency. Therefore, while the use of deionized water can be an effective method for cleaning solar panels, it is important to consider the availability and quality of water resources in the area before adopting this method.

Brush cleaning is a method of cleaning solar panels using a soft-bristled brush to scrub the surface of the panel, removing dirt and debris. This method is effective at removing stubborn stains and build-up that may not be removed by water cleaning or manual labour cleaning alone. Brush cleaning is particularly useful in areas with hard water, where mineral deposits may accumulate on the surface of the solar panel over time. The advantages of brush cleaning include its ability to remove stubborn stains and build-up, as well as its relatively low cost compared to other cleaning methods. Brush cleaning can also be done without the use of chemicals, making it an environmentally friendly cleaning option. Additionally, brush cleaning can be done with minimal water usage, making it an ideal choice for areas with limited water resources. However, there are also some disadvantages to brush cleaning. Improper use of the brush can result in scratches or damage to the surface of the solar panel, which can reduce its efficiency over time. Additionally, brush cleaning can be time-consuming, particularly for larger solar panel arrays. To minimise the risk of damage to the solar panel during brush cleaning, it is important to use a soft-bristled brush and to follow manufacturer guidelines for cleaning. It is also recommended to avoid using abrasive cleaners or tools, which can scratch the surface of the solar panel.

Self-cleaning coatings are a type of protective coating that can be applied to solar panels to reduce the need for manual cleaning (Syafiq et al., 2022). These coatings are typically made of hydrophobic materials, which repel water and prevent dirt and debris from sticking to the surface of the panel. Some self-cleaning coatings are also designed to break down organic matter, such as bird droppings or pollen, which can further reduce the need for cleaning (Arabatzis et al., 2018). The advantages of self-cleaning coatings include their ability to reduce the need for manual cleaning, which can save time and resources. Some studies have also shown that self-cleaning coatings can improve the overall energy output of solar panels. However, there are also some disadvantages to self-cleaning coatings. These coatings can be expensive to apply, and their effectiveness may be reduced over time as they are exposed to the elements. Additionally, some self-cleaning coatings may not be suitable for all climates or environmental conditions (Wu et al., 2022). Despite these limitations, self-cleaning coatings are becoming increasingly popular in the solar industry, as they offer a low-maintenance option for keeping solar panels clean and efficient. As research in this area continues, it is likely that new and improved self-cleaning coatings will be developed, further expanding the possibilities for this technology.

2.3 Robotics in Solar Panel Cleaning: State of Art

Robotic technology is advancing rapidly and is being applied to various industries, including the solar energy industry. The use of robotic systems for solar panel cleaning is gaining popularity due to its potential to improve the efficiency and effectiveness of solar panel cleaning operations. The state of the art in robotics for solar panel cleaning involves the development and deployment of autonomous cleaning robots that can identify and clean solar panels without human intervention. These robots are equipped with advanced sensors, algorithms, and control systems that allow them to navigate complex terrain and clean solar panels with precision and accuracy (Kumar et al., 2018).

Several companies had already developed and deployed robotic systems for solar panel cleaning. For example, Ecoppia, a company based in Israel, has developed a water-free cleaning robot that uses advanced technology to clean solar panels in a fast, efficient, and cost-effective manner (Ecoppia, 2023). Similarly, Indian start-up, Skilancer Solar, has developed a robotic system that can clean solar panels on a large scale using a combination of brush cleaning and water-based cleaning methods. However, despite the advances made in robotics for solar panel cleaning, there are still some limitations and challenges that need to be addressed. For example, the high cost of these robotic systems and the need for skilled technicians to operate them may limit their widespread adoption. Additionally, there may be concerns around the safety and reliability of these systems, especially when operating in harsh environmental conditions.

Future directions in robotics for solar panel cleaning may involve the development of more sophisticated and cost-effective systems that can operate autonomously and adapt to changing environmental conditions. There may also be opportunities for the integration of artificial intelligence and machine learning techniques to improve the efficiency and accuracy of solar panel cleaning robots (Mir et al., 2020).

Overall, the state of the art in robotics for solar panel cleaning is rapidly evolving, and there is significant potential for further development and innovation in this area. By addressing the limitations and challenges of current systems, and leveraging emerging technologies and techniques, the efficiency and effectiveness of solar panel cleaning operations can be improved, ultimately leading to increased energy production and a more sustainable future.

2.4 Solar Panel Cleaning Robots: Existing Solutions and their Limitations

2.4.1 Water-free Cleaning Robot

Water-free cleaning robot that utilises air flow mechanism is a type of solar panel cleaning robot that does not require any water to clean the solar panels. Instead, these robots use air flow and the aid of microfibres pads or rolling brushes to remove dirt and debris from the surface of the panels. When moving across the panel's surface, the combination of air flow and the operation of rolling brush direct the dust and debris to a specific direction. One of the main advantages of water-free cleaning robots is that they are environmentally friendly as they do not use any water during the cleaning process. This means that they do not generate any wastewater or require any additional resources to clean the panels. Additionally, they are suitable for cleaning solar panels located in areas where water is scarce or expensive, such as desert regions or remote locations (Fan et al., 2022). Water-free cleaning robots are generally quicker and more efficient than manual cleaning methods as they do not require any additional setup or clean-up time. However, the effectiveness of water-free cleaning robots may be limited when it comes to heavily soiled panels or stubborn debris such as bird droppings. In these cases, water-based cleaning methods may be more effective. Water-free cleaning robots may also not be as effective at removing stubborn debris such as bird droppings or tree sap, which can require more aggressive cleaning methods.

2.4.2 Solar Brush Robots

Solar brush robots are a type of cleaning robot used for cleaning solar panels. They typically use a rotating brush to scrub the surface of the panels and remove dirt and debris. These robots are generally smaller and less expensive than other types of solar panel cleaning robots, making them a popular choice for many applications.

One of the main advantages of solar brush robots is their affordability. These robots are generally less expensive than other types of cleaning robots, making them accessible to many people. They are also easy to operate, as they typically only require a power source and a water supply to function. Solar brush robots are generally effective at removing debris from the surface of the solar panels, as the rotating brush can scrub the surface and remove dirt and grime. They are typically lightweight and portable, making them easy to transport and use in a variety of applications (Noh et al., 2020).

However, solar brush robots also have some disadvantages. One of the main limitations is their effectiveness on very dirty panels. In some cases, the brushes may not be able to remove all debris from the surface of the panels, requiring additional cleaning methods. Solar brush robots may not be suitable for use in areas with high wind or other adverse weather conditions, as the brushes may not be able to effectively clean the panels in these conditions. There is a risk of damage to the solar panels if the brushes are not properly calibrated, which could lead to scratching or other damage. These robots may not be suitable for cleaning panels that are located in areas with limited access or difficult terrain, as they typically require a flat surface to operate effectively.

2.4.3 Cleaning Robot with Brush and Water

Robotic systems that use a combination of brush cleaning and water-based cleaning methods are a type of solar panel cleaning robot that uses rotating brushes to scrub the surface of the panels and water to rinse away any dirt or debris (Ronnaronglit and Maneerat, 2019). The water is typically supplied by a tank on the robot or through a hose connected to an external water source. The brush cleaning method is effective for removing stubborn debris such as bird droppings or tree sap, while the water-based cleaning method ensures a thorough and complete cleaning of the panels.

One of the main advantages of robotic systems that use a combination of brush cleaning and water-based cleaning methods is their effectiveness in cleaning heavily soiled panels. The combination of brush and water-based cleaning can remove even the most stubborn debris. These systems are generally faster and more efficient than manual cleaning methods as they do not require any additional setup or clean-up time. Robotic cleaning systems that use water-based methods can help conserve water by using a closed-loop system that recycles and filters the water, reducing the amount of water needed for cleaning. These systems are suitable for cleaning solar panels located in areas with access to water, such as urban or suburban areas.

One of the main limitations of robotic systems that use water-based cleaning methods is the potential for water damage to the electrical components of the solar panels. Careful consideration must be given to the amount of water used and the pressure at which it is applied to the panels. Robotic cleaning systems that use water-based methods can be more expensive than other types of solar panel cleaning robots due to the additional equipment required for water storage and filtration. These systems may not be suitable for cleaning solar panels located in areas with limited access to water or in water-scarce regions. The brushes used by these robotic cleaning systems may need to be replaced frequently to maintain their effectiveness, which can be an additional cost.

In conclusion, robotic systems that use a combination of brush cleaning and water-based cleaning methods are effective in cleaning heavily soiled solar panels. They are generally faster and more efficient than manual cleaning methods and can help conserve water. However, careful consideration must be given to avoid potential water damage to the electrical components of the solar panels, and these systems may not be suitable for all locations due to water availability and cost considerations. The brushes used by these systems may also need frequent replacement, which can be an additional cost.

2.4.4 Robotic Arm-Based Cleaning Robot

Robotic arm-based cleaning systems are a type of solar panel cleaning robot that uses a robotic arm equipped with brushes and nozzles to clean solar panels (Mondal and Bansal, 2015). The system is controlled by a computer program, which directs the robotic arm to move along the surface of the panels and clean them using the brushes and nozzles. It was found that these systems are effective at removing debris from solar panels due to the use of brushes and nozzles.

One of the main advantages of robotic arm-based cleaning systems is their versatility. The robotic arm can be programmed to clean solar panels of various shapes and sizes, making them suitable for use in a wide range of applications. These systems are also faster and more efficient than manual cleaning methods, as they do not require any additional setup or clean-up time (Gupta, 2022). Additionally, robotic arm-based cleaning systems are typically more effective at removing debris than other types of cleaning robots due to the use of brushes and nozzles. They are also suitable for cleaning solar panels located in areas with limited access, as they do not require a source of water to operate.

However, these systems have some limitations. One of the main drawbacks is their cost. These systems can be more expensive than other types of solar panel cleaning robots due to the complexity of the robotic arm and the computer programming required to control it. Another limitation is that robotic arm-based cleaning systems may not be suitable for use in areas with high wind or other adverse weather conditions, as the robotic arm may be damaged or may not be able to clean the panels effectively in these conditions. Additionally, the brushes used by these systems may need to be replaced frequently to maintain their effectiveness, which can be an additional cost. There is also a potential risk of damage to the solar panels if the brushes or nozzles are not properly calibrated, which could lead to scratching or other damage.

In summary, robotic arm-based cleaning systems have several advantages, including their versatility, efficiency, and effectiveness at removing debris. However, they also have some limitations, such as high cost and potential damage to the solar panels if not calibrated correctly. Overall, these systems may be a suitable option for cleaning solar panels in various applications, but careful consideration of the specific needs and requirements of the system is necessary before implementation.

2.5 Control Systems and Sensors for Solar Panel Cleaning Robots

The control system and sensors are crucial components of solar panel cleaning robots that ensure efficient and safe operation. The control system manages the movement and cleaning mechanism of the robot, while sensors detect and avoid obstacles, prevent collisions, and ensure accurate navigation. Various studies have explored different approaches to the control system and sensor design for solar panel cleaning robots.

The easiest and most common way to develop a control system for a robot is using a microcontroller. The two most popular microcontrollers used for robot prototype development are the Arduino and the Raspberry Pi. The application of microcontrollers is important for the initial stage of robot development. For a simple solar panel cleaning robot, an Arduino Uno is already enough to handle all the operations of the robots (Noh et al., 2020). The prototype proposed by Noh et al. (2020) consists of the wheel motors, water pump, cleaning brush, and ultrasonic sensor as outputs and inputs components. The Arduino Uno used in the project is powerful enough to handle all the outputs and inputs by the hardware components.

The next solution to the control system is the programmable logic controller (PLC). PLC offers a high level of reliability and durability, which makes them well-suited to be used in industrial applications. Furthermore, the application of PLC programming on the solar panel cleaning robot could increase the flexibility and scalability of the robot. Modifications or updates to the programming could be done easily. In the solar panel cleaning mechanism proposed by Hou et al (2016), he appreciates the high reliability and compact structure of PLC control. He claims that the PLC programming is easy to master and has already applied in vast amounts of engineering fields (Hou et al., 2016). However, PLC control is not suitable for applications that require complex decision-making. The application that requires a complex decision-making process will cause the PLC program to be very complex which is not desirable.

In the initial stage of a robot development, the control system will focus on the control and proper calibration of the hardware, so a microcontroller which serves to process the electrical and electronic signals will be enough. After the development of the basic operations, the proceeding stage of developing the smart detection system requires a more powerful processing unit to perform either image processing or recognition algorithms. The smart detection system allows the solar panel cleaning robot to be fully automated and intelligent. The 2 control systems mentioned above achieve automatic cleaning by routine program. The cleaning process depends more on the feedback by the sensors. The intelligent detection system allows the solar panel cleaning robot to make decisions by itself. To declare a totally smart automatic robot, the solar panel cleaning robot must be able to recognize solar panels, identify dirt and be able to understand its location on the site. Currently, there are smart solar panels recognition systems used to recognize the location of solar panels through machine vision (Yao and Hu, 2017). As the robot recognizes the solar panels, the development of the smart system could continue in dirt identification. Image processing and machine vision are the most advanced and reliable solutions to achieve dirt identification. A simpler method to achieve dirt identification is the Arduino collar recognition proposed by Olorunfemi et al. (2023). Lastly, the robot must know its position at the solar panels site so that it could decide its movement to complete the whole cleaning operation by itself. By gathering these skills, an artificial intelligence solar panel cleaning robot could be achieved.

In summary, the control system and sensors are essential components of solar panel cleaning robots that ensure efficient and safe operation. Three common methods to construct a control system are discussed which are the microcontroller method, PLC programming method, and artificial intelligence method. All these methods are useful depending on the requirements and expectations on the robot. The microcontroller method is simple and easy to achieve. The PLC programming method is fast and useful for low-complexity applications. The artificial intelligence method could be the final goal in robot development.

2.6 Design Considerations for Solar Panel Cleaning Robots

The design considerations for a solar panel cleaning robot are crucial in ensuring that the robot can effectively clean the solar panels while minimising the risk of damage to the solar panels. The following are some key design considerations that must be considered in designing a solar panel cleaning robot. Figure 2.1 shows the summary of the design considerations of a solar panel cleaning robot.

One of the primary considerations in designing a solar panel cleaning robot is the cleaning mechanism. The cleaning mechanism should be able to remove dirt, dust, and debris from the surface of the solar panel without causing any damage. The use of different cleaning mechanisms, such as brushes, wipers, or air blowers, can be explored based on the type of solar panel and the type of debris to be removed. Different cleaning mechanisms may have different levels of effectiveness and may impact the surface of the solar panel differently. Thus, the suitable cleaning mechanism should be chosen based on the context such as the location of the solar panels site and the type of soiling.

Next, mobility is also an important consideration in the design of a solar panel cleaning robot. The robot must have the mobility to move around the surface of the panel, move up and down, as well as side to side, to clean the entire surface effectively. The robot should also be able to navigate around obstructions, such as wiring or mounting brackets, and handle changes in the slope of the panel.

Furthermore, the power supply is another critical consideration in the design of a solar panel cleaning robot. The robot should be able to operate for an extended period without needing to be recharged or refuelled. Solar-powered robots are an option, but they may not be suitable for cleaning panels in areas with limited sunlight or shaded areas. For a battery powered robot, the battery life will be a crucial factor on the operating time of the robot. For a large-scale solar panel farm, a battery powered cleaning robot may not be a wise selection. A battery powered cleaning robot could only operate within a small range. Therefore, the best power supply method will be the direct electricity power supply through the wiring method. The wire handling method should be considered to avoid distractions to the mobility of the robot.

Moreover, the control system is essential for ensuring that the robot can effectively clean the panels. The control system should be able to guide the robot around the panel and adjust the cleaning mechanism as needed to clean the surface effectively. The control system should also be able to monitor the robot's performance and detect any issues that may arise. Different solutions of the control systems could be selected based on the requirements. The most advanced solutions will be the artificial intelligence method. However, even the artificial intelligence method requires the basic signal transmission between the processing unit and the hardware components. Thus, the control system should be constructed from the basic operations, and enhanced gradually to achieve the final goal, which is the smart system.

Lastly, Safety is a crucial consideration in the design and operation of solar panel cleaning robots, especially given their proximity to electrical equipment. To minimise the risk of accidents, the robot must be equipped with sensors that can detect obstacles and prevent collisions with the solar panel or other equipment. The design should also ensure that the robot cannot damage the solar panel or fall off it during operation. In addition, it is vital to handle the use of water in the cleaning process carefully to avoid any contact with the electronic circuits, which could damage the robot or, worse still, cause a fire hazard due to a short-circuit condition. Therefore, proper insulation and waterproofing measures must be implemented to ensure the robot's safety and prevent any potential hazards.

In summary, the design considerations for a solar panel cleaning robot include the cleaning mechanism, mobility, power supply, control system, and safety. By considering these factors, designers can create effective and safe solar panel cleaning robots. Figure 2.1 shows the summary of the design considerations of a solar panel cleaning robot.

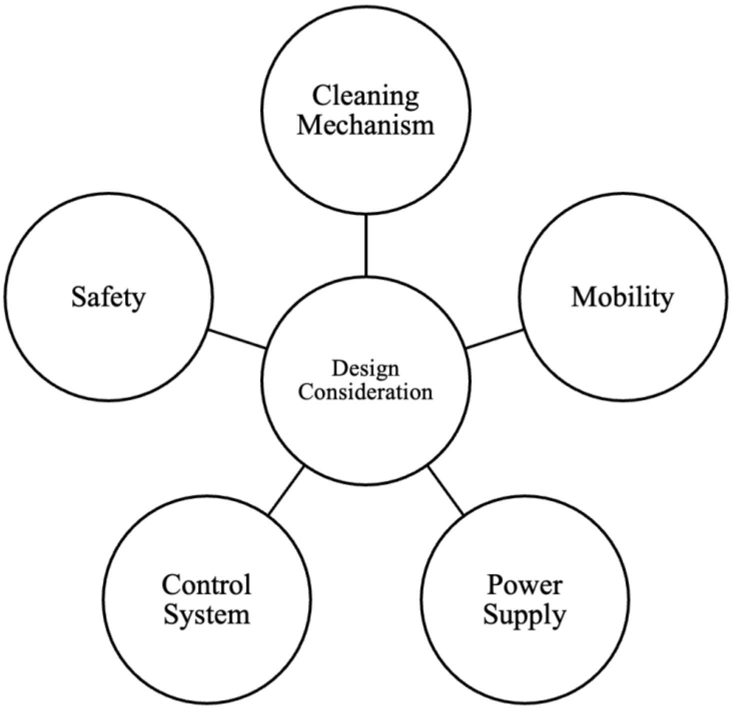

Figure 2.1: Design Considerations of Solar Panel Cleaning Robot.

2.7 Power and Energy Management of Solar Panel Cleaning Robots

The power and energy management of solar panel cleaning robots is a crucial aspect of their design, as they need to operate for extended periods without requiring frequent recharging or refuelling. These robots typically use a combination of renewable and non-renewable energy sources, including solar panels, batteries, and fuel cells, to power their operation. The design of the power and energy management system for a solar panel cleaning robot involves selecting the appropriate energy sources, optimising energy efficiency, and managing energy consumption to ensure the robot's long-term operation. Figure 2.2 shows the summary of the power and energy management of the solar panel cleaning robot.

One of the key factors to consider when designing the power and energy management system for a solar panel cleaning robot is the type of energy source to use. Solar panels are an obvious choice for powering these robots, as they can harness energy from the sun and store it in batteries for later use. However, solar panels may not be suitable for areas with limited sunlight or shaded areas. In such cases, other energy sources such as batteries or fuel cells may be used to supplement or replace the solar panels.

Another critical aspect of power and energy management for solar panel cleaning robots is optimising energy efficiency. Energy-efficient design is necessary to minimise energy consumption and maximise the robot's operating time. This involves using energy-efficient components, reducing weight and size, and minimising power losses in the system.

Next, managing energy consumption is also crucial to ensure the robot's long-term operation. Energy management systems must monitor the robot's energy consumption and adjust energy sources accordingly to prevent the batteries from running out of charge. This involves implementing intelligent energy management systems that optimise the use of renewable and non-renewable energy sources, such as solar panels and batteries.

Moreover, the selection of energy storage systems is also essential to the power and energy management of solar panel cleaning robots. Batteries are a common energy storage system used in these robots, as they can store energy from renewable sources such as solar panels and provide power when needed. However, batteries have limited capacity, which can limit the robot's operating time. Fuel cells can provide longer operating times as they convert chemical energy directly into electrical energy.

In summary, the power and energy management of solar panel cleaning robots involve selecting the appropriate energy sources, optimising energy efficiency, managing energy consumption, and selecting suitable energy storage systems. By considering these factors, designers can create efficient and sustainable solar panel cleaning robots that can operate for extended periods without requiring frequent recharging or refuelling. Figure 2.2 shows the summary of the power and energy management of the solar panel cleaning robot.

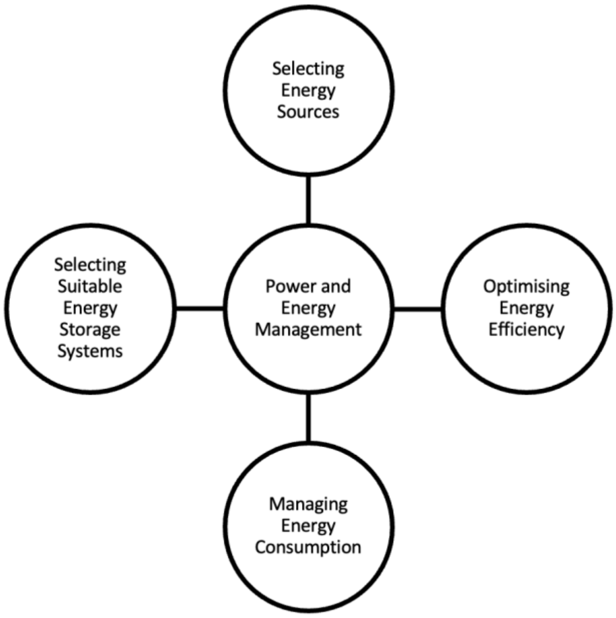

Figure 2.2: Power and Energy Management of Solar Panel Cleaning Robot.

2.8 Environmental Impact and Sustainability of Solar Panel Cleaning Robots

The use of solar energy has increased in recent years due to the need for clean and renewable energy sources. However, the maintenance of solar panels remains a challenge. Over time, solar panels can get dirty, reducing energy efficiency. As a solution, the use of solar panel cleaning robots has become increasingly popular. Although these robots can improve the efficiency of solar panels, it is important to consider their environmental impact and sustainability.

One major environmental impact to consider is the energy required to manufacture and operate the robots. The manufacturing process of solar panel cleaning robots requires significant energy, which contributes to greenhouse gas emissions. In addition, the operation of the robot requires electricity, which may be generated from non-renewable sources. These factors should be considered when assessing the overall carbon footprint of the robot.

Another significant impact to consider is the potential for water waste. Most solar panel cleaning robots use water to clean the panels, and if not properly managed, the use of large amounts of water can lead to water scarcity and contamination. However, there are innovative solutions to minimise water waste, such as the use of recycled water and the development of water-saving cleaning technologies.

Sustainability is another important aspect to consider when evaluating the overall impact of solar panel cleaning robots. The sustainability of a robot can be evaluated based on its durability, recyclability, and end-of-life management. It was found that some robots have a short lifespan due to their electronic and mechanical components wearing out quickly. This can lead to a significant amount of waste and increased environmental impact. To improve sustainability, robots should be designed with materials that can be easily recycled, and the end-of-life management of the robots should be carefully planned.

In addition to the manufacturing and operation of the robots, the transportation of the robots should also be considered. Transportation emissions can contribute to the carbon footprint of the robot. To minimise the transportation impact, robots can be designed to be easily assembled on site, reducing the need for transportation.

In conclusion, solar panel cleaning robots have the potential to improve the efficiency of solar panels, but their environmental impact and sustainability should be carefully considered. To minimise negative impacts, it is important to use renewable energy sources to power them, minimise water waste, and design them with recyclable materials. These considerations will contribute to the development of a sustainable solar energy ecosystem.

2.9 Comparative Analysis of Solar Panel Cleaning Robots

Solar panel cleaning robots have become increasingly popular in recent years as they provide an efficient and cost-effective way to maintain and clean solar panels. There are many different types of solar panel cleaning robots available, each with its own unique features and benefits. The comparative analysis of some of the most popular solar panel cleaning robots is done. Table 2.1 shows the summary of the solar panel cleaning robots mentioned in the paragraphs.

Firstly, the Ecoppia E4 robot is a fully autonomous, water-free cleaning system that uses a combination of microfiber and airflow to clean solar panels (Ecoppia, 2023). It is powered by solar energy and is designed to work in harsh weather conditions. The robot can clean up to 10,000 solar panels per day and has a cleaning efficiency of up to 99%. It also has a low power consumption rate and can operate in extreme temperatures, making it an ideal solution for large-scale solar panel installations.

The SolarBrush robot is a waterless cleaning system designed for solar panel maintenance (Robotics Business Review, 2013). It utilises a rotating brush to remove dust, debris, and other particles from solar panels. With its high cleaning efficiency, the SolarBrush robot can clean up to 1,200 solar panels per day. The robot is compact and lightweight, making it easy to transport and move around solar installations. Additionally, the SolarBrush robot is equipped with an autonomous navigation system that allows it to move around solar panels and obstacles without human intervention. It is also powered by solar panels, making it a sustainable and environmentally friendly solution for solar panel maintenance.

In addition, the SunBrush Mobil is a robotic system designed for cleaning solar panels without the use of water (SunBrush Mobil, 2023). It utilises a rotating brush system to effectively remove dust, dirt, and other debris from solar panels. With its high cleaning efficiency, the SunBrush Mobil can clean up to 200 panels per hour. The system is mounted on a vehicle, making it easy to transport and shift around large solar installations. Additionally, the SunBrush Mobil has a low power consumption and can operate in extreme temperatures, making it a reliable and efficient option for solar panel maintenance.

Lastly, the Helios Hexacopter is a drone designed specifically for the cleaning and maintenance of solar panels (Coxworth, 2022). Its water-based cleaning system utilises a combination of spray and brush technology to effectively remove dust, dirt, and other debris from solar panels. The Helios Hexacopter is powered by a rechargeable battery, making it a more sustainable option compared to traditional cleaning methods. With a cleaning efficiency of up to 95%, the Helios Hexacopter can clean up to 100 panels per hour at heights of up to 50 metres, making it a versatile option for large-scale solar installations. Additionally, the Helios Hexacopter is designed with a portable and compact frame, allowing for easy transportation and deployment to various locations. The drone can also be equipped with additional sensors and cameras for panel inspection and maintenance, making it a comprehensive solution for solar panel cleaning and upkeep.

In conclusion, there are many different types of solar panel cleaning robots available, each with its own unique features and benefits. When choosing a solar panel cleaning robot, it is important to consider factors such as cleaning efficiency, power consumption rate, and the ability to operate in extreme temperatures. Table 2.1 shows the summary of the solar panel cleaning robots mentioned in the paragraphs.

Table 2.1: Comparative Analysis of Solar Panels Cleaning Robots.

Robot Name	Cleaning System	Power Source	Capacity	Other Features
Ecoppia E4	Water-free (microfiber & airflow)	Solar energy	Up to 10,000 panels/day	Autonomous, low power consumption, can operate in extreme temperatures
SolarBrush	Water-free (rotating brush)	Battery	Up to 1200 panels/day	Autonomous navigation, powered by solar energy, compact and lightweight
SunBrush mobil	Water-free (rotating brush)	Petrol Fuel	Up to 200 panels/hour	Mounted on a vehicle, low power consumption, can operate in extreme temperatures
Helios Hexacopter	Water-based (spray & brush)	Battery	Up to 100 panels/hour	Operated by a drone, can clean at heights of up to 50 metres, portable and compact design, can also inspect panels for damage

2.10 Summary

In conclusion, the literature review has highlighted several important aspects of the solar panel cleaning robots. Despite the potential benefits of solar panel cleaning robots, there are several research gaps that need to be addressed in future studies.

Firstly, most of the studies have focused on the technical aspects of solar panel cleaning robots, including trajectory planning, control, and navigation. However, there is a lack of research on the economic feasibility of implementing solar panel cleaning robots, which is an important consideration for potential users. Future research can investigate the cost-benefit analysis of using solar panel cleaning robots compared to manual cleaning methods.

Secondly, the environmental impact of solar panel cleaning robots needs to be explored further. While solar panel cleaning robots have the potential to reduce water consumption and improve energy efficiency, the production and disposal of these robots may have negative environmental impacts. Therefore, future studies can focus on the life cycle assessment of solar panel cleaning robots to evaluate their environmental performance.

Thirdly, the effect of different cleaning techniques on the performance of solar panels needs to be investigated. Currently, there is limited research on the most effective cleaning technique for solar panels, and it is unclear which cleaning method is the most appropriate for different types of solar panels. Therefore, future studies can conduct comparative analysis of different cleaning techniques for solar panels.

Fourthly, there is a need to investigate the social acceptance of solar panel cleaning robots. Solar panel cleaning robots are a relatively new technology, and it is important to understand how potential users perceive them. Future studies can explore the attitudes of potential users towards solar panel cleaning robots and identify factors that influence their acceptance or rejection.

Lastly, the literature review has revealed the need for standardisation of testing and evaluation methods for solar panel cleaning robots. Standardisation of testing methods can improve the accuracy and reliability of the results obtained from different studies, and it can facilitate the comparison of the performance of different solar panel cleaning robots.

In summary, this literature review has identified several research gaps and future directions that need to be addressed to improve the efficiency, effectiveness, and sustainability of solar panel cleaning robots. By addressing these research gaps, solar panel cleaning robots can become a more viable and sustainable technology for cleaning solar panels.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In this chapter, the methodology and work plan done of the project is presented in detail. The solar panel cleaning robot consisted of two parts, which are the moving frame and cleaning robot. The moving frame carries the cleaning robot while the cleaning robot cleans the solar panels. The overall project can be divided into 3 sections, mainly the mechanical structure, the electrical and electronic circuit systems, and the software systems. The methodology sections will present the design of the mechanical structure, circuit systems, and the flow chart of the Arduino codes. Besides, the hardware used to construct the prototype will be listed down in this chapter. Lastly, the work plan section will present the project milestones and the Gantt Chart of the project.

3.2 Design Considerations

In this project, the cleaning robot targets industrial rooftop solar panels. A typical industrial rooftop could hold about 100 solar panels. The solar panels will be arranged into groups or arrays. Figure 3.1 shows an example of solar panels arrangement on an industrial rooftop. The recent common practice of solar panels installation suggested that a pathway should be reserved between the solar panel arrays for future services and maintenance. It is recommended to maintain a clearance around the entire solar panel array and establish a pathway between the rows to ensure safe and easy maintenance (Renewable Energy Laboratory et al., 2018). Normally, the industrial rooftop solar panels will suffer from the bird drops, dust, and watermarks issues. Therefore, the solar panels cleaning robot should be able to get rid of the stubborn and aggressive form of soiling, especially the bird drops.

Figure 3.1: Nine Arrays of Solar Panels on Industrial Rooftop.

The targeted solar panels site utilises array-arrangement. There will be gaps among the arrays. It would be an issue for the robot to move across the gap to the next array. Therefore, the robot was designed to avoid direct contact of robot wheels on the surface of the solar panels, instead a moving rail is designed for the cleaning robot. For the robot to move across the solar panels during cleaning operations, rails should be prepared for the robot so that the robot could move all over the solar panels, at the same time the wheels do not have contact with the surface of the solar panels. If the rails are constructed all over the solar panel frames, it could cost a high amount of expenses. The more the solar panels, the higher the costs required to construct and install the rails, which is very impractical. This project suggested a moving frame to replace the construction of high-cost redundant rail. The solar panels cleaning robot consists of two main parts which are the moving frame and cleaning robot. The moving frame, serving as the rail, carries the cleaning robot to the desired location, while the cleaning robot performs the cleaning tasks.

Next, the solar panels are installed with specific tilting angles. The moving frame was designed to be horizontal for the cleaning robot to move back and forth on the moving frame. To deal with the tilting angles of the solar panels, linear actuators are used. Linear actuators hold the cleaning brush, so that the cleaning brush could move downwards to clean low-level position. Lastly, a high-speed rotating brush will be used in the robot to remove stubborn dirt, especially bird drops and water marks. Water will be sprayed to the solar panels to aid the cleaning process.

In brief, the design considerations covered the movement of the robot across the solar panels, the installation method of the solar panels, and the type of dirt to be cleaned. In this project, the robot was designed to be moved on a moving frame, so that the wheels of the cleaning robot would not contact directly to the surface of the solar panels. This design ensures that the surface of the solar panels will not be damaged by the robot body and solves the gap issues of the array-arrangement. Next, a pair of linear actuators will be used to hold the cleaning brush so that they could bring the cleaning brush to a lower position for solar panels installed with tilting angle. Lastly, a high-speed rotating brush and a water sprayer will be used to clean stubborn dirt. Table 3.1 summarises the problems and solutions accordingly.

Table 3.1: Design Considerations.

Problems	**Solutions**
Gaps among solar panel arrays.	Moving Frame carries the cleaning robot.
Direct contact of robot on the solar panel surface.	Moving Frame carries the cleaning robot.
Tilting angle installation of solar panel.	Linear actuator holds the cleaning brush.
Stubborn dirt.	High-speed rotating brush with water sprayer.

3.3 Mechanical Structural Design

The first stage of the project started with the mechanical structure design. The mechanical structure design was done in AutoCAD software. Figure 3.2 shows the complete design of the solar panel cleaning robot. The solar panel cleaning robot consists of two parts which are the moving frame and cleaning robot. The moving frame serves as a track for the cleaning robot. The cleaning robot moves on top of the moving frame to perform the cleaning operation.

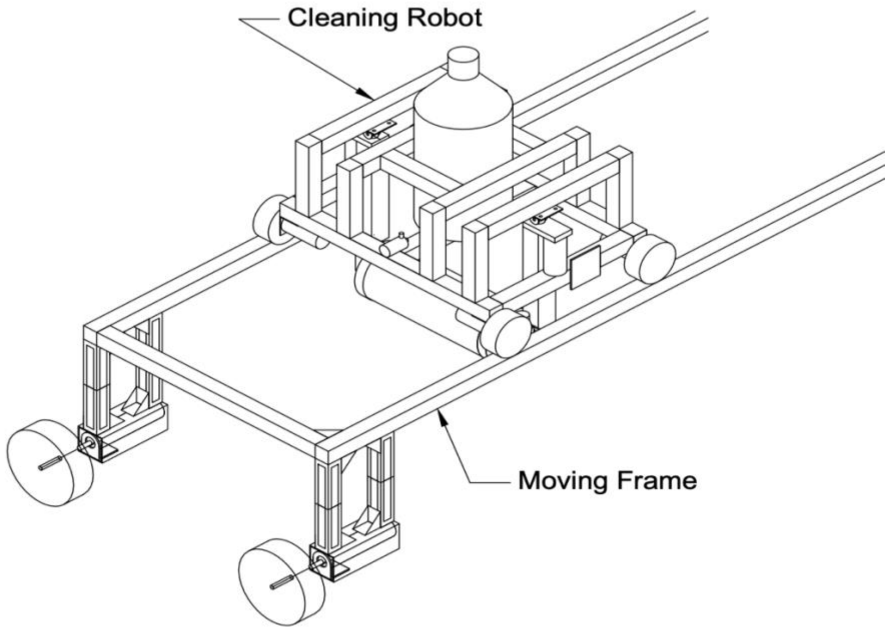

Figure 3.2: Solar Panel Cleaning Robot Overview.

The mechanical structure designs were drawn as shown in the figures below. Figure 3.3 and Figure 3.4 show the orthographic and isometric drawing of the moving frame respectively. The full-size figures will be inserted in the appendices if the details of the design are needed for study purposes. The orthographic drawing consists of the top view, front view, and the side view of the moving frame. The moving frame is designed to have a length of 4360 mm which is connected by four 1-metre aluminium profiles and one 360 mm aluminium profile. In the isometric drawing of the moving frame, only one side of the moving frame was drawn. The purpose of the isometric drawing is to provide better visualisation of the overall design.

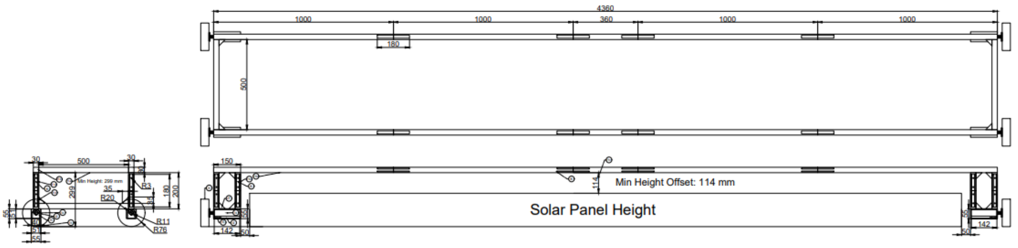

Figure 3.3: Orthographic Drawing of Moving Frame.

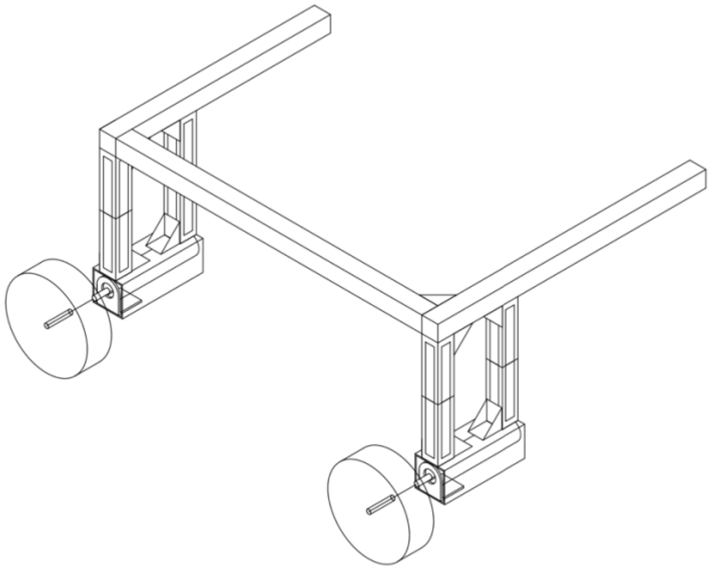

Figure 3.4: Isometric Drawing of Moving Frame.

Figure 3.5 shows the orthographic drawing of the cleaning robot. The orthographic drawing of the cleaning robot consists of the top view, side view, and the front view of the cleaning robot. The blue lines represent the dimensions of the drawings.

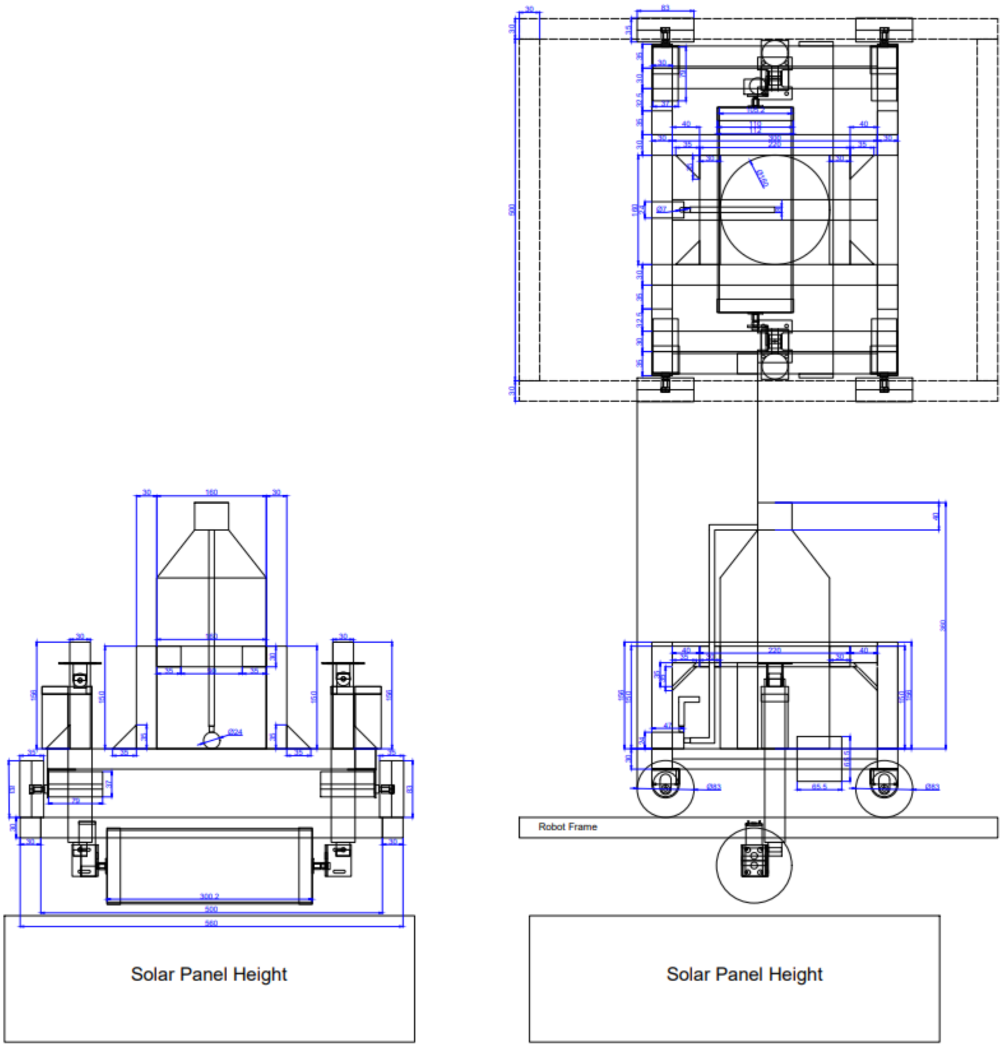

Figure 3.5: Orthographic Drawing of Cleaning Robot.

Figure 3.6 shows the isometric drawing of the cleaning robot. All the drawings were drawn in the initial design stage. After constructing the real hardware, there would be modifications done on the prototype. The drawings serve as a guide to determine the materials and components required for the prototype. Most importantly, the drawings provided a visualisation guide for the developer to avoid overlooking considerations.

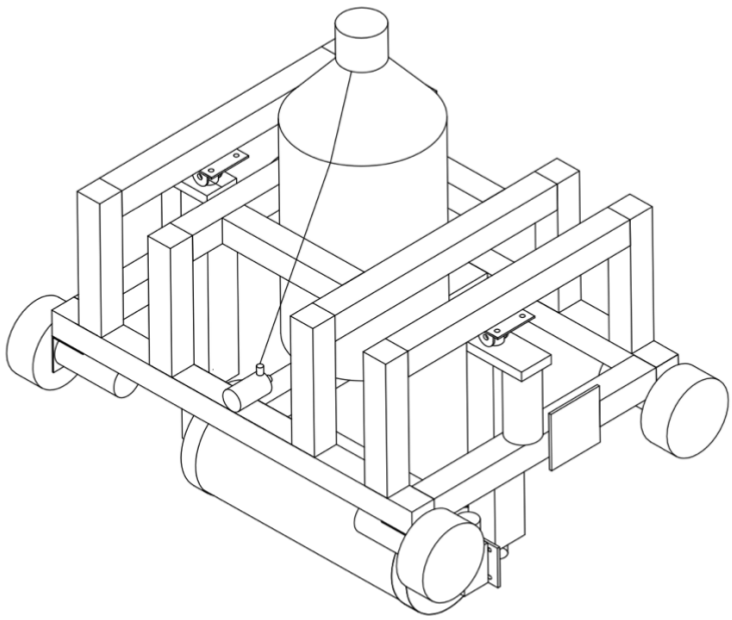

Figure 3.6: Isometric Drawing of Cleaning Robot.

3.4 Electrical and Electronic Circuit Design

After the mechanical structure design, the materials and components required by the robot were confirmed. The second stage of the project was the electrical and electronic circuits design. It was decided to use electrical supply from the socket to power up the robot. Therefore, the circuit design would consider the 240 V AC power supply. The overall project consists of two products, which are the moving frame and the cleaning robot. The two products will have their Arduinos serve as the processing unit. The electronic circuits design was based on the processing unit. Two separated circuits could be noticed from Figure 3.7. The circuit design was done through drawing of schematic diagrams by draw.io online software. The schematic diagram of the moving frame and the cleaning robot is shown in Figure 3.7. There are two processing units which are the Nano Compatible CH340, and the Arduino Mega. The CH340 is an

Arduino Nano produced by another company. It is compatible with the real Arduino Nano.

There would be only one AC power supply from the socket. Although the robot design can be divided into two parts, both of them are still being considered as one robot. Therefore, only one power supply used is more practical and convenient. From the power supply, there would be two wires connected parallelly to two different switching power supplies to convert 240 V AC to 24 V DC. The switching power supplies were chosen to provide 24 V DC due to the reason that all the motors used for the wheel applications required 24V. For the Arduinos, 7-12 V DC is required to provide optimum operating voltage to them. It could be noticed that there are two buck converters used to power up the Arduinos. They step down the voltage from 24V DC to 12V DC.

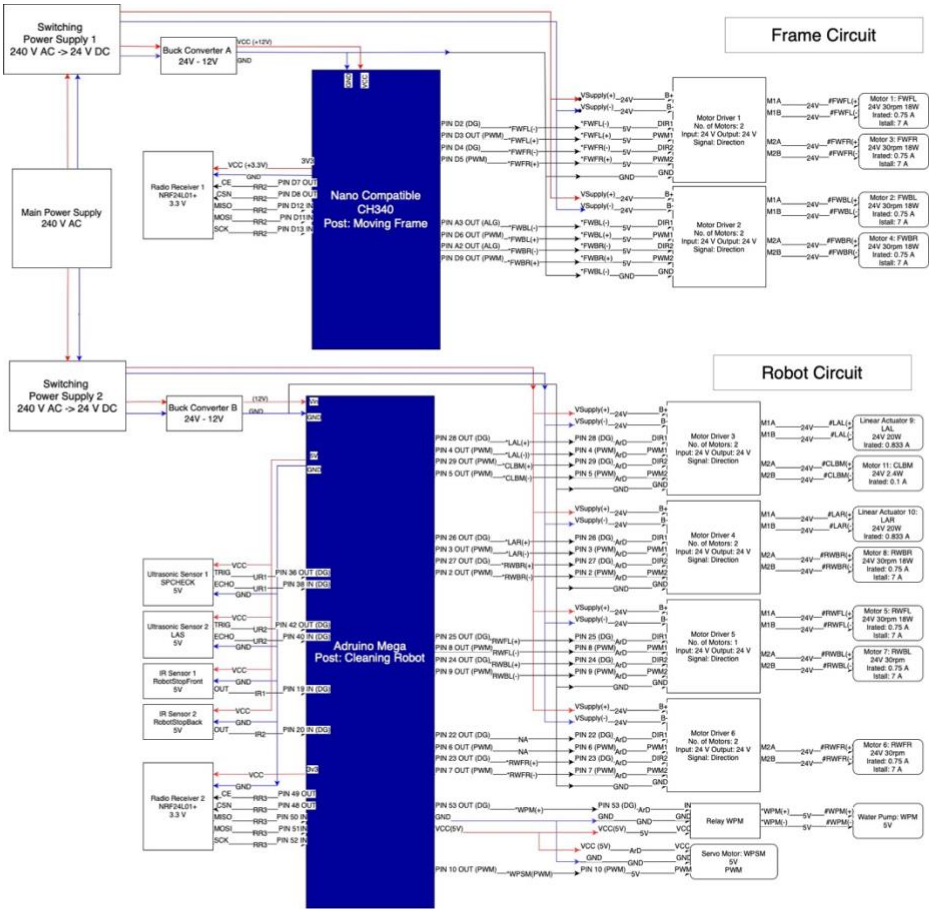

Figure 3.7: Overall Circuit Schematic Diagram.

3.4.1 Moving Frame Circuit Design

Nano Compatible CH340 is used as the processing unit of the moving frame circuit. The moving frame circuit consists of 4 wheels and a radio transceiver. The connections of each input and output are shown in Figure 3.8.

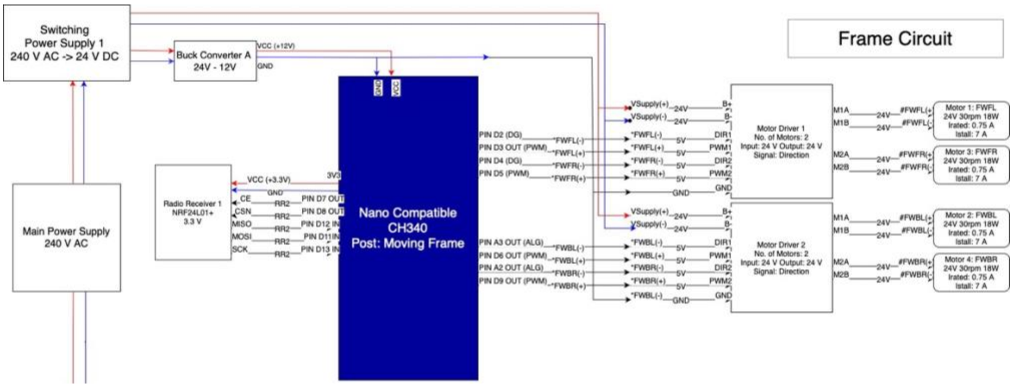

Figure 3.8: Moving Frame Circuit Schematic Diagram.

3.4.2 Cleaning Robot Circuit Design

Arduino Mega is used as the processing unit of the cleaning robot circuit. The cleaning robot circuit consists of 4 wheel-motors, 2 linear actuators, 1 cleaning brush motors, 1 water pump, 1 servo motor, 2 ultrasonic sensors, and 2 IR sensors. Figure 3.9 shows the circuit schematic diagram of the cleaning robot.

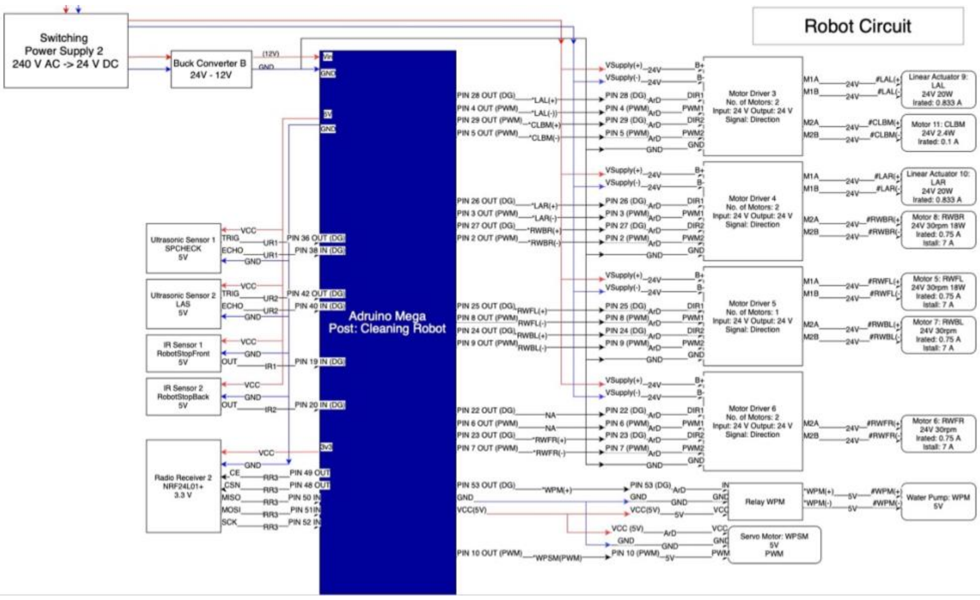

Figure 3.9: Cleaning Robot Circuit Schematic Diagram.

3.5 Hardware and Software Chosen

3.5.1 Hardware Materials and Components

Table 3.2 shows the materials and components used. The materials and components shown in the table are those highlighted main components used for the construction of the prototype.

Table 3.2: Materials and Components Used.

Components	**Quantity**
Aluminium Profile (30 mm x 30 mm)	18 meters
Aluminium Square Tube (55 mm x 55 mm)	4 x 150 mm
PVC Pipe (D = 110 mm, L = 300cmm)	1
Cushion Brush (360 mm)	2
Wheels Motor - 30 rpm (GA36Y-555-CE)	8
Cleaning Brush Motor - 150 rpm (JGY-370-CE)	1
Linear Actuators (L = 250mm, Extend = 150 mm)	2
Cleaning Brush Motor Coupler	2
Mecanum Wheels (152 mm)	4
Cleaning Robot Rubber Wheels	4
Water Pump	1
Motor Driver (MDD10A)	6
Radio Transceiver (nRF24L01+)	3
Arduino Mega	1
Arduino Nano	1
InfraRed Sensor (SN-IR-MOD)	2
Ultrasonic Sensor (HC-SR04)	2
Switching Power Supply (220 AC – 24 DC)	2
Buck converter	3

3.5.2 Software

Three software were used throughout the project. They were the AutoCAD, draw.io, and Arduino IDE. AutoCAD software was used to draw the prototype in the planning and design stage. The AutoCAD illustrated the model of the prototype to provide good visualisation so that the suitable hardware could be chosen. Figure 3.10 shows the interface of the AutoCAD software.

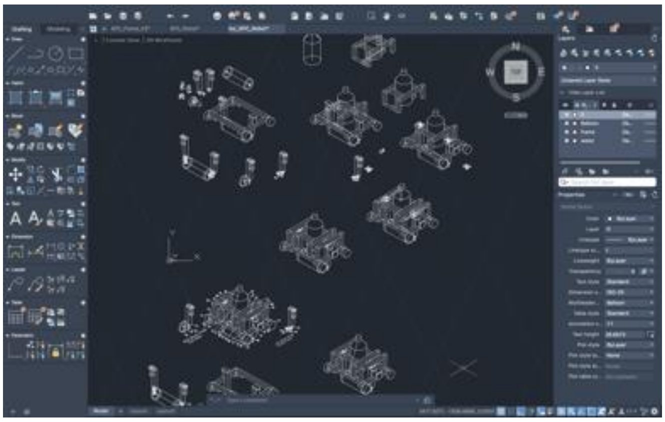

Figure 3.10: AutoCAD Software Interface

Next, draw.io software was used to draw circuit schematic diagrams and programming flowcharts. The circuit schematic diagram was important to illustrate the electrical and electronic circuits of the robot. There were a lot of wire connections for power supply and signal transmission through Arduinos. The circuit schematic diagram would record the pins connections for every component. It served as a guide for electrical and electronic hardware construction. Figure 3.11 shows the interface of the draw.io online software.

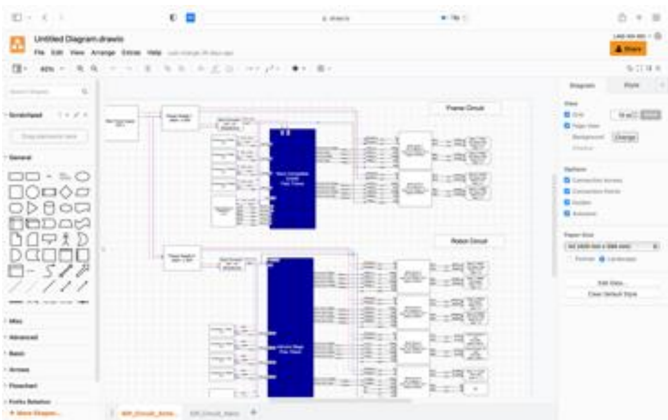

Figure 3.11: Draw.io Online Software Interface

Lastly, 2 Arduinos are used in the project, which are the Arduino Mega and Arduino Nano. Hence, Arduino IDE was used to write and compile the Arduino Codes. Arduino IDE was also used to upload the written codes to the Arduinos. Furthermore, Arduino IDE provided a serial monitor function which helped the user to trace the condition of the program during the practical testing and debugging task. Figure 3.12 shows the interface of the Arduino software.

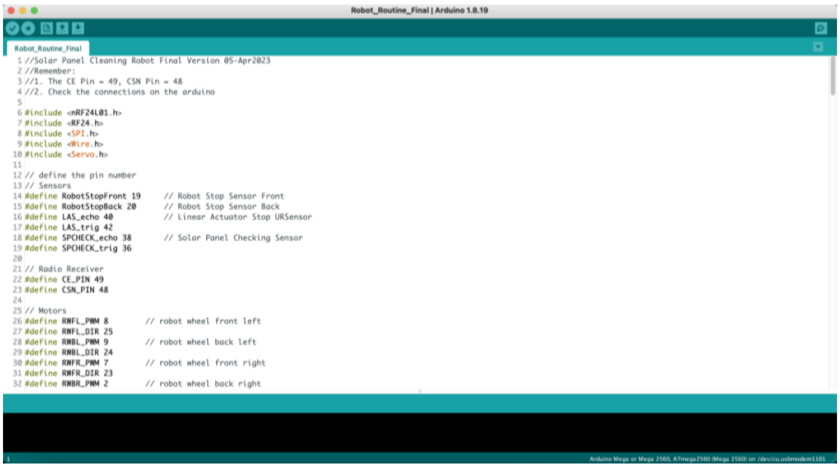

Figure 3.12: Arduino Software Interface

3.6 Testing Environment

Figure 3.13 shows the illustration of the testing environment. In the prototype demonstration, the size of the moving frame would be scaled down due to the lack of space in the indoor testing environment. The length of the moving frame was reduced from 4360 mm to 2000 mm. The middle section of the moving frame was removed. The moving frame used for practical testing had a length of 2 metres only, which was wide enough to cover the length of the solar panel.

The testing environment was set to have 3 solar panels with the size of 1.64 m x 0.992 m for each panel. The 3 solar panels were arranged in columns. The group arrangement of the solar panels is called a solar array. The solar array in Figure 3.9 consists of 1x3 (row x col) solar panels. Figure 3.14 marks the cleaning column which will be cleaned sequentially by the robot. The robot will clean the 1st cleaning column followed by the 2nd until the last column. Each cleaning column is about 30 cm (300.2 mm), which is the length of the cleaning brush. The robot will move horizontally in the testing environment.

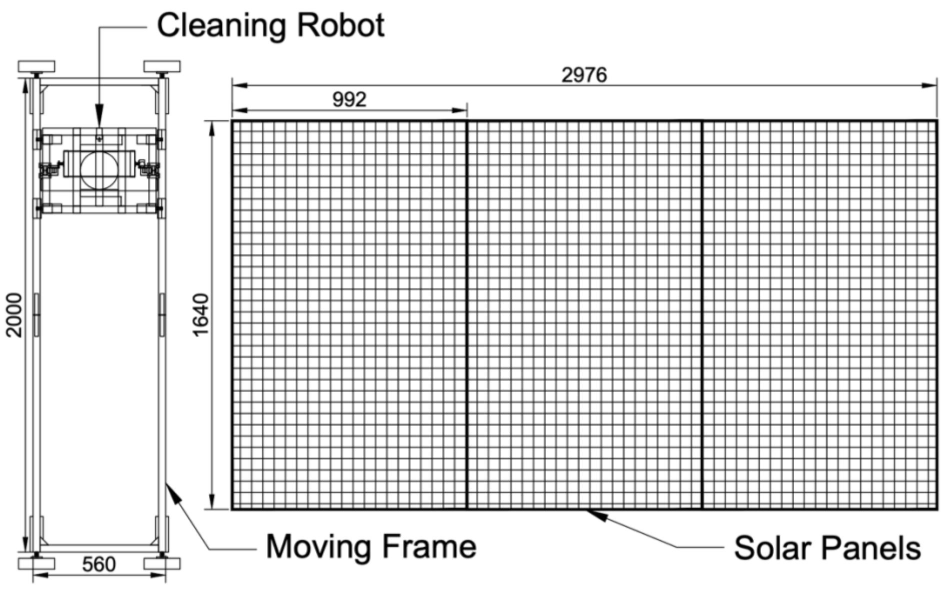

Figure 3.13: Testing Environment Drawing.

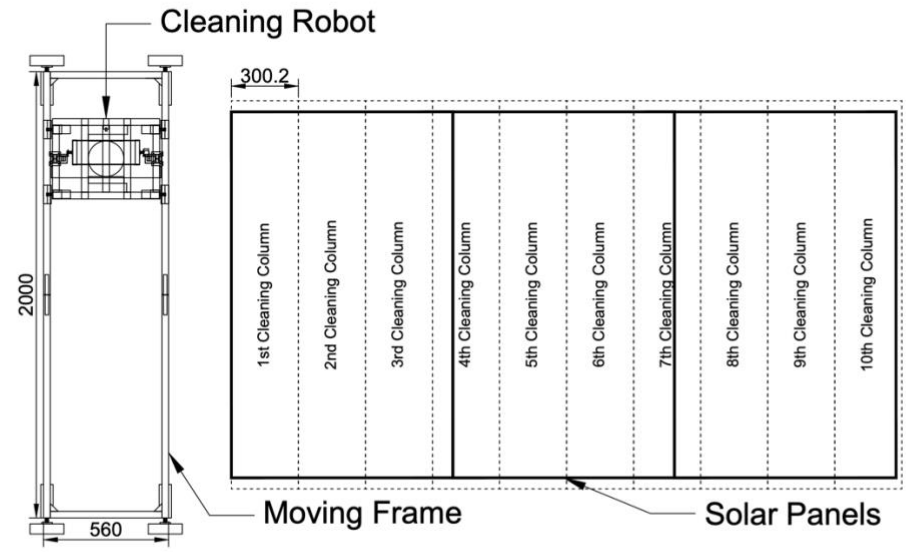

Figure 3.14: Cleaning Column of Solar Panel Array.

3.7 Programming Flowchart

Figure 3.15 shows the flowcharts of the moving frame and the cleaning robot. The communications between the two Arduino are represented in coloured lines. The red lines show the transmitting of messages from the cleaning robot to the moving frame, while the blue lines show the transmitting of messages from the moving frame to the cleaning robot. On planning the flowchart of the programs, some assumptions have to be made. Firstly, the robot should be prepared at the first cleaning position before the switch is turned on. The moving frame will be assumed at the first cleaning position, and the cleaning operation will start without checking the position of the moving frame. The cleaning robot always returns to the original position when the switch is turned on. Most importantly, the moving frame must be placed at the correct position before the switch is turned on.

In the beginning of the program, both programs will perform the setup operations. After the setup preparation, the moving frame will wait for the message “Ori Posi” from the cleaning robot. On the other hand, the cleaning robot will return to its original position during the setup preparation. If the cleaning robot is already in the starting position (original position), the “RobotStopBack” sensor will detect obstacles and stop the back movement of the cleaning robot. Now, the original position of the cleaning robot is achieved. Then, the cleaning robot will start the cleaning operation directly without checking the presence of the solar panel since the assumption has been made before that the robot will be placed directly on the first cleaning position before the switch starts.

After the first cleaning operation, the cleaning robot will transmit the message “Ori Posi” to the moving frame. The “Original_Position” function is included inside the “Cleaning_operation” function. Hence, the cleaning robot will return to its original position after every cleaning operation. As the moving frame receives the “Ori Posi” message, the moving frame will move forward for 5 seconds, which is about 30 cm to the next cleaning column. After sending the message “Ori Posi”, the cleaning robot will wait for the message “Check_SP” from the moving frame. The “Check_SP” message serves to tell the cleaning robot to check for the presence of the solar panel. The cleaning robot will continue the cleaning if the solar panel is present. In contrast, the cleaning robot will not perform the cleaning if the solar panel is not present. The “Check_SP” message will be sent by the moving frame after the moving frame completes the 5-second front movement. On the completion of front movement, the moving frame will tell the cleaning robot to check the presence of the solar panel. The cleaning robot will send “SP_Yes” to the moving frame if the solar panel is present, while “SP_No” will be sent if the solar panel is absent.

In the condition in which the solar panel is present, the cleaning robot will transmit the message “SP_Yes” to the moving frame and wait for the message “Clean” from the moving frame. In the moving frame, if the message “SP_Yes” is received, the moving frame will transmit the message “Clean” to the cleaning robot. The cleaning robot will perform the next cleaning operation after receiving the message “Clean” from the moving frame.

In the condition in which the solar panel is absent, the cleaning robot will transmit the message “SP_No” to the moving frame and undergo an 8-second delay before it starts to check the presence of the solar panel again. This condition is designed for the completion of cleaning on one array. After cleaning all the solar panels in one array, the moving frame will move out from the array. Hence, the solar panel checking sensor will not detect the presence of the solar panel. When the moving frame receives the message “SP_No”, it will start to move backwards. In the beginning of moving backwards, the moving frame may still remain out of range of the solar panel array. The solar panel checking sensor will detect the absence of the solar panel in this duration of time. Therefore, the 8-second delay of the cleaning robot is designed to wait for the moving frame to return into the solar panel array. The moving frame will definitely return to the solar panel array within 8 seconds. After 8 seconds, the solar panel checking sensor on the cleaning robot will start detecting the presence of the solar panel. The goal of this checking procedure is to detect the absence of the solar panel when the moving frame arrives at the initial position. The solar panel checking sensor will repeat the checking procedure until it detects the absence of a solar panel. Then, a message “Reached Initial” will be sent to the moving frame to stop the backward movement.

After the moving frame stops, it will move forward for 2.5 seconds. When the moving frame stops, it is located outside of the solar panel array. The 2.5-second forward movement is to move the moving frame back into the solar panel array so that the cleaning brush will be prepared in the correct position. Finally, the moving frame will send the message “Clean” to the cleaning robot. The routine cleaning is restarted.

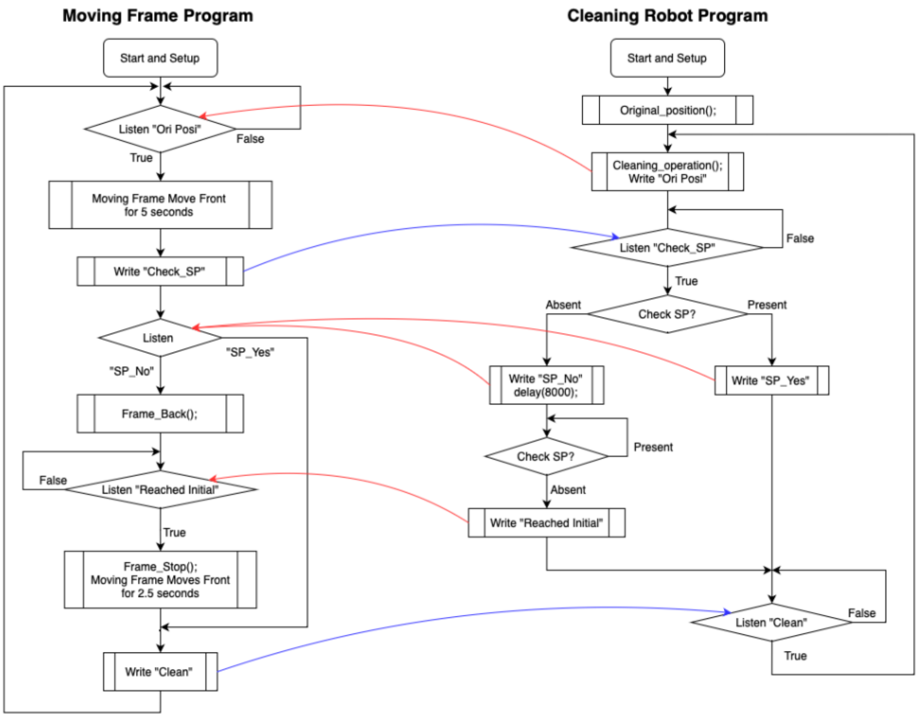

Figure 3.15: Programming Flowcharts of Overall Robots.

Figure 3.16 shows the illustration of the robot operation based on the flowchart in Figure 3.15. The operation will be described in numbering form according to the number marked in Figure 3.16. The project is considered a success if the robot could complete the operation.

The robot operation steps are:

1. The robot is prepared at the first cleaning column before the switch is turned on.
2. The power supply is switched on. The cleaning robot will start the cleaning operation on the 1st cleaning column. The cleaning robot moves from the red position to the green position, then it returns from the green position to the red position.
3. The 1st cleaning column is completed. The moving frame carries the cleaning robot to the 2nd cleaning column.
4. The same cleaning operation is repeated as in the 1st cleaning column. The cleaning operation is repeated until the moving frame moves out the solar panel array.
5. The moving frame completes the cleaning on the solar array. It is located at the outside of the solar panel array.
6. The moving frame carries the cleaning robot to the initial position. The moving frame will keep on moving to the left (as shown in the 6th step of Figure 3.16) until the solar panel checking sensor detects the absence of the solar panel.
7. When the solar panel checking sensor detects the absence of the solar panel, the moving frame will stop. The moving frame will move to the right for 2.5 seconds to adjust its position to the 1st cleaning column.
8. The moving frame and the cleaning robot are located at the 1st cleaning column as step 1. Step 1 to 7 repeats until the switch is off.

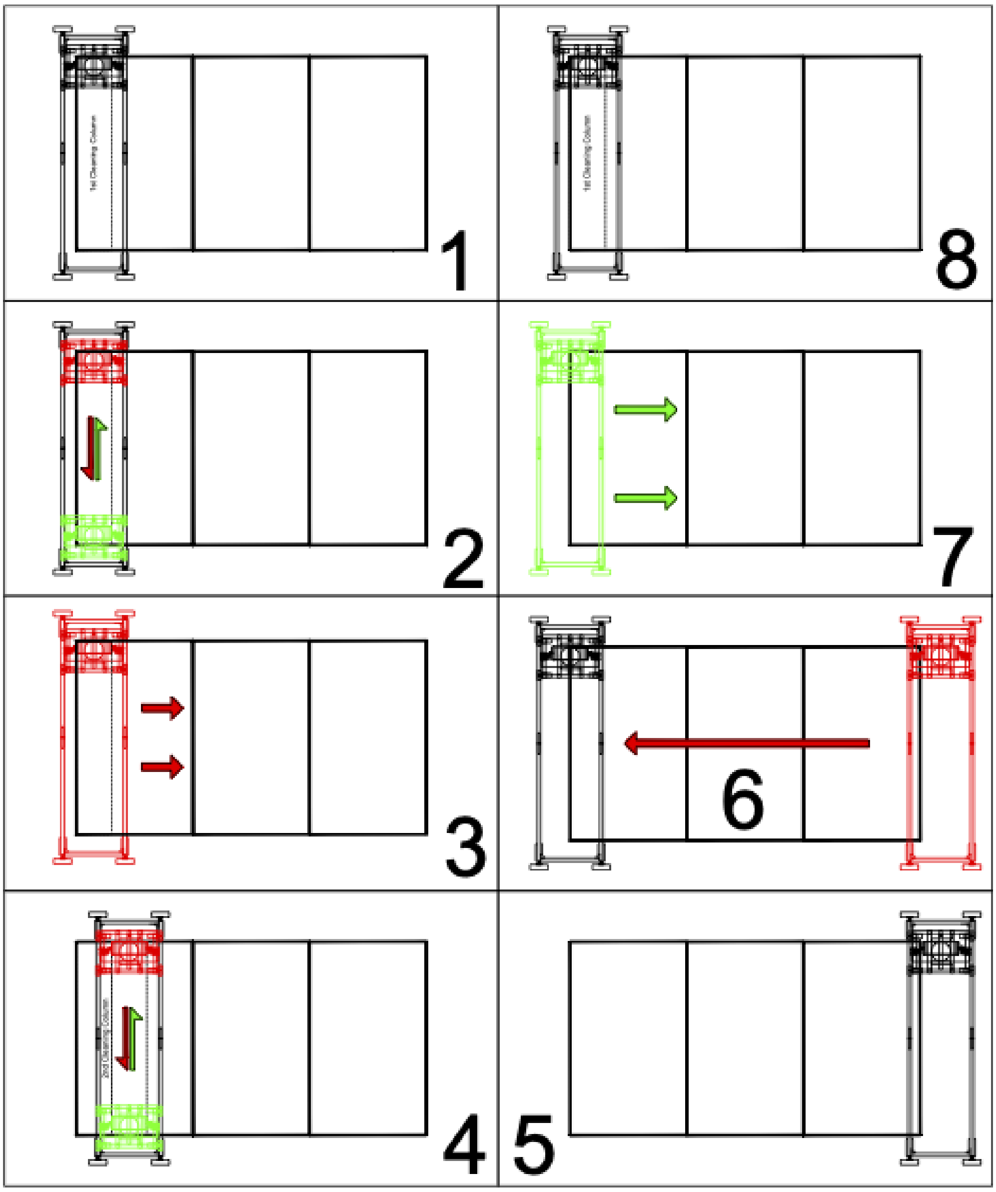

Figure 3.16: Robot Operation Illustration.

3.8 Experimental Planning and Setup

Figure 3.17 shows the flowchart of the project planning. In this project, the design of the robot was formulated to enhance the smoothness of the project. The orthographic drawings recorded the dimensions of the robot design, while the isometric drawings provided visualisation in the beginning stage. Next, the electrical and electronic circuits design was drafted to list the electrical and electronic components systematically. All the draft drawings were prepared for the purchase of materials and components. The construction of the robot could start after all the required materials and components were obtained.

The mechanical body of the robot was constructed followed by the electrical and electronic circuits. Every component, especially the electrical and electronic components would be tested individually before the assembly of components. When the prototype construction was completed, the basic functions of the robot such as moving the wheels, lowering down the linear actuators, and switching on the water pump would be tested.

The next stage would be defining the testing environment. The prototype should be able to perform tasks in the testing environment automatically. Figure 3.16 shows the illustration of the operation of the robot in the testing environment. In the testing environment, three solar panels were arranged in a row. The robot would clean the solar panels from the starting point to the ending point, then the robot would return to the starting point. The process would repeat endlessly. By achieving this, the prototype would be considered as a success model. The practical testing and debugging would focus on distance movement of the robot as well as the timing, so that the routine could be repeated smoothly.

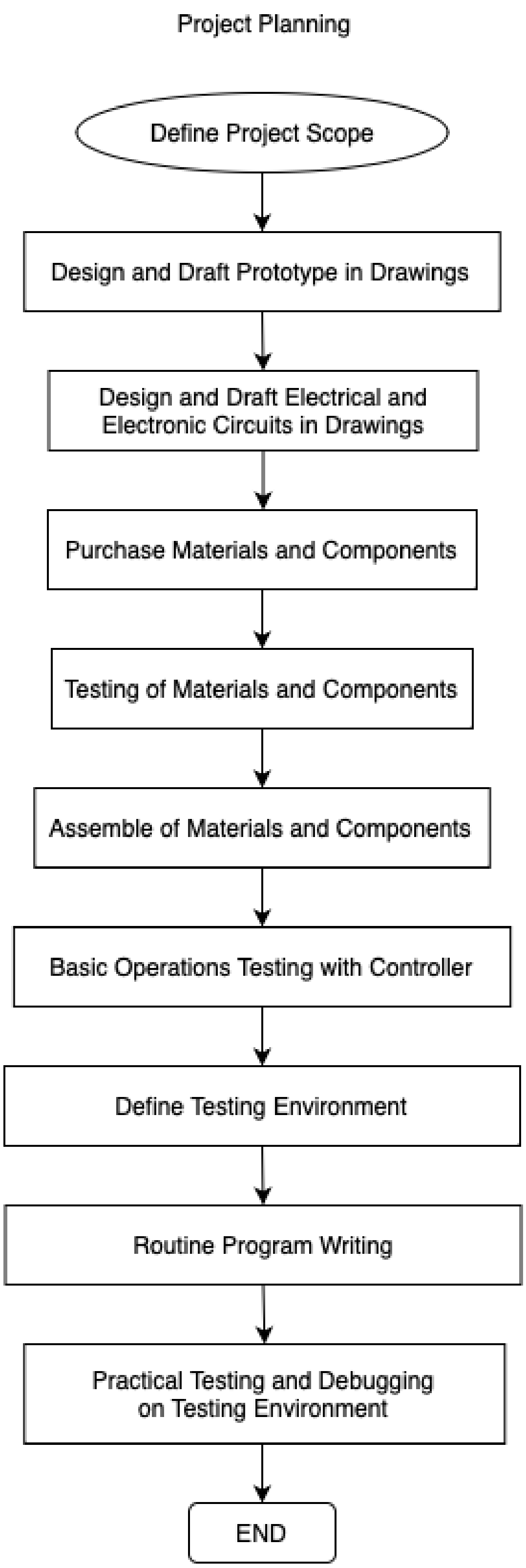

Figure 3.17: Flowchart of Project Planning.

3.9 Work Plan

The project was planned with schedule to ensure the smoothness of the project. All the activities or milestones could be completed in time with the milestones and dates scheduled. The planning of the work would serve as a guide to complete the project. The milestones and period of the project was determined together with the weeks.

3.9.1 Milestones and Duration

Table 3.3 shows the milestones and duration for each activity. The milestones and duration were planned to serve as reference during the project timeline.

Table 3.3: Milestones and Duration.

Trimester	Milestones	Duration (Weeks)	Remark
FYP1 (13 Weeks)	Literature Review	9	Week 1 - 9
	Drawings of FRAME	1	Week 1
	Drawings of CLEANING ROBOT	2	Week 2 - 3
	Purchase of Hardware Materials	2	Week 4 - 5
	Circuit Design and Schematic Drawing	2	Week 5 - 6
	Arduino Program Writing	2	Week 6 - 7
	Mechanical Hardware Construction	2	Week 7 - 8
	Circuit Board Construction	2	Week 8 - 9
	Assembly of Hardware and Circuits	2	Week 9 -10
	Testing and Debugging of Prototype	4	Week 10 - 13
	Progress Report Writing	6	Week 8 - 13
Break (2 Weeks)	Improvement of Mechanical Hardware	5	Week 1 - 2
FYP 2 (13 Weeks)			Week 1 - 3
	Testing Environment Set Up	2	Week 1 - 2
	Application of Automated System	2	Week 3 - 4
	Practical Testing and Debugging	4	Week 4 - 7
	Final Report Writing	5	Week 8 - 12

3.9.2 Gantt Chart

Table 3.4 shows the Gantt chart of the project. The project was divided into two phases. The activities for each phase are listed clearly in the Gantt chart.

Table 3.4: Gantt Chart.

Trimester			Final Year Project 1													Break		Final Year Project 2											
Phase	No.	Project Activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W1	W2	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12
1	M1	Literature Review	■	■	■	■	■	■	■	■	■																		
	M2	Drawings of FRAME	■																										
	M3	Drawings of CLEANING ROBOT		■	■																								
	M4	Purchase of Hardware Materials				■	■																						
	M5	Circuit Design and Schematic Drawing					■	■																					
	M6	Arduino Program Writing						■	■																				
	M7	Mechanical Hardware Construction							■	■																			
	M8	Circuit Board Construction								■	■																		
	M9	Assembly of Hardware and Circuits									■	■																	
	M10	Testing and Debugging of Prototype										■	■	■	■														
	M11	Progress Report Writing								■	■	■	■	■	■														
2	M12	Improvement of Mechanical Hardware														■	■	■	■	■									
	M13	Testing Environment Set Up																■	■										
	M14	Application of Automated System																		■	■								
	M15	Practical Testing and Debugging																			■	■	■	■					
	M16	Final Report Writing																							■	■	■	■	■

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In Chapter 4, the result of the project, the solar panel cleaning robot is presented. This chapter will cover the prototype presentation, the programming techniques and considerations, and the discussions on the project prototype. In the prototype presentation, the highlighted parts of the prototype will be presented in detail together with figures accordingly. In the programming sections, the programming techniques used in writing the Arduino codes will be discussed. The last section of the chapter will discuss the considerations made on the hardware prototype.

4.2 Prototype Presentation

4.2.1 Prototype Overview

Figure 4.1 shows the overall robot prototype. The cleaning robot is located on the moving frame. The moving frame is a mechanism to carry the cleaning robot. The moving frame ensures the cleaning robot can move on top of the solar panel during the cleaning task. The moving frame serves as a rail to guide the movement of the cleaning robot. The cleaning robot does not move directly on the surface of the solar panel. The wheels of the cleaning robot are moving on the rail, while the cleaning brush extends downwards to reach the solar panel. The presence of a moving frame as a rail guide, the cleaning robot will always move front and back only on the moving frame.

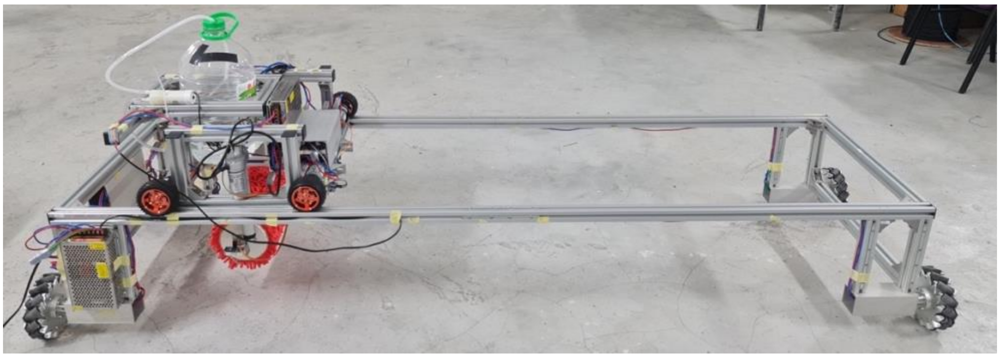

Figure 4.1: Solar Panel Cleaning Robot Prototype.

4.2.2 Cleaning Robot on the Moving Frame

Figure 4.2 shows the condition of the cleaning robot on the moving frame. Figure 4.3 provides the front view of the cleaning robot. From Figure 4.2 and Figure 4.3, it could be noticed that the cleaning robot is staying inside the moving frame instead of exactly on top of the moving frame. The location of the cleaning robot wheels allows the cleaning robot to remain in the moving frame. This is to avoid the cleaning robot from falling from the moving frame during the cleaning operation. The falling of the cleaning robot from the moving frame is caused by the unsynchronised speed of the cleaning robot wheels. The speed of each robot wheel is not the same. Although the speeds of the wheels were measured to be as similar as possible among each other, there is still a slight difference among 4 of them. Therefore, the cleaning robot was designed to stay in the moving frame to eliminate the possibility of the robot to fall out from the moving frame. This design arose a new problem, which is that the cleaning robot base that is located inside the moving frame would occasionally collide and rub against the moving frame. This problem will affect the movement of the robot since greater force is required to deal with the friction. Besides, the consistent collision and friction will cause wear and tear of materials. Therefore, a cushion brush was designed to cushion the spaces between cleaning robot base and the moving frame rail.

Figure 4.2: The Cleaning Robot.

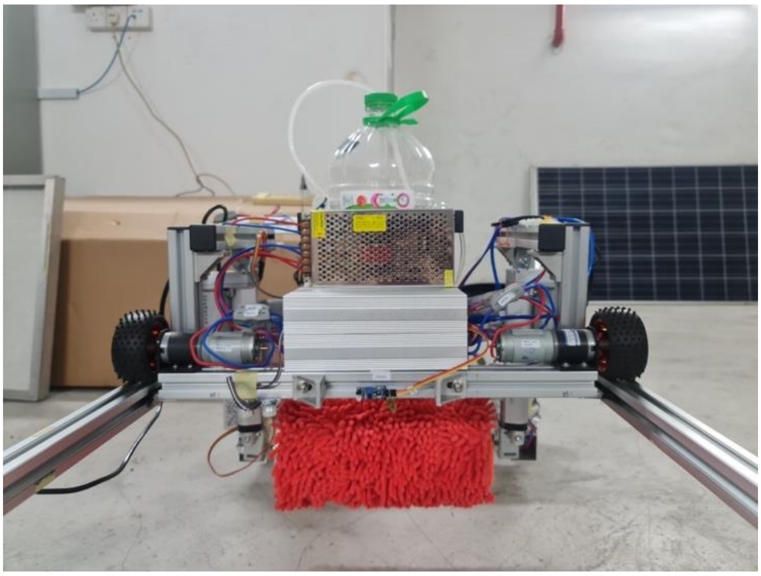

Figure 4.3: Front View of the Cleaning Robot.

4.2.3 Cushion Brush of the Cleaning Robot

Figure 4.4 shows the location of the cushion brush on the cleaning robot. Due to different speeds of the motors, the movement of the cleaning robot will not be exactly straight on the moving frame. As the cleaning robot moves offset from the track, the cushion brush will prevent the cleaning robot from colliding with the moving frame. Furthermore, the cushion brush will reduce the friction between the cleaning robot base and the moving frame. Thus, the smooth movement of the cleaning robot on the moving frame could be ensured.

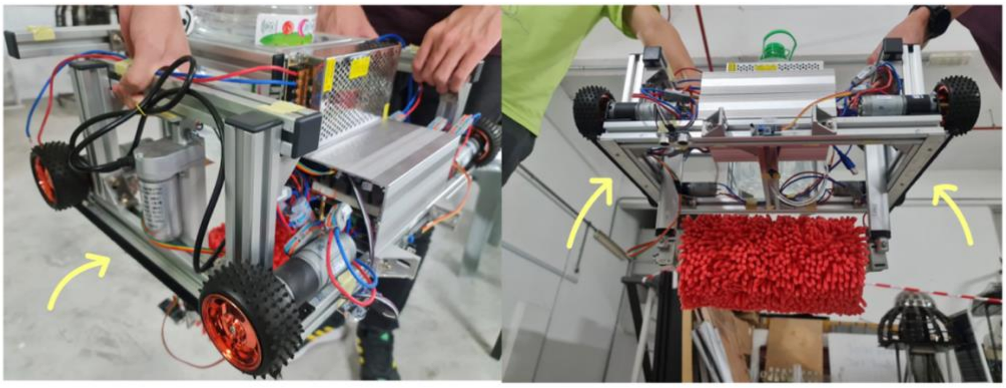

Figure 4.4: Cushion Brush of the Cleaning Robot.

4.2.4 Electronic Box of the Moving Frame

Figure 4.5 shows the electronic box of the moving frame. The electronic box of the moving frame is located at the left side. The electronic box of the moving frame contains the electronic components such as the motor drivers, buck converters, Arduino Nano, and the radio transceiver. Figure 4.6 shows the electronic circuits of the moving frame in the electronic box. All the important electronic components are compacted inside the electronic box. The electronic box could provide physical protection to the electronic components to avoid careless contact which will lead to broken connections of the components. There is a program uploader wire connected to the Arduino Nano. The program uploader is stretched to the outside so that the program uploading work could be done easily even if the electronic box is installed onto the moving frame. This practice is encouraged during the prototype testing and debugging stage.

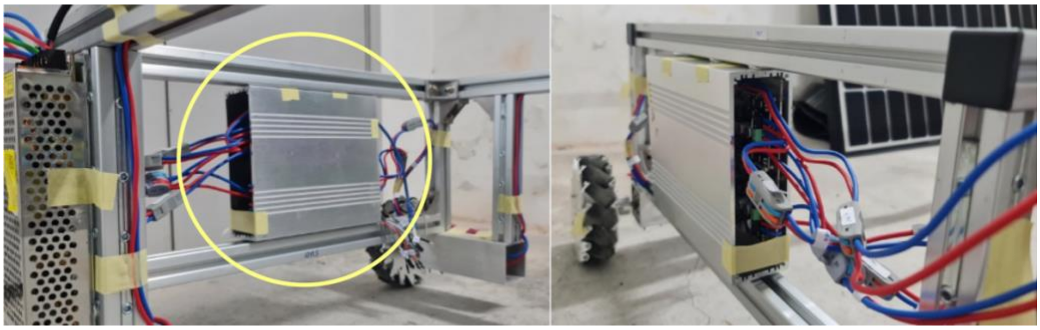

Figure 4.5: Electronic Box of the Moving Frame.

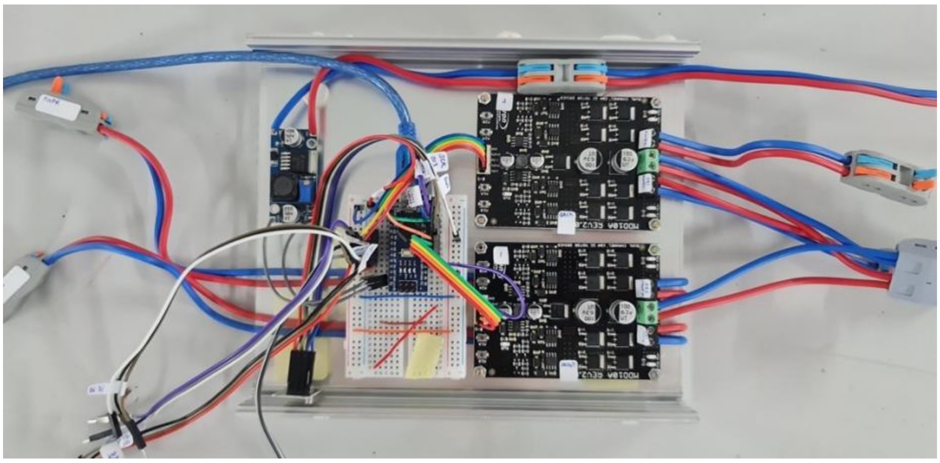

Figure 4.6: Electronic Circuits of the Moving Frame.

4.2.5 Electronic Box of the Cleaning Robot

Figure 4.7 shows the location of the electronic box of the cleaning robot. Similarly, the electronic box contains all the important electronic components of the cleaning robot. The cleaning robot uses more electronic components than the moving frame. There is one Arduino Mega, 4 motor drivers, a radio transceiver, and a buck converter. Just like the electronic box of the moving frame, all the important electronic components are compacted inside the electronic box. The electronic box could provide physical protection to the electronic components to avoid careless contact which will lead to broken connections of the components. The program uploader of the Arduino Mega used for the cleaning robot is also stretched to the outside so that the program uploading work could be done easily even if the electronic box is installed onto the cleaning robot.

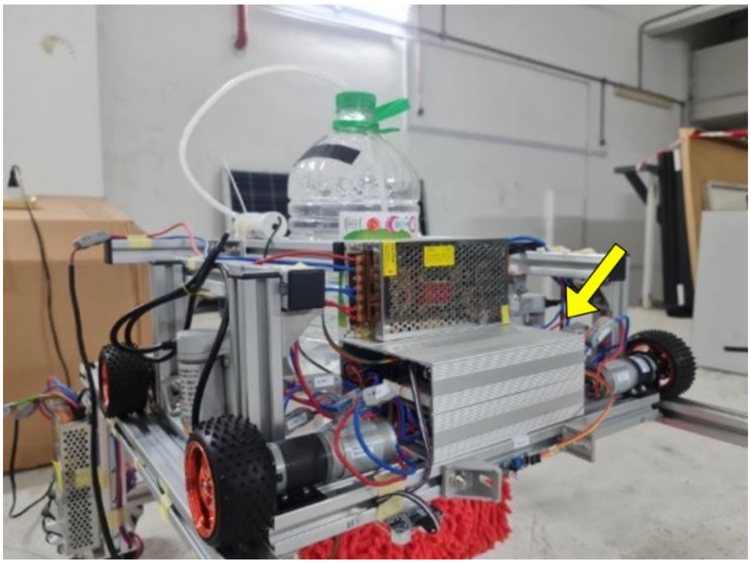

Figure 4.7: Location of Electronic Box of the Cleaning Robot.

Figure 4.8 shows the electronic circuits of the cleaning robot before they were inserted into the electronic box. The electronic circuits were designed to have two layers so that all the electronic components could be fit into the electronic box. The bottom layer consists of 4 motor drivers only. The connections of the motor drivers from the Arduino and to the target motors were determined and confirmed in the beginning stage of construction. The total motors will be used on the cleaning robot was confirmed, there will not be any changes to the connections. Therefore, all the motor drivers are located in the bottom layer. In the upper layer, there are the Arduino Mega, buck converter, radio transceiver, and a breadboard for connection purposes. During the practical testing and debugging stage, the connections on the Arduino pins would undergo plenty of changes to fit and improve the design. Therefore, the Arduino Mega and the breadboard must be located on the upper layer, which is the most convenient location for any amendment on the electronic circuits. Figure 4.9 shows the top view of electronic circuits in the electronic box. The electronic circuits together with the box are already installed onto the cleaning robot. It could be noticed from Figure 4.9 that the electronic circuits consist of complicated wire connections. Therefore, all the jumper wires were labelled with white stickers to present their roles and purposes. The stickers also marked down which pins should be connected.

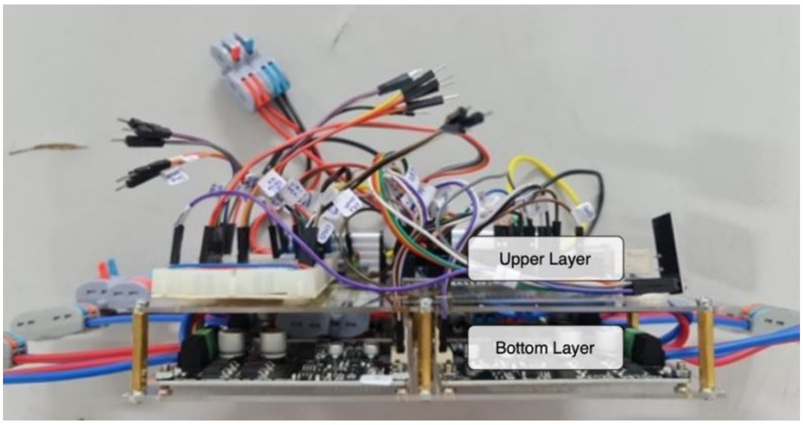

Figure 4.8: Two Layers of Electronic Circuits of the Cleaning Robot.

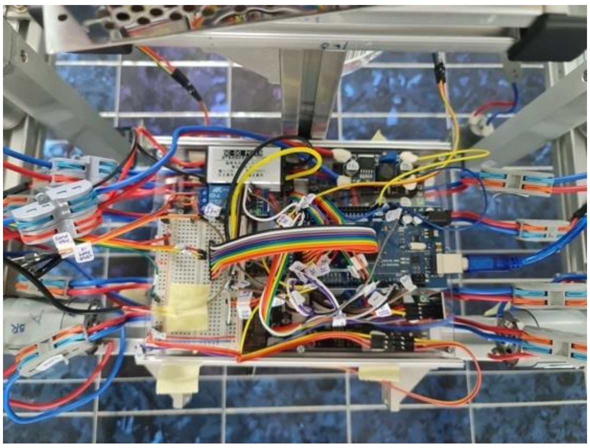

Figure 4.9: Top View of Electronic Circuits of the Cleaning Robot.

4.2.6 Use of Wire Connectors

From the two electronic boxes, it could be noticed that plenty of wire connectors are used. Figure 4.10 shows the wire connectors used in both the cleaning robot and the moving frame. In this project, the prototype would undergo many tests and debugging. The wire connector plays a very important role to disconnect the electronic components if necessary. On the electronic component side, such as the motor driver, the wire connection uses screw method. On the motor side, the wire connection uses the soldering method. Any of the methods are firm enough to hold the wires, but they are not suitable for practical testing and debugging work. The use of wire connectors solved the issue. On the motor driver side, a wire was prepared and screwed to the motor driver, while on the motor side, a new wire was soldered to the motor. The two wires were connected by a wire connector. Therefore, when the electronic circuit was needed to be removed from the cleaning robot, all the wire connectors would be opened and disconnected. It could be noticed from Figure 4.10 that the wire connectors are also being labelled with white stickers for labelling purposes.

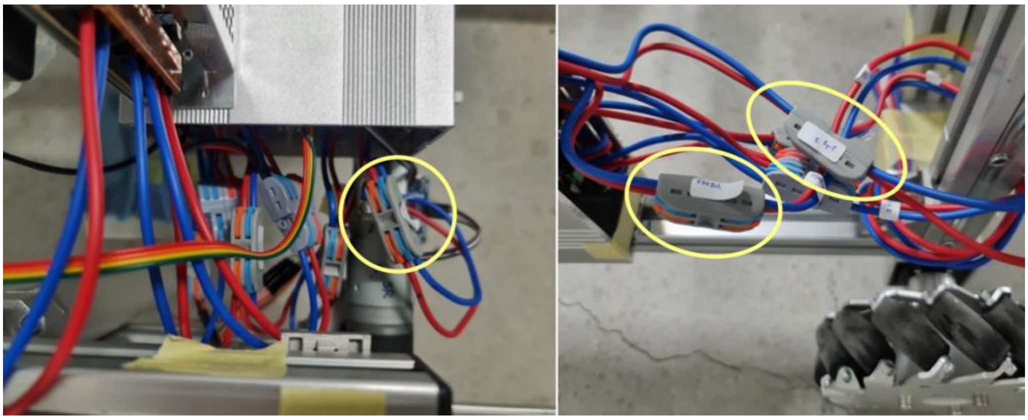

Figure 4.10: Use of Wire Connectors.

4.2.7 Power Supply Management of the Prototype

Figure 4.11 shows the schematic diagram to describe the connections of the power supply. The electrical and electronic circuits design section mentioned that one power supply would be used to power up the whole robot. However, there are two different robot bodies with two same switching power supplies. The power supply from the socket is connected to the switching power supply of the moving frame. From the same node, the wires are connected to the cleaning robot. The switching power supply of the moving frame and the cleaning robot will obtain 240 V AC. Figure 4.12 shows the wire connections at the switching power supply of the moving frame. The 240 V AC is supplied from the socket to the switching power supply of the moving frame. From the switching power supply of the moving frame, new wires will conduct 24V DC to the electronic circuit box of the moving frame. At the node of the power supply to the switching power supply of the moving frame, new wires are connected from the node to the cleaning robot to supply 240 V AC to the switching power supply of the cleaning robot. Figure 4.13 shows the power supply to the switching power supply of the cleaning robot.

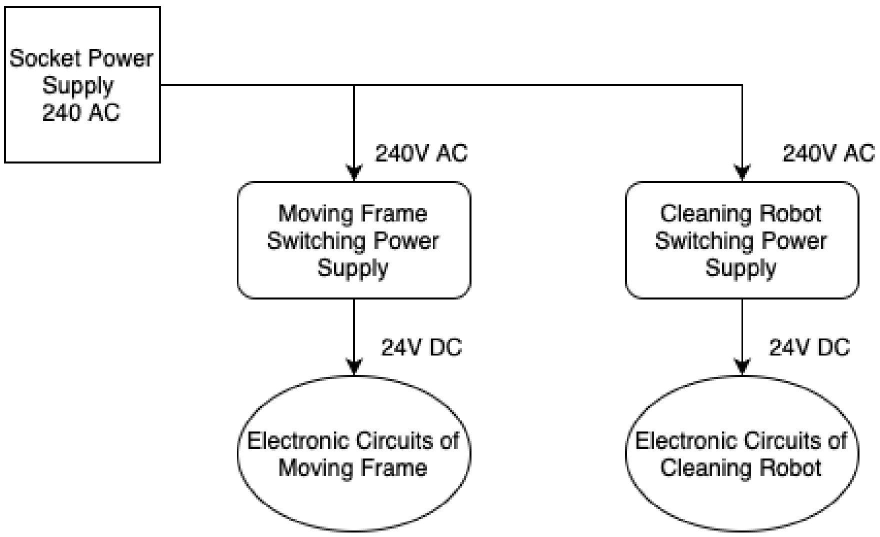

Figure 4.11: Schematic Diagram of Power Supply Management.

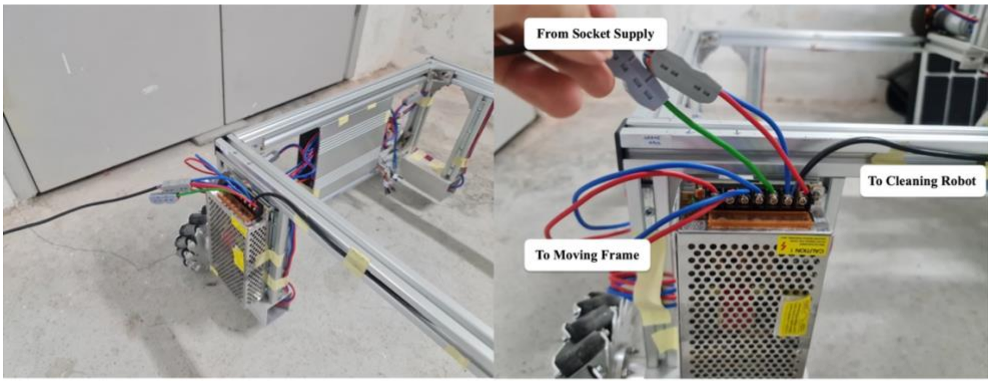

Figure 4.12: Wire Connections at the Moving Frame.

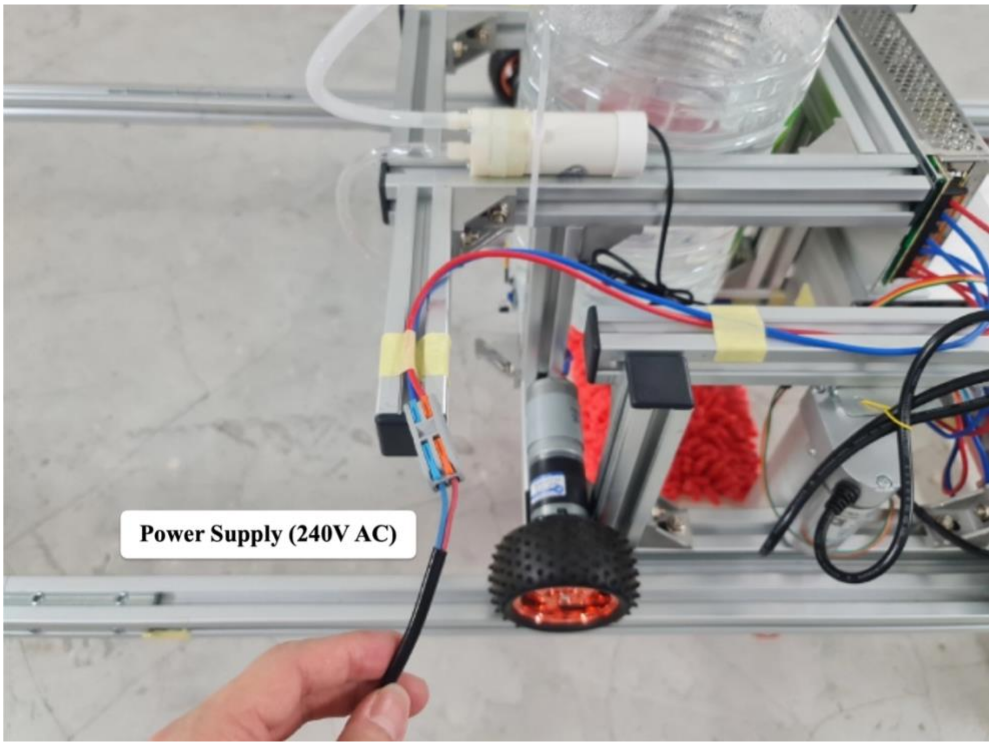

Figure 4.13: Power Supply to the Cleaning Robot.

4.2.8 Wire Handling Method

Figure 4.14 shows the wire handling method of the cleaning robot during cleaning operation. In this project, the socket power supply was used to power up the robot instead of using a battery. Therefore, the wires should be handled properly to avoid distortion during cleaning operation. The moving frame could be considered as the main body of the cleaning robot. The moving frame does not have frequent movement as the cleaning robot. Therefore, the connection from the socket power supply is more stable and safer to be connected to the switching power supply of the moving frame, instead of the switching power supply of the cleaning robot. From the switching power supply of the moving frame, the 240 AC power supply is branched in parallel to the switching power supply. It could be noticed from Figure 4.14 that the wire connected from the moving frame to the cleaning robot is fixed to the track of the moving frame until a certain distance (almost half the length of the moving frame). Figure 4.15 shows the extended wire supporter on the cleaning robot. By fixing certain wire on the moving frame track and the extended wire supporter, the wire supplying power to the cleaning robot will not be distracting the movement of the cleaning robot during the cleaning task as the robot moves front and back on the moving frame. Figure 4.14 shows the condition of the wire when the cleaning robot is located near to the right side of the moving frame and the condition of the wire when the robot is located at the end of the right side of the moving frame.

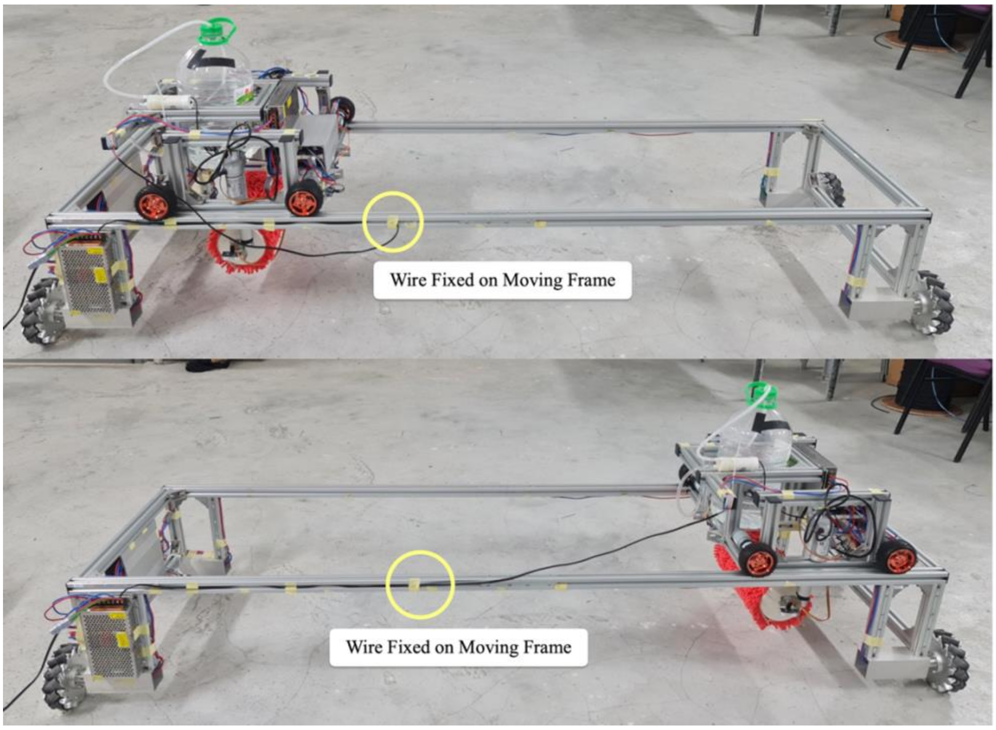

Figure 4.14: Cleaning Robot Movement Wire Handling Method.

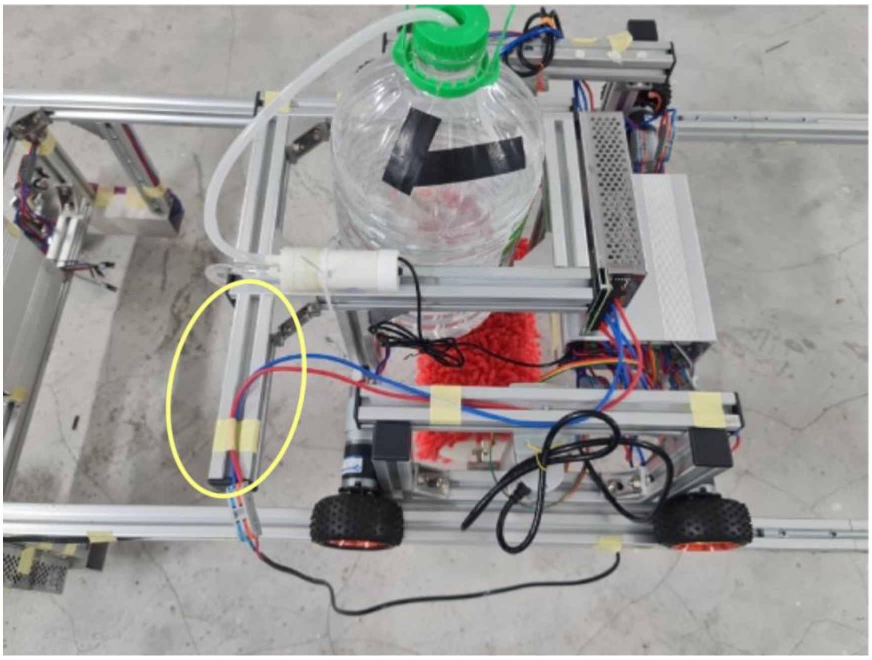

Figure 4.15: Wire Supporter on the Cleaning Robot.

4.2.9 Cleaning Tools and Components

Figure 4.16 shows the water tank and water pump on the cleaning robot, while Figure 4.17 shows the water sprayer directed from the water pump to the bottom of the cleaning robot. From Figure 4.16, it could be noticed that a water pipe is connected between the water tank and the water pump. The water pump will pump out the water from the water tank and direct the water to the water sprayer. The water sprayer used on the cleaning robot could be adjusted to obtain required spraying patterns such as atomizing mode and injecting mode.

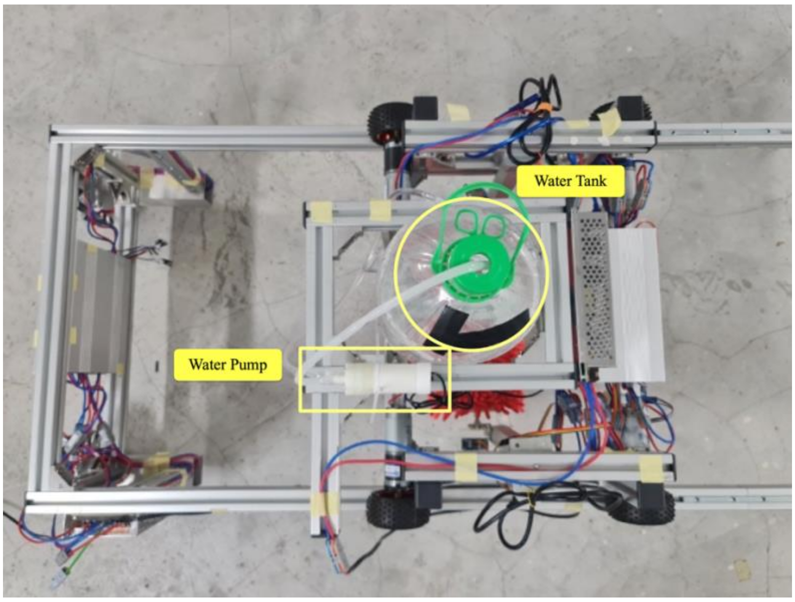

Figure 4.16: Water Tank and Water Pump on the Cleaning Robot.

Figure 4.17: Water Sprayer.

Figure 4.18 shows the cleaning brush of the robot. The cleaning brush is constructed with microfiber cloths and a PVC pipe. The cleaning brush is held by two linear actuators. One motor is installed on the left linear actuator to rotate the cleaning brush during cleaning operation.

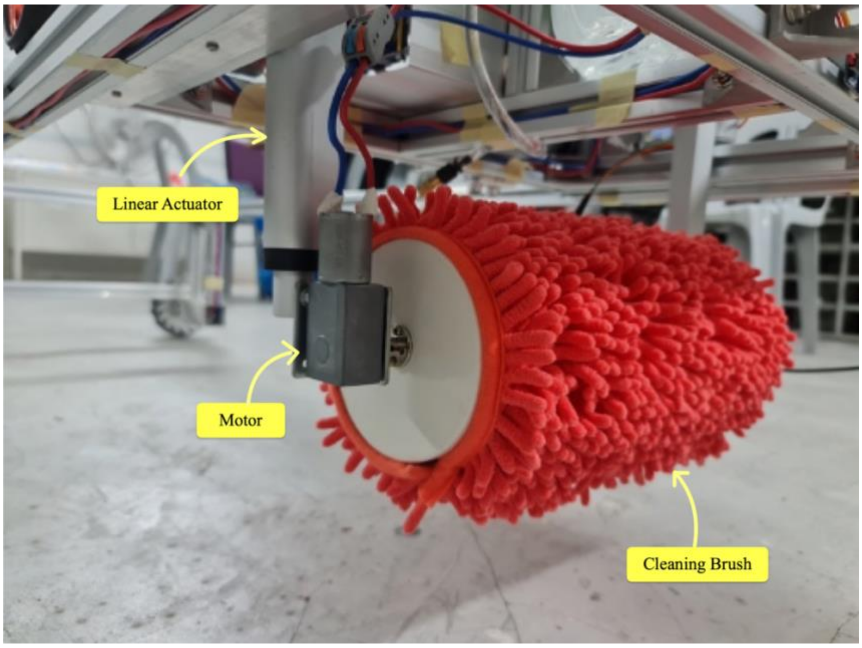

Figure 4.18: Cleaning Brush and Motor Hold by Linear Actuators.

4.2.10 Sensors Application

Figure 4.19 shows the infrared sensors used on the cleaning robot to stop its movement when it arrives at both the right and left ends of the moving frame. It could be noticed from Figure 4.19 that two L-connectors of the aluminium profile are installed on both sides of the infrared sensors. The L-connectors serve to protect the infrared sensors during the malfunction of the sensor detection. Before the Arduino program was reliable during the practical testing and debugging stage, the cleaning robot frequently collided to the moving frame end, which caused the transmitter and receiver of the sensor to be broken. Therefore, this safety measure was designed to protect the infrared sensors. In the real product, the sensors are suggested to be inserted into the robot body instead of placing them outside of the robot.

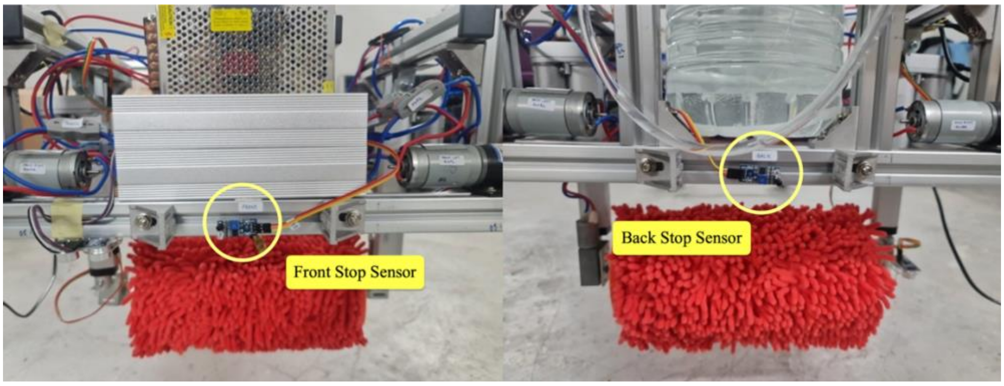

Figure 4.19: Front and Back Stop Sensors.

Figure 4.20 shows the linear actuator stop (LAS) checking sensor used to decide the position of the cleaning brush. At the beginning of the cleaning operation, the linear actuator will bring the cleaning brush down to the solar panels. An ultrasonic sensor is used to measure the distance between the cleaning brush and the solar panels surface. The ultrasonic sensor is set to check for 7 cm when the cleaning brush is moving down to the solar panel surface. The cleaning brush will stop moving downwards when 7 cm is achieved. During the cleaning operation, the cleaning brush sensor will check the distance throughout the process. This checking can be used on different installation angles of the solar panels. The cleaning brush will move upwards and downwards during cleaning by ensuring that the distance between the solar panel surface and the cleaning brush will always be maintained at 7 cm.

Infrared sensor is not suitable to be used in this condition due to the working principle of the infrared sensor. The infrared wave emitted by the transmitter will be absorbed by a dark colour surface. The dark colour surface of the solar panels will affect the sensing condition. During the practical testing and debugging stage, the infrared sensor was adjusted so that the Arduino would receive a “false” input when an obstacle was detected at a certain range, for example 3 cm. However, when the tuned infrared sensor was installed to the cleaning brush, the sensor did not output the same result as tuned. This was due to the dark colour of the solar panels surface. Therefore, an ultrasonic sensor is used in this condition as the working principle of the ultrasonic sensor ensures that the sensor will not be affected by the colour of the obstacles. The differences between the infrared sensor and the ultrasonic sensor will be discussed in the following discussion section in detail.

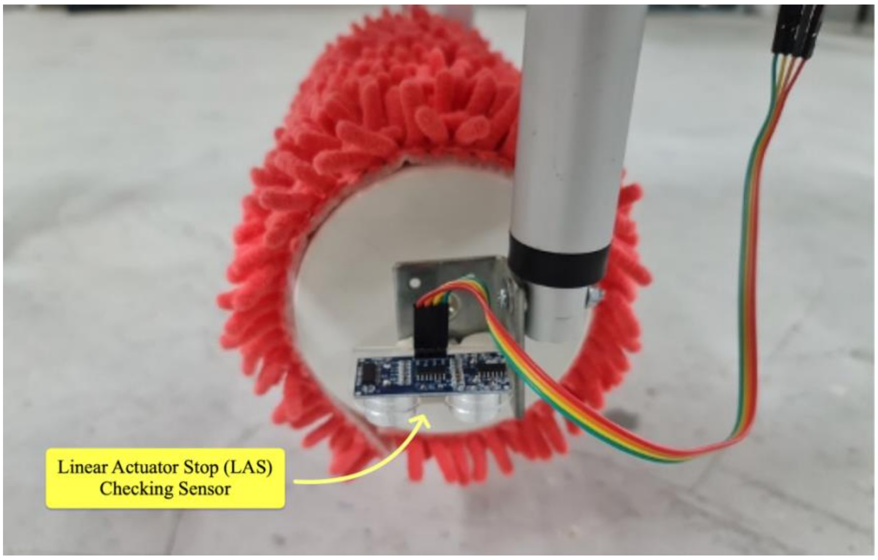

Figure 4.20: Linear Actuator Stop (LAS) Checking Sensor.

Figure 4.21 shows the solar panel (SP) checking sensor. The ultrasonic sensor is located at the right edge in the front of the cleaning robot. The ultrasonic sensor is used to detect the presence of solar panels. After cleaning up one cleaning column, the moving frame will move 5 seconds which is the length of the cleaning brush. When the moving frame completes the 5-second movement, the robot must determine whether there is still a solar panel to be cleaned. If a solar panel is detected, the cleaning robot will continue to clean, else the moving frame will carry the cleaning robot to return to initial position. The presence of the solar panel is determined through measuring the distance. The shorter measured distance indicates the solar panel is present, while the longer distance indicates the solar panel is not present.

Two distances had to be measured which are the distance from sensor to solar panel and the distance from sensor to ground (no solar panel). On measuring the distance from sensor to solar panel, the measurement shows 23 and 24 due to the bouncing issue of the electronic component. On measuring the distance from sensor to the ground, the measurement shows 26 and 27. The measurement below 24 indicates the presence of a solar panel. The flowchart of the program was discussed in the methodology section. The detailed writing of the program will be discussed in the discussion.

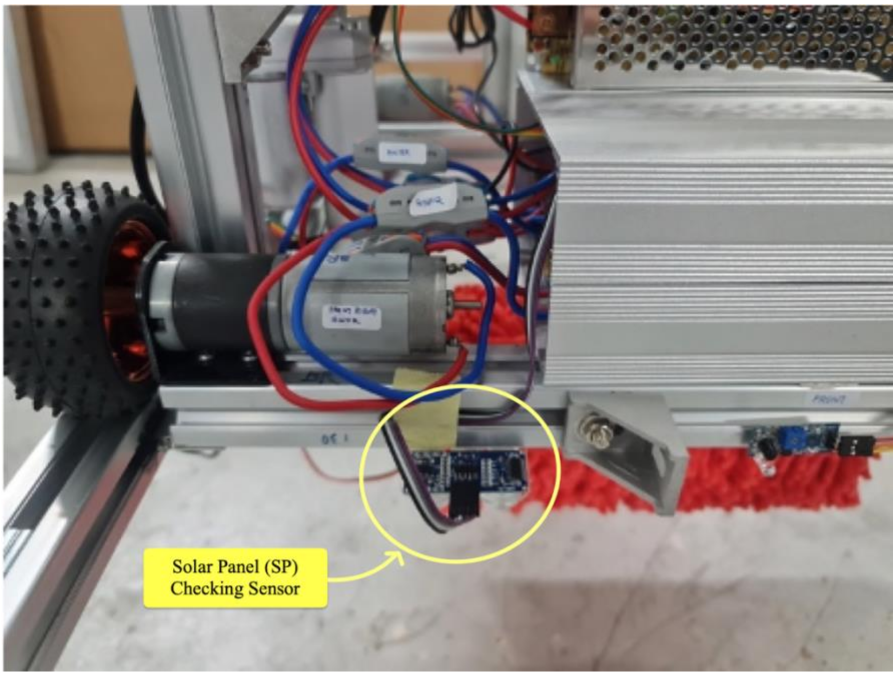

Figure 4.21: Solar Panel (SP) Checking Sensor.

4.3 Programming Techniques and Considerations

In this section, the programming techniques used in writing the Arduino codes will be presented and explained in detail. Besides, the programming considerations will also be discussed in this section. The code portion will be presented together with the explanation. The figures of the code will be marked properly and attached with concise tips. The complete codes of the moving frame and cleaning robot will be attached in the appendix chapter (Appendix B).

4.3.1 Communications between two Arduinos

In this project, two Arduinos are used for both the moving frame and the cleaning robot. In the methodology chapter, it was mentioned that the communications between the Arduinos were achieved by the radio transceivers. Figure 4.22 shows the addresses of pipes used in the project. The codes in Figure 4.22 were screenshotted from the cleaning robot codes. Figure 4.23 shows the assignment of addresses to the pipes. For the cleaning robot Arduino Mega, the reading pipe uses the pipe 1 address, while the writing pipe uses the pipe 2 address. On the other hand, for the moving frame Arduino Nano, the reading pipe will use the pipe 2 address, while the writing pipe will use the pipe 1 address which is reversed compared to the Arduino Mega.

In order to let the radio transceiver to work under receiving mode, the Arduino requires the command “radio.startListening();”. To let the radio transceiver to work under transmitting mode, the Arduino requires the command “radio.stopListening();”. Figure 4.24 shows the example to use the radio transceiver in different modes.

```
const uint64_t pipe1 = 0xE8E8F0F0E1LL;
const uint64_t pipe2 = 0xE8E8F0F0AALL;
RF24 radio(CE_PIN,CSN_PIN);
```

Figure 4.22: Addresses of Pipes of Cleaning Robot Codes.

```
radio.begin();
radio.openReadingPipe(1,pipe2);
radio.openWritingPipe(pipe1);
```

Moving Frame

```
radio.begin();
radio.openReadingPipe(1,pipe1);
radio.openWritingPipe(pipe2);
```

Cleaning Robot

Figure 4.23: Setting of Pipes.

```
radio.startListening();                    // Listening Mode On
do{
    if(radio.available()) {
        radio.read(msg, sizeof(msg));
        Serial.println((String)"Pending Clean: "+ msg);
    }
    delay(500);
} while(strcmp(msg, "Clean") != 0);

cleaning_operation();

radio.stopListening();                    // Writing Mode On
strcpy(msg, "Ori Posi");
radio.write(&msg, sizeof(msg));
Serial.println(msg);
delay(5000);
```

Figure 4.24: Commands to Change Modes.

4.3.2 Predefined default position

To decide the routine and operation of the robot, some assumptions must be made. The robot must be placed at the first cleaning position before the switch is turned on. The first cleaning position refers to the position and place that the cleaning robot could start cleaning without checking any sensor. Figure 4.25 shows the setup program of the cleaning robot. After the basic setup of the Arduino, the robot will start moving back to its original position. This practice is to ensure that the robot will always begin the cleaning operation at the original position, which is the left end of the moving frame. Whenever the switch is turned on, the robot will move to the original position (left end of the moving frame). The cleaning operation will be followed by the time when the cleaning robot arrives at the original position. There is no checking of the sensor to adjust the robot to desired position in the setup program. All the checking of sensors will only be discovered in the looping program.

```
void setup(){
    Serial.begin(9600);
    radio.begin();
    radio.openReadingPipe(1,pipe1);
    radio.openWritingPipe(pipe2);

    for(int i = 0; i< (sizeof(output_pin)/sizeof(output_pin[0])); i++) {
        pinMode(output_pin[i], OUTPUT);
        digitalWrite(output_pin[i], LOW);
    }

    pinMode(WPM,OUTPUT);
    digitalWrite(WPM,HIGH);        //Water Pump Relay "HIGH" to switch off
    pinMode(LAS_trig, OUTPUT);
    pinMode(LAS_echo, INPUT);
    pinMode(SPCHECK_trig,OUTPUT);
    pinMode(SPCHECK_echo,INPUT);
    pinMode(RobotStopFront,INPUT_PULLUP);
    pinMode(RobotStopBack,INPUT_PULLUP);
    Serial.println("Done Setup");

    //Robot Return Original Position
    original_position();
}
```

Setup Preparation

Cleaning Robot Return Original Position

Figure 4.25: Setup Program of the Cleaning Robot.

Figure 4.26 shows the codes of the cleaning robot, written to check the presence of the solar panel. In the first line of the code, the radio transceiver is converted into transmitting mode to send the message about the presence of the solar panel to the moving frame. If the solar panel checking sensor reads the presence of the solar panel, the message "SP_Yes" will be transmitted to the moving frame. Else, the message "SP_No" will be transmitted.

It is assumed that the absence of the solar panel indicates the robot arrives at the end of the solar panels. All the solar panels had been cleaned. Therefore, the robot should return to the initial position to repeat the cleaning routine as designed. The moving frame will receive the "SP_No" message and start to move backwards to the initial position. After writing the "SP_No" message, the Arduino Mega of the cleaning robot will stop doing anything for 8 seconds (delay(8000);). To avoid complicated computing logic, dummy checking of the solar panel is replaced with the delay function. During the 8-second delay, the robot will return into the solar panels array, so the solar panel checking sensor will sense the presence of the robot again. After 8 seconds, the SP Checking sensor will repeat the sensing task until it senses the absence of the solar panel, a message of "Reached Initial" will be sent to the moving frame. Meanwhile, the moving frame will wait for the message "Reached Initial" to stop the backward movement.

```
radio.stopListening();
if(check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
    strcpy(msg,"SP_Yes");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
} else {
    strcpy(msg,"SP_No");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    //Wait for frame to return into SP
    //So that I could read SP_no when the Frame is moved out SP
    delay(8000);
    while (check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
        strcpy(msg,"Return Initial");
        radio.write(&msg, sizeof(msg));
        Serial.println(msg);
    }
    strcpy(msg, "Reached Initial");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    delay(500);
}
```

Solar Panel Detected (Present)

Solar Panel Not Detected (Absent)

Figure 4.26: Checking the Presence of Solar Panel.

Figure 4.27 shows the cleaning operation task of the cleaning robot. The cleaning operation task consists of the commands to control the operations of the robot. At the beginning of the task, the linear actuator will be moved down to reach the surface of the solar panel. The ultrasonic sensor is used to determine the offset of the brush and the solar panel surface. The ultrasonic sensor will return the reading repeatedly until the distance detected by the ultrasonic sensor is equal or lesser than the brush offset predefined (brush offset = 7). Then, the linear actuator stops, the brush starts to rotate, the water pump pumps, and the robot starts to move on the moving frame. The cleaning operation starts. Meanwhile, the infrared sensor at the front side of the cleaning robot will be read to determine whether the cleaning robot reaches the end. At the same moment, before the cleaning robot reaches the end, the linear actuator sensor will continuously check the distance, so that the cleaning brush could be adjusted to optimum location. Figure 4.28 shows the illustrations of solar panels installed with tilting angle. If the solar panel is installed with a tilting angle, the cleaning robot may move from the higher location to a lower location. Thus, the cleaning brush must be lowered down to achieve the surface. When the cleaning robot arrives at the end of the moving frame, the original position task will be called to return the cleaning robot to the initial position.

```
void cleaning_operation() {
  Linear_Actuator_Down();
  do {
    distance = check_URsensor(LAS_trig,LAS_echo);
  } while (distance > brush_offset);
  Linear_Actuator_Stop();
  Brush_On();
  Water_Pump_On();
  Robot_Front();
  while(digitalRead(RobotStopFront) == HIGH) {
    Serial.println("Cleaning...");
    if(check_URsensor(LAS_trig,LAS_echo) > brush_offset) {
        Linear_Actuator_Down();
    } else if(check_URsensor(LAS_trig,LAS_echo) == brush_offset) {
        Linear_Actuator_Stop();
    } else if(check_URsensor(LAS_trig,LAS_echo) < brush_offset) {
        Linear_Actuator_Up();
    }
  }
  original_position();
}
```

Adjust Linear Actuator to Cleaning Position

Always ensure the cleaning brush position at brush_offset = 7 during cleaning

Cleaning Robot return to original position after cleaning

Figure 4.27: Cleaning Operation of the Cleaning Robot.

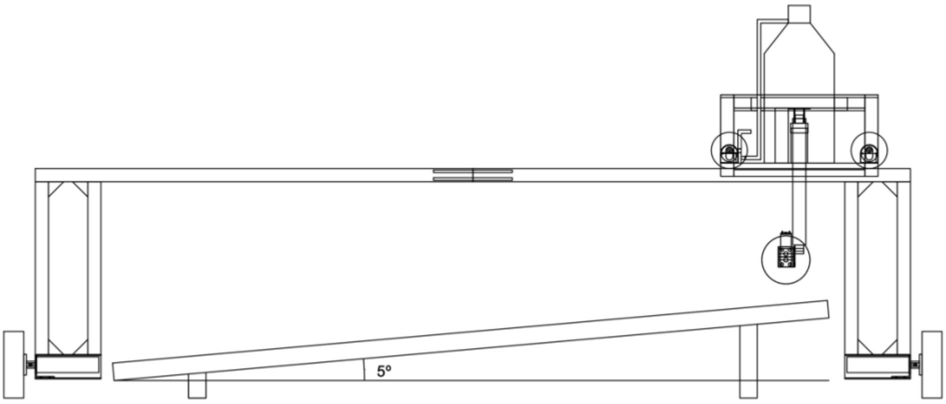

Figure 4.28: Solar Panels Installation with Tilting Angle.

4.3.3 Frame Routine Program

Figure 4.29 shows the setup program of the moving frame robot. Unlike the cleaning robot, the setup program of the moving frame only performs setting up tasks. It could be noticed that the reading pipe of the moving frame is set to be pipe 2, while the writing pipe of the moving frame is set to be pipe 1, which is the reverse of the cleaning robot.

```
void setup() {
      // put your setup code here, to run once:
      Serial.begin(9600);
      radio.begin();
      radio.openReadingPipe(1,pipe2);
      radio.openWritingPipe(pipe1);
      for(int i = 0; i< (sizeof(output_pin)/sizeof(output_pin[0])); i++) {
          pinMode(output_pin[i], OUTPUT);
          digitalWrite(output_pin[i], LOW);
          //Serial.println(output_pin[i]);
      }
      Serial.println("Done Setup");
}
```

Figure 4.29: Setup Program of the Moving Frame.

Figure 4.30 shows the first portion of the loop function of the moving frame. After setting up the Arduino, the moving frame will wait for the message “Ori Posi” from the cleaning robot to indicate that the cleaning robot has returned to the original position. Figure 4.31 shows the first portion of the loop function of the cleaning robot. When the cleaning robot completes the cleaning operation, the cleaning robot will transmit the message “Ori Posi” to the moving frame. When the message “Ori Posi” is received by the moving frame, the moving frame will move forward for 5 seconds. The purpose of this forward move is to bring the cleaning robot to the next column for following cleaning. The 5-second delay is measured according to the pre-set speed of the moving frame. The cleaning brush has a length of 30 cm. The moving frame should not move more than 30 cm so that the cleaning brush will not miss any portion of the solar panel. Therefore, the moving frame will move for 5 seconds, which is approximately 30 cm on the ground.

```
void loop() {
    radio.startListening();
    do{
        if(radio.available()) {
            radio.read(msg, sizeof(msg));
        }
        Serial.println((String)"Pending Ori Posi: "+ msg);
        delay(500);
    } while(strcmp(msg, "Ori Posi") != 0);

    Serial.println("Frame Front 5 Seconds");
    Frame_Front();
    delay(5000);       //only move 5 seconds = 300 mm
    Frame_Stop();
```

Moving Frame waits for message "Ori Posi"

Moving Frame moves 300 mm forward

Figure 4.30: Moving Frame waits for "Ori Posi" to move forward.

```
void loop(){
    cleaning_operation();
    radio.stopListening();
    strcpy(msg,"Ori Posi");
    radio.write(&msg, sizeof(msg));
    delay(5000);
```

Cleaning Robot write message "Ori Posi" to Moving Frame after cleaning operation

Figure 4.31: Cleaning Robot writes "Ori Posi" to Moving Frame.

In this project, regardless of the message transmitting task, the moving frame only performs two tasks, mainly the forward move to the next column and return to initial position. The code portion in Figure 4.32 shows the decision-making method used in the moving frame to decide whether it will move to the next column or return to its initial position. Before deciding, the moving frame must receive either "SP_Yes" or "SP_No" from the cleaning robot. The Arduino program was written to receive specified commands to ensure that the robot could receive the accurate command before performing the task. Else, the robot will repeat the reading until the correct command is received. If this practice is not applied, the program could possibly crash and be stuck in infinite looping.

As the moving frame receives any of the messages, the program will stop looping for messages, and proceed to the next section. If "SP_No" is received, the moving frame is out of the solar panel range, so it must return to the initial position. The moving frame starts to move backwards. While moving backwards, the moving frame will continuously receive signals from the cleaning robot until the message “Reached Initial” is received. Then, the moving frame will stop. Here is the main highlight of this section. After the moving frame stops for 1 second, the moving frame moves forward for 2.5 seconds. As the moving frame moves backward to initial position, the solar panel checking sensor will read the presence of the solar panel. A change of condition is required to trigger the next procedure. Thus, the solution provided is to detect the absence of a solar panel and transmit the message to the moving frame. Figure 4.33 shows the Arduino code of the cleaning robot that transmits “Reached Initial” to the moving frame when the solar panel checking sensor reads a value greater than 24 (solar panel is absent). However, when the sensor reads the absence of the solar panel, the cleaning brush will not be in the correct position for cleaning. Therefore, the moving frame will move 2.5 seconds forward by itself to bring the cleaning brush to the accurate position for next cleaning.

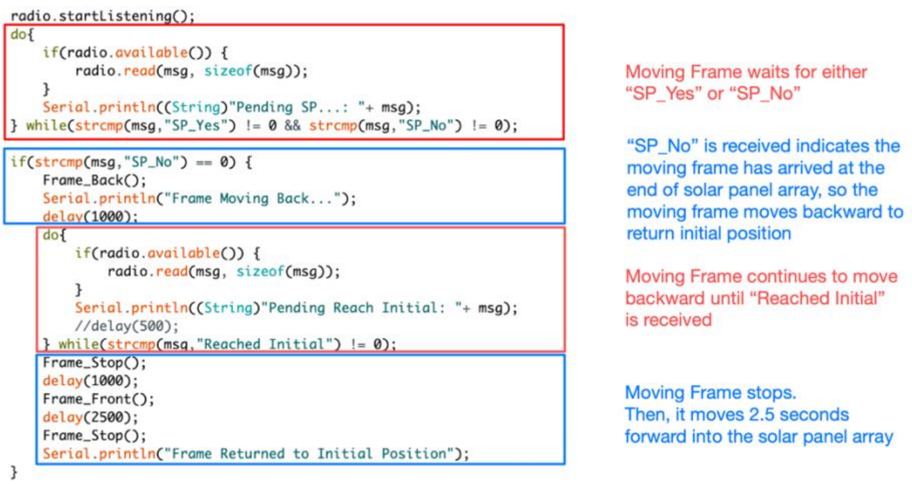

Figure 4.32: Moving Frame decides to return initial position.

```
radio.stopListening();
if(check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
    strcpy(msg,"SP_Yes");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
} else {
    strcpy(msg,"SP_No");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    //Wait for frame to return into SP
    //So that I could read SP_no when the Frame is moved out SP
    delay(8000);
    while (check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
        strcpy(msg,"Return Initial");
        radio.write(&msg, sizeof(msg));
        Serial.println(msg);
    }
    strcpy(msg, "Reached Initial");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    delay(500);
}
```

SPCheck sensor reads value <= 24
indicates the presence of solar panel,
"SP_Yes" is transmitted to Moving Frame

Else, "SP_No" is transmitted

After "SP_No" is transmitted,
cleaning robot waits for 8 seconds
before checking the presence of
solar panel again

SP Absent -> "Return Initial"
SP Present -> "Reached Initial"

Figure 4.33: Cleaning Robot calls Moving Frame to return.

4.4 Testing Environment Operation

Figure 4.34 shows the testing environment of the project. The testing environment consists of 3 solar panels arranged in 1 row. This 1x3 (row x col) arrangement is considered as an array. Figure 4.35 shows the position of the robot on the first cleaning column of the solar panel array. The robot will perform the cleaning operation as described in Chapter 3 (Figure 3.16). Figure 4.36 shows the robot arrives at the end of the solar panel array. Figure 4.37 shows the solar panel checking sensor senses the absence of the solar panel when the robot arrives at the end of the solar panel array. The position of the solar panel checking sensor and its sensing direction are marked in Figure 4.37. The video link to watch the operation of the robot is attached after the paragraph.

Video Link: https://youtu.be/bPiAaaOew8w

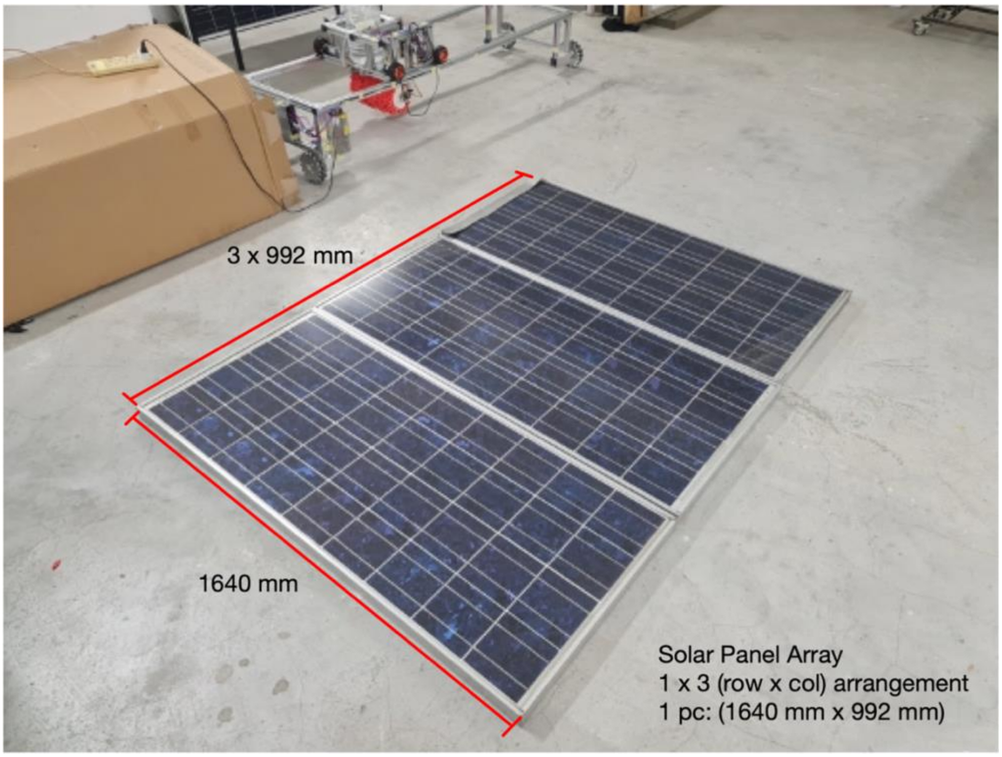

Figure 4.34: Solar Panel Array Testing Environment.

Figure 4.35: Robot positioned at the first cleaning column.

Figure 4.36: Robot arrived at the end of array.

Figure 4.37: SP Checking Sensor senses the absence of solar panel.

4.5 Discussions

4.5.1 Different Motor Speed and Adjustment

In this project, there are 8 dc motors used for the wheel application. Four motors are used on the cleaning robot for front and back movement and four motors are used on the moving frame for Mecanum wheels application. These 8 motors are the same model, which is the GA36Y-555-CE, with 30 rpm speed. However, it was found that all the motors are having different speeds even they were given with the same PWM value. To solve this issue, there are two methods, which are the application of motor encoder and the manual adjustment of motor speed. The motor encoder could be mounted to the motor so that a closed loop system could be achieved. In this project, the motor encoder was not being used due to lack of considerations in the beginning stage of the project planning. In the beginning of the project, this issue was not considered. The design of the prototype did not consider the space for the motor encoders. Besides, there is lack of funding to purchase up to 8 motor encoders. Hence, the second solution was chosen.

The solution used to adjust the motor speed was setting the PWM value manually. Figure 4.38 shows the method for both moving frame wheels and cleaning robot wheels. One of the motors used in the moving frame has double speed compared to the others although the specifications stated on the motor are the same for all the 8 motors. In the moving frame, the PWM value of “max_speed” was predefined as 30. Due to the double fast motor, the other 3 motors were adjusted to have the same speed as the fastest motor. In the cleaning robot, the PWM value of “wheel_speed” was predefined as 255, which is the maximum PWM value. The slowest motors among the 4 motors used on the cleaning robot was taken as reference. The other 3 motors were adjusted to have the same speed as the slowest motor.

During the measurement of motor speed, it was found that the same PWM value did not result in the same speed when the rotating direction of the motor was reversed. For example, the “FWBL_PWM” was assigned with 62 (30+32) for the front movement, while it was assigned with 60 for back movement. This phenomenon was discovered during the adjustment of the speed of the linear actuators. Therefore, the front movement of and back movement of the motors were measured separately to obtain the speed as synchronised as possible.

The speeds of the motors were not the same perfectly at the end by using any of the methods. For the motor encoder method, the closed loop feedback will continuously adjust the speed to minimise the error between the wheels. However, the manual adjustment could not achieve synchronisation as good as the motor encoder method. The PWM value is a discrete value. This causes that the error among the motors could not be eliminated. For example, for “FWBL_PWM” with the speed of 62 and “FWFR_PWM” with the speed of 61, “FWBL_PWM” will be slightly faster than “FWFR_PWM”. The minor error could only be noticed when the wheels rotate over 30 turns. It could be noticed that one of the markings on the wheel moved slightly faster than the other. Thus, the motor encoder method is recommended for precise application. In this project, the minor error did not affect much on the testing environment due to its small-scale area. However, the future development of the project should take into this consideration to achieve precise movement of the robot.

```
void Frame_Front() {
    digitalWrite(FWFL_DIR,HIGH);
    digitalWrite(FWBL_DIR,HIGH);
    analogWrite(FWFR_DIR,255);
    analogWrite(FWBR_DIR,255);

    analogWrite(FWFL_PWM, max_speed);
    analogWrite(FWBL_PWM, max_speed+32);
    analogWrite(FWFR_PWM, max_speed+31);
    analogWrite(FWBR_PWM, max_speed+32);
}

void Frame_Back() {
    digitalWrite(FWFL_DIR,LOW);
    digitalWrite(FWBL_DIR,LOW);
    analogWrite(FWFR_DIR,0);
    analogWrite(FWBR_DIR,0);

    analogWrite(FWFL_PWM, max_speed);
    analogWrite(FWBL_PWM, max_speed+30);
    analogWrite(FWFR_PWM, max_speed+33);
    analogWrite(FWBR_PWM, max_speed+32);
}

void Robot_Front() {
    digitalWrite(RWFL_DIR, LOW);
    digitalWrite(RWBL_DIR, LOW);
    digitalWrite(RWFR_DIR, LOW);
    digitalWrite(RWBR_DIR, LOW);
    acceleration(RWFL_PWM, RWBL_PWM, RWFR_PWM, RWBR_PWM,wheel_speed);
    analogWrite(RWFL_PWM, wheel_speed);
    analogWrite(RWBL_PWM, wheel_speed-2);
    analogWrite(RWFR_PWM, wheel_speed-9);
    analogWrite(RWBR_PWM, wheel_speed-12);
}

void Robot_Back() {
    digitalWrite(RWFL_DIR, HIGH);
    digitalWrite(RWBL_DIR, HIGH);
    digitalWrite(RWFR_DIR, HIGH);
    digitalWrite(RWBR_DIR, HIGH);
    acceleration(RWFL_PWM, RWBL_PWM, RWFR_PWM, RWBR_PWM, wheel_speed);
    analogWrite(RWFL_PWM, wheel_speed-12);
    analogWrite(RWBL_PWM, wheel_speed-10);
    analogWrite(RWFR_PWM, wheel_speed-2);
    analogWrite(RWBR_PWM, wheel_speed);
}
```

Figure 4.38: Manual Adjustment of PWM Values.

4.5.2 Adjustable Robot Feature and its Characteristics

Solar panels installation did not have standard specifications in terms of tilting angles, installation height, group arrangement etc. Most of the contractors would determine the installation method according to their previous experiences together with the situation on site. In this project, the solar panel cleaning robot considered some of the aspects such as solar panel installation height, tilting angles of solar panels, and array-arrangement combinations of the solar panels.

Firstly, the installation height of the solar panels was considered and included into the design consideration of the robot. In the testing environment, the solar panels were placed directly on the ground. This could be considered as the lowest installation height. Most of the solar panel installation in the industrial rooftop uses a special design metal frame to hold the solar panel. Sometimes, the metal frames will be very low, but the purpose of the metal frame is to avoid placing the solar panels directly on the ground or rooftop surface. In this project, the leg of the moving frame could be customised to fit the installation height. For a large-scale solar panel rooftop, which has more than 100 solar panels, the owner is encouraged to own a customised robot. The moving frame leg length is not encouraged to be adjustable frequently due to the wires connected to the wheels. Therefore, a dimension-customised moving frame leg is suggested to the customers.

Next, the tilting angles of the solar panel installation could be solved by adjusting the moving frame leg and the linear actuators. The linear actuators will be the main consideration to tackle the different tilting angles problem. In the constructed prototype, the linear actuators used could extend up to 150 mm (15 cm). Therefore, it could be understood that the lifted height of the solar panel with different tilting angles should not be more than 150 mm. Figure 4.39 shows the relationship between the tilting angle, solar panel length, and the lifted height of the solar panel. The longer the solar panel, the higher the sensitivity of tilting angle to the lifted height. For a long solar panel, a small change in the tilting angle may result in big changes in the lifted height. This project focuses on the solar panel site on the rooftop. Normally, the tilting angles of the solar panel mounting on the rooftop is very small. Most of the time, the solar panels are placed directly on a simple metal frame without tilting angle. This mounting method is very convenient and low cost.

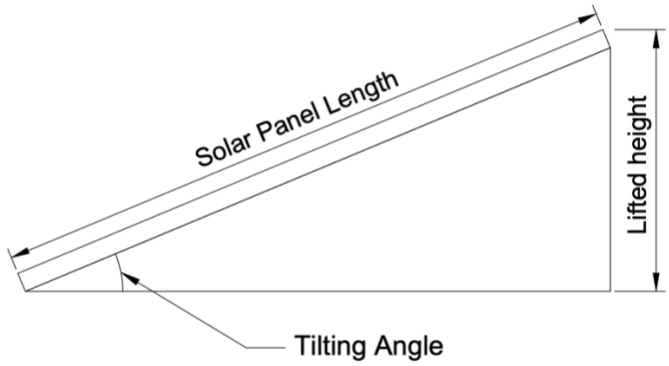

Figure 4.39: Relationships between Tilting Angles and Height.

Table 4.1: Specifications of Linear Actuator.

Extension (mm)	Length of Body (mm)
50	150
100	200
150	250
200	300
250	350
300	400
350	497
400	547
450	597
500	647

Table 4.1 shows the specifications of linear actuators. The minimum extension of the linear actuator is 50 mm. For extension more than 1200 mm, the linear actuator must be customised by the supplier. In this project, the extension is considered maximum at 500 mm. Figure 4.40 shows the factors to be considered in deciding the length of the moving frame leg and the extension of the linear actuator. The first step to choose a suitable linear actuator is to determine the extension required for the condition. The extension of the linear actuator must be greater than the lifted height. By selecting the extension of the linear actuator, the body length of the linear actuator will be obtained. The offset between the highest point of the solar panel and the cleaning brush must

be more than 40 mm (4 cm). By considering the cleaning brush offset, the length of the moving frame leg could be determined.

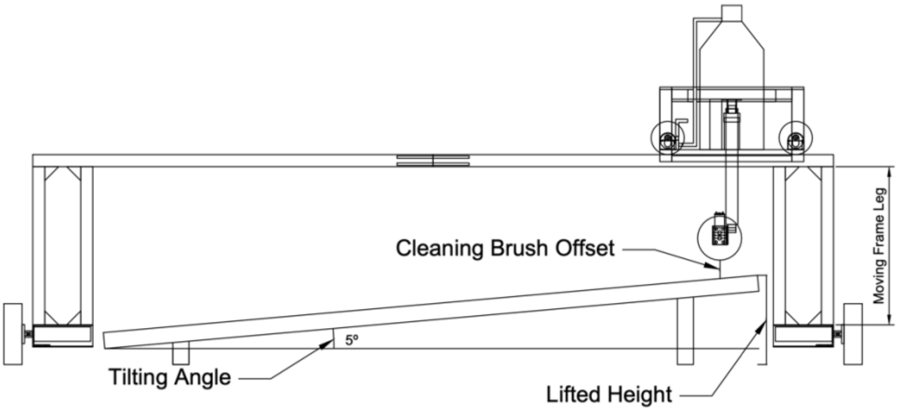

Figure 4.40: Factors to Considered on Robot Dimensions.

Figure 4.41 shows the design of the moving frame leg and the extension of the linear actuator for the condition where the mounting of the solar panel has a tilting angle of 5 degrees. The lifted height is 142.94 mm. The extension of the linear actuator is chosen to be 200 mm, instead of 150 mm. The 150 mm extension is too close to the lifted height value, so the 200 mm extension is chosen to have more tolerance. The linear actuator with 200 mm extension will have a body length of 300 mm. The cleaning brush offset is set to be 40 mm. The length of the moving frame leg is calculated to have 397.36 mm. The length of the moving frame leg could be rounded up to a closer integer (400 mm) to ease cutting work of the aluminium profile.

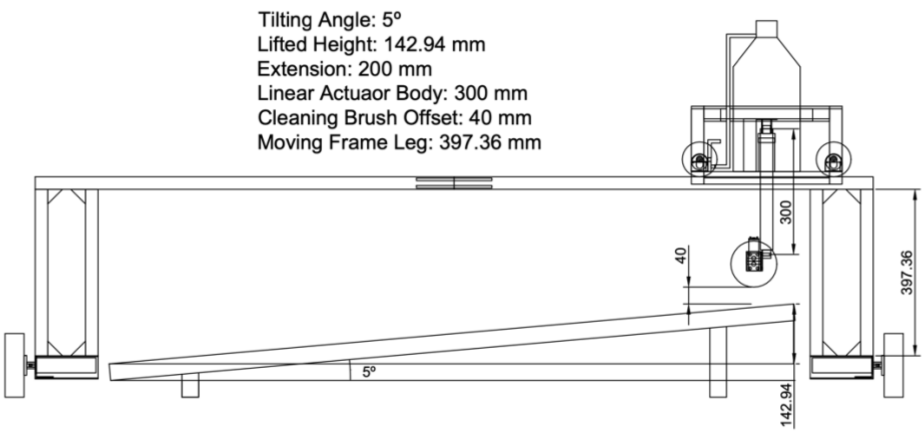

Figure 4.41: Calculation Example of 5 degrees Tilting Angle.

Lastly, the array-arrangement combinations of the solar panel installation. In this project, the design of the robot was referring to the solar panels site, which has 9 arrays, of which one array consists of 2x10 (row x col) solar panels. In the testing environment, the robot was only tested on one array consisting of 1x3 solar panels. Most of the solar panel installation in the industry will practise 2-row arrangement in one array. Different solar panels sizes and arrangement will be a significant issue to be considered. In this project, the moving frame track could be extended to fit the row length of an array. Figure 4.42 shows the increased length of the moving frame to fit into the design of 2-row arrangement. The length of the moving frame will be increased based on the vertical length of the solar panels array. A longer moving frame is required to fit into the solar panel array with a greater number of rows.

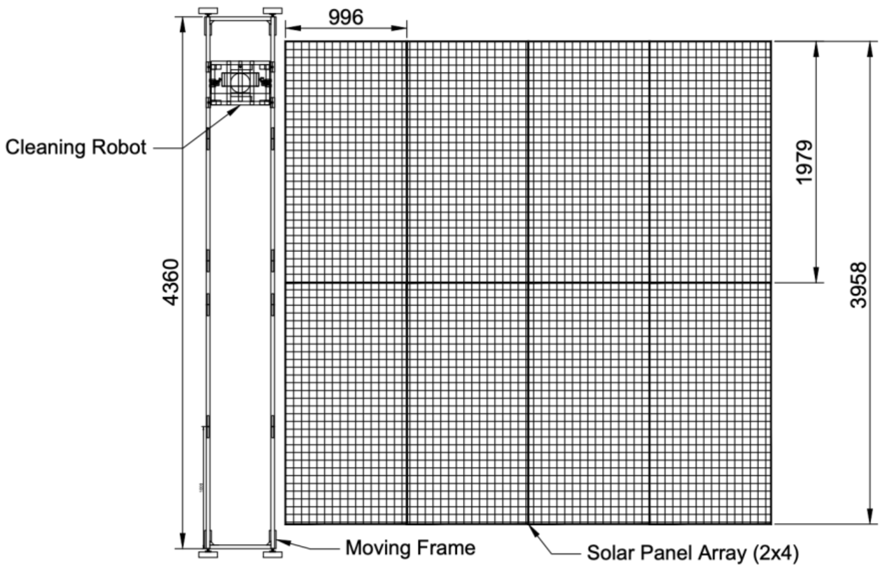

Figure 4.42: 2-Row Solar Panel Array.

In brief, the design of the robot considered the three conditions, which are the installation height, tilting angles, and the array-arrangement combinations. The solutions provided are to customise the dimensions of the robot as well as choosing suitable dimensions of components, such as the linear actuator. The height of the moving frame could be adjusted to fit into different mounting heights of solar panels. The length of the moving frame could be adjusted to fit the length of the solar panel arrangement. By choosing the suitable linear actuator, the cleaning brush could achieve the surface of the solar panels with different tilting angles. The mechanism designed for the adjustment of the length of the moving frame leg either mechanically or electronically is not necessary. The robot customised for one specific situation could work perfectly on the specific location. The electronic adjustment mechanism may make the robot look advanced but not necessary and not cost-effective. For example, if the length moving frame leg could be controlled for higher solar panels installation, more components are required to achieve the enhancements. However, the feature does not help in the cleaning operation. On the other hand, the mechanical adjustment mechanism could be accepted reluctantly. Therefore, the dimension of the robot is suggested to be designed for different scenarios, instead of designed to achieve high flexibility on a robot.

4.5.3 Selection of Sensors

In this project, two types of sensors are used, which are the infrared sensor and the ultrasonic sensor. These two sensors are the most used in prototype construction, easiest to be purchased, and cost effective. Both components have their advantages and disadvantages.

In the early stage of the project, the infrared sensor was chosen to be used for all distance measurement. The infrared sensor could only provide digital output to the Arduino. To adjust the distance for the infrared sensor to produce a low output to the Arduino, manual adjustment of the potentiometer of the sensor board could be achieved. However, the infrared sensor did not work well on the solar panel surface due to the dark colour of the solar panel surface. During the experimental stage, the sensor was adjusted to determine 7 cm with a white paper. When the sensor was installed to the cleaning brush to detect the solar panel, the cleaning brush did not stop at 7 cm, the infrared sensor did not detect an obstacle. Therefore, for the condition that requires the involvement of a solar panel surface, an ultrasonic sensor would be used. The infrared sensors are used in situations where precise detection is not required such as stopping the cleaning robot when it reaches the end of the moving frame.

The paragraph above mentioned the disadvantages of the infrared sensor especially on the accuracy aspects. The reason that the IR sensors are still being used in this project could be discovered through Table 4.2. Table 4.2 shows the differences between the infrared sensor and the ultrasonic sensors based on their accuracy, use of pins, code complexity, size, and cost.

Infrared sensor has lower accuracy compared to ultrasonic sensor as mentioned in the condition above that the infrared sensor could not perform well on different surfaces. Infrared sensor works on light reflection. For the surface that does not reflect light, the infrared sensor would not detect it as an obstacle. This characteristic could be utilised in other scenarios, but not in this project. On the other hand, the ultrasonic sensor works on ultrasonic wave reflection. The high-frequency sound wave would not be affected by the colour of the surface. Therefore, it could produce more accurate results compared to the infrared sensor.

Next, the infrared sensor produces either true or false value to the Arduino. The infrared sensor requires only one input pin to the Arduino. On the other hand, the ultrasonic sensor requires one output pin and one input pin to the Arduino. By using one ultrasonic sensor, two pins must be reserved for it. For the moving frame which uses Arduino Nano, the number of pins is limited. If more ultrasonic sensors are going to be used on the moving frame, the processing unit of the moving frame must be replaced with another that consists of more input and output pins. From the discussions of the number of pins used, the topic could be extended to the code complexity of the application. Figure 4.43 and Figure 4.44 show the codes used to read the outputs of the infrared sensor and the ultrasonic sensor respectively. For the infrared sensor, one line of code is required to read the output of the sensor, which is the “digitalRead”. For the ultrasonic sensor, several codes are required to measure and calculate the distance of the obstacles. Thus, a function was written to hold the codes so that only one line of code is required to call the function to check the distance measured by the ultrasonic sensor. Figure 4.45 shows the function written to calculate and return the distance.

```
void original_position(){
    Robot_Stop();
    Brush_Stop();
    Water_Pump_Stop();
    Linear_Actuator_Up();
    delay(1000);
    //Return Original Position
    Robot_Back();
    while(digitalRead(RobotStopBack) == HIGH) {
      Serial.println("Returning to Original Position");
    }
    Robot_Stop();
    Linear_Actuator_Stop();
    delay(2000);
}
```

Figure 4.43: Code Used to Read Infrared Sensor.

```
radio.stopListening();
if(check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
    strcpy(msg,"SP_Yes");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
} else {
    strcpy(msg,"SP_No");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    //Wait for frame to return into SP
    //So that I could read SP_no when the Frame is moved out SP
    delay(8000);
    while (check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
        strcpy(msg,"Return Initial");
        radio.write(&msg, sizeof(msg));
        Serial.println(msg);
    }
    strcpy(msg, "Reached Initial");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    delay(500);
}
```

Figure 4.44: Code Used to Read Ultrasonic Sensor.

```
int check_URsensor(int trigPin, int echoPin) {
    // Clears the trigPin
    digitalWrite(trigPin, LOW);
    delayMicroseconds(2);
    // Sets the trigPin on HIGH state for 10 micro seconds
    digitalWrite(trigPin, HIGH);
    delayMicroseconds(10);
    digitalWrite(trigPin, LOW);
    // Reads the echoPin, returns the sound wave travel time in microseconds
    long duration = pulseIn(echoPin, HIGH);
    // Calculating the distance
    int distance = duration * 0.034 / 2;
    Serial.println(distance);
    return distance;
}
```

Figure 4.45: Function for Ultrasonic Sensor Checking.

Furthermore, the size of the infrared sensor is smaller than the ultrasonic sensor. Figure 4.46 shows the infrared sensor and the ultrasonic sensor side by side to show the size difference. The smaller size infrared sensor can be installed easily onto the robot. Due to the close distance between the transmitter and receiver of the infrared sensor, the sensor does not occupy much space on the robot. On the other hand, the size of the ultrasonic sensor is bigger than the infrared sensor. The transmitter and receiver of the ultrasonic sensor are much bigger compared to the infrared sensor. The distance between the transmitter and receiver is a critical issue for the sensors. Figure 4.46 shows that the distance between the transmitter and receiver of the infrared sensor is about 1 cm, while the distance between the transmitter and receiver of the ultrasonic sensor is about 4.5 cm. If the position of the ultrasonic sensor is not considered properly, there might be a chance where the receiver could not receive the reflected wave from the obstacles. Therefore, the position of the ultrasonic sensor needed to be considered properly so that the transmitted sound wave could be reflected to the receiver efficiently to obtain accurate reading. Lastly, the cost for one infrared sensor is RM 1.90, while RM 4.90 is needed to purchase one ultrasonic sensor.

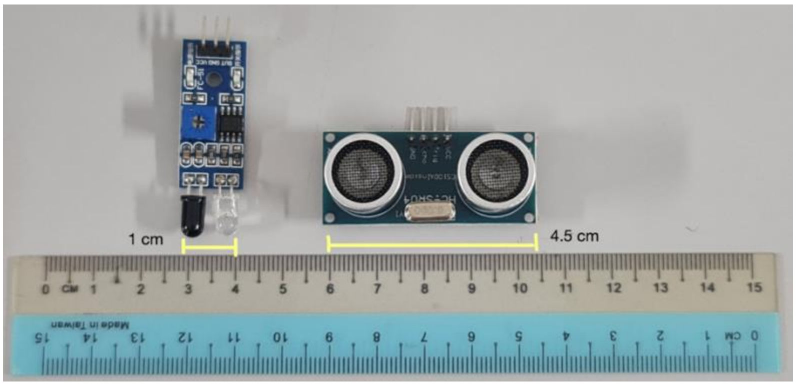

Figure 4.46: Infrared Sensor vs. Ultrasonic Sensor.

In summary, the accuracy of the infrared sensor is lower than the ultrasonic sensor. One pin is required by the infrared sensor, while two pins are required by the ultrasonic sensor. The code complexity of the infrared sensor is lower than the ultrasonic sensor. The size of the infrared sensor is smaller than the ultrasonic sensor. The price of the infrared sensor is cheaper than the ultrasonic sensor. Table 4.2 summarises the differences between the infrared sensor and the ultrasonic sensor. However, the ultrasonic sensor is recommended to replace all the infrared sensors due to its accuracy. A more powerful Arduino could be chosen to replace the Arduino Nano to solve the limitation of the pins. The complex code of the ultrasonic sensor could be written into a function as shown in Figure 4.44 and Figure 4.45. The price of an ultrasonic sensor which is 2.5 times compared to the infrared sensor is worth due to its accuracy and performance.

Table 4.2: Comparisons of Infrared Sensor and Ultrasonic Sensor.

Infrared Sensor	**Differences**	**Ultrasonic Sensor**
Low	**Accuracy**	High
One	**Use of Pins**	Two
Simple	**Code Complexity**	Complex
Smaller	**Size**	Bigger
RM 1.90	**Cost**	RM 4.90

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The project design comes with hardware and software design, where both work coherently to achieve the development of a solar panel cleaning robot. This project includes the hardware drawing, electronic circuits design, programming flowchart design, mechanical hardware construction, electrical and electronic circuits construction, and practical testing and debugging of the robot prototype with software. Throughout the development of the project, the flow of carrying out a complete project from an idea to a complete prototype was learnt. The relevant knowledge such as selection of materials and components and the use of software (AutoCAD, draw.io, Arduino IDE) were acquired.

This project introduced a brand new idea on developing a solar panel cleaning robot. The robot consists of two main parts which are the moving frame and the cleaning robot. The moving frame serves as the rail for the movement of the cleaning robot. The design of the moving frame eliminated the construction of rails that cost a lot for a large-scale solar panel site. Besides, the moving frame carries the cleaning robot so that the cleaning robot does not move directly on the surface of the solar panel. This consideration prevents the damage of the solar panels due to the weight of the cleaning robot and the wheel movement of the cleaning robot directly on the surface of the solar panels. Furthermore, the application of linear actuators allows the cleaning brush to reach the solar panel at different heights due to the installation of the solar panel with tilting angle.

At the end of the project, the solar panel cleaning robot could perform cleaning operations on the pre-defined testing environment automatically. The testing environment consists of 3 solar panels arranged in 1 row. By completing the operation on the testing environment, the solar panel cleaning robot developed in this project is considered as a success.

The existing methods of cleaning the solar panels were studied. A solar panel cleaning robot was developed and able to perform automatic cleaning operation on the pre-defined testing environment. The performance of the robot developed was evaluated. All the aims and objectives of the project were achieved.

5.2 Recommendations for Future Work

In this project, a complete prototype of a solar panel cleaning robot had been built. However, there are several improvements that could be accomplished in the future to enhance the overall performance of the robot.

Firstly, the material used to construct the structural body of the robot. In this project, an aluminium profile was used to construct the moving frame body and the cleaning robot body. The weight of the cleaning robot is heavy due to the high-density aluminium profile. Aluminium profile was selected for the prototype construction due to its availability of accessories in the market which makes the construction work convenient and fast. It is recommended that the structural material of the cleaning robot could use a lighter material to reduce the weight of the cleaning robot. However, the moving frame could still use the aluminium profile as the heavy structure of the moving frame could ensure the stability of the overall robot.

Next, the power supply and water supply handling method could be improved. In this project, the robot uses power supply from the power socket and a water tank to store water for cleaning purposes. To operate the robot in a large-scale solar panel site, power supply from socket and water supply from water tap are necessary. Therefore, the wire and hose handling method should be enhanced so that the wires and hose would not cause distractions to the robot during cleaning operation. On the other hand, if the robot operates within a small range of solar panel sites, battery power supply and water tank are recommended. With the use of a battery and water tank, the problems with the wire and hose could be eliminated.

Lastly, machine vision technology could be integrated into the robot. In this project, the operation of the robot depends on the sensors. To make the robot smarter, machine vision is one of the solutions. To apply machine vision, the usage of cameras could be considered. Besides, the processing unit of the robot could be replaced with a more advanced processor to provide higher computing power. The mature machine vision technique allows the robot to obtain the dirt identification system, self-locating ability, and smart cleaning operation.

In conclusion, the future development of the solar panel cleaning robot can focus on reducing the weight of the cleaning robot, water and power supply handling method and the integration of machine vision. In fact, there is always room for improvement. However, the improvement should be made based on the context to produce a robot that is suitable for the target environment.

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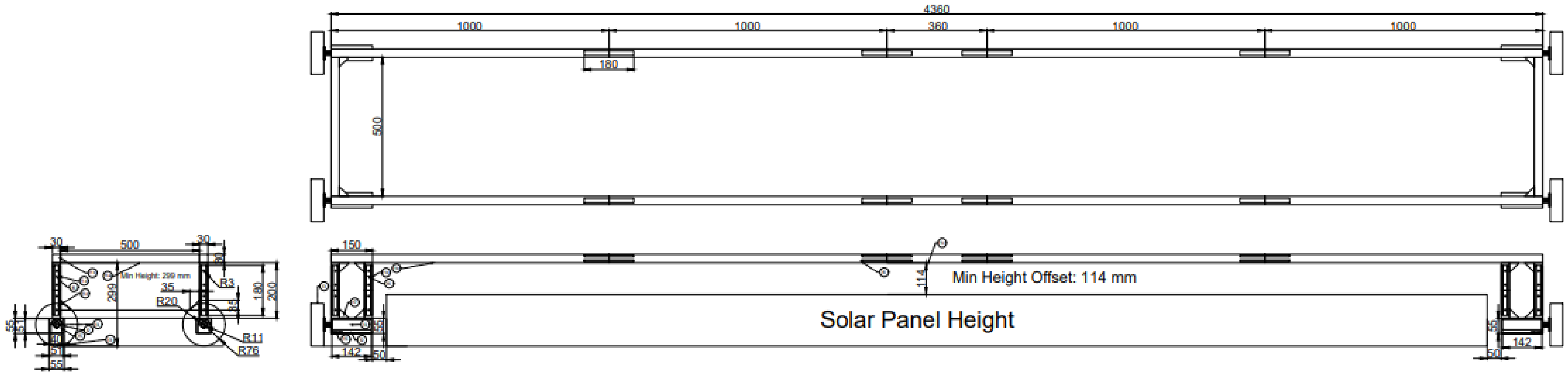
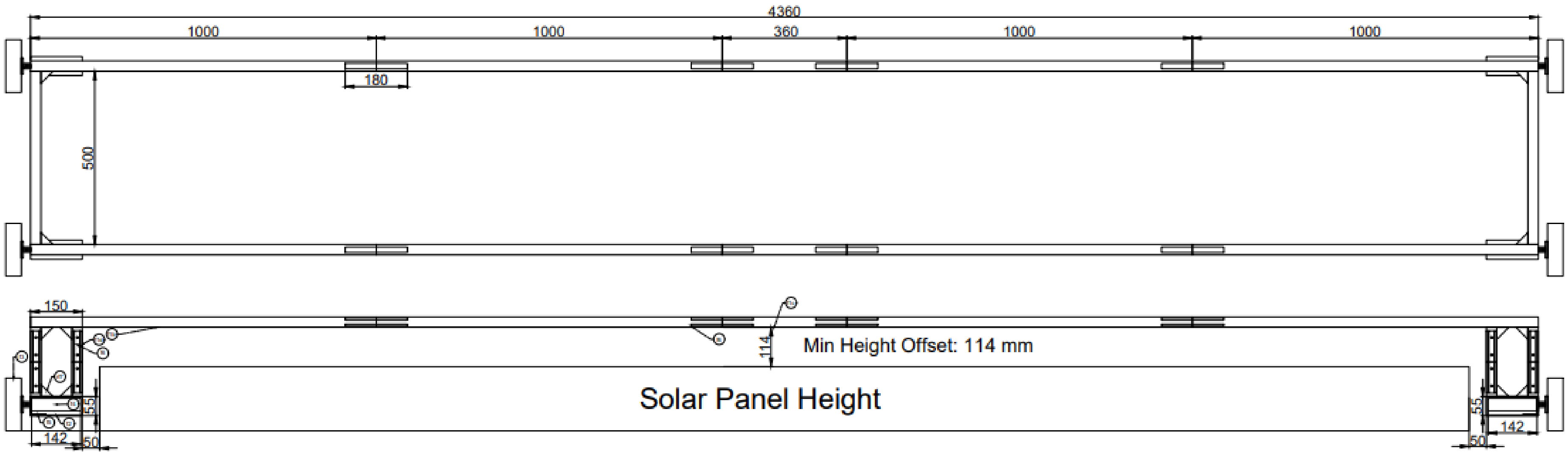
APPENDICES

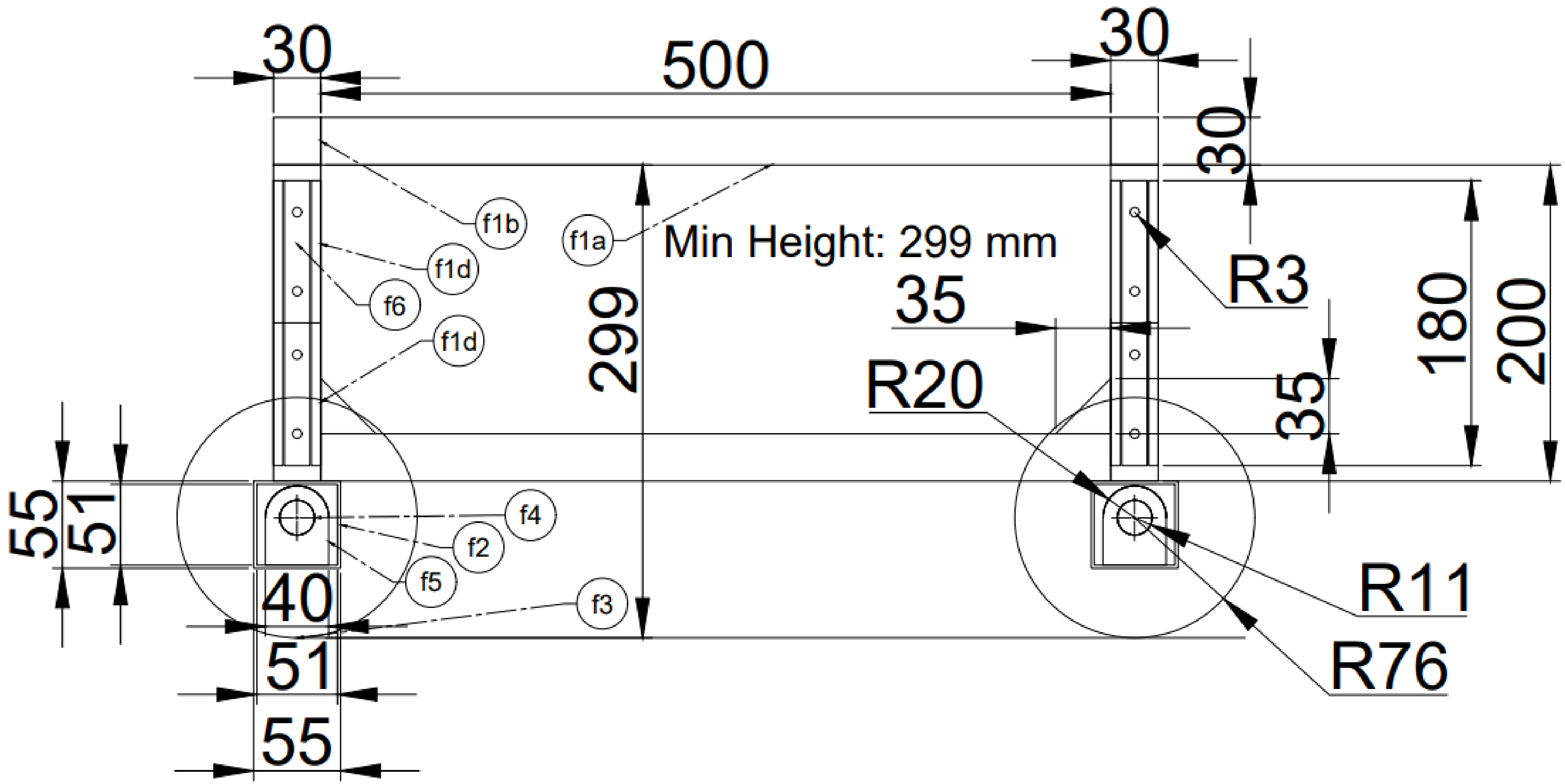
Appendix A: Drawings



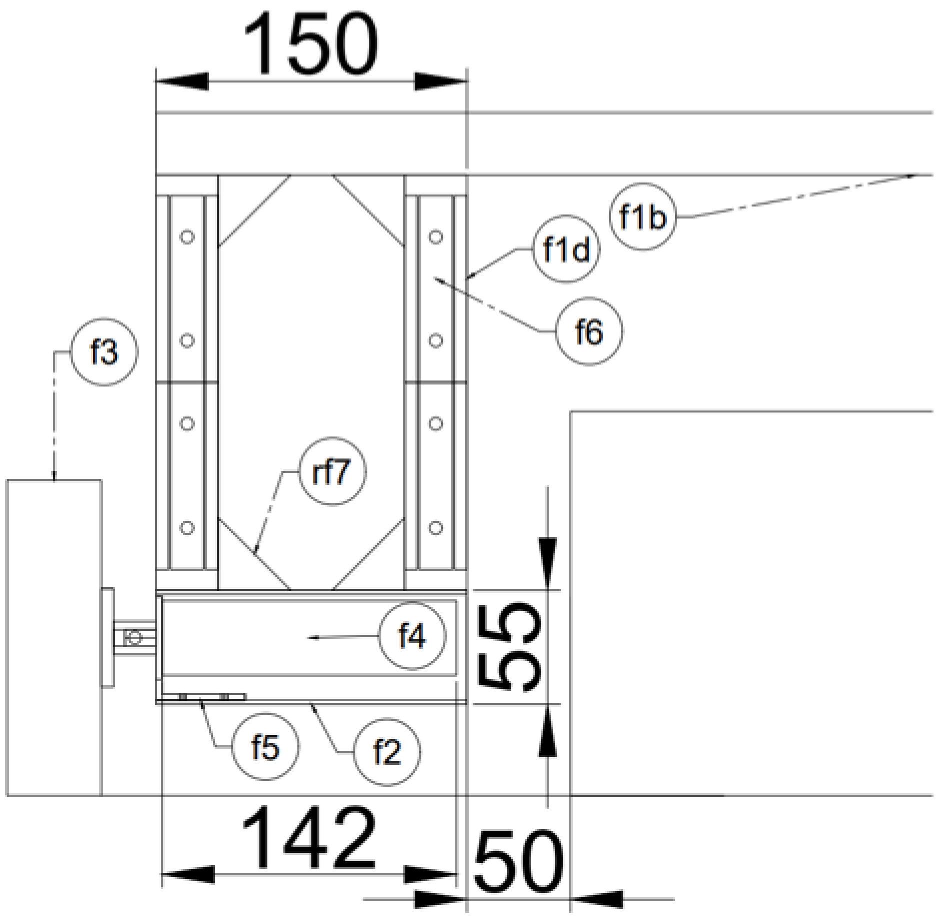
Drawing A-1: Moving Frame Orthographic Drawing - Full View



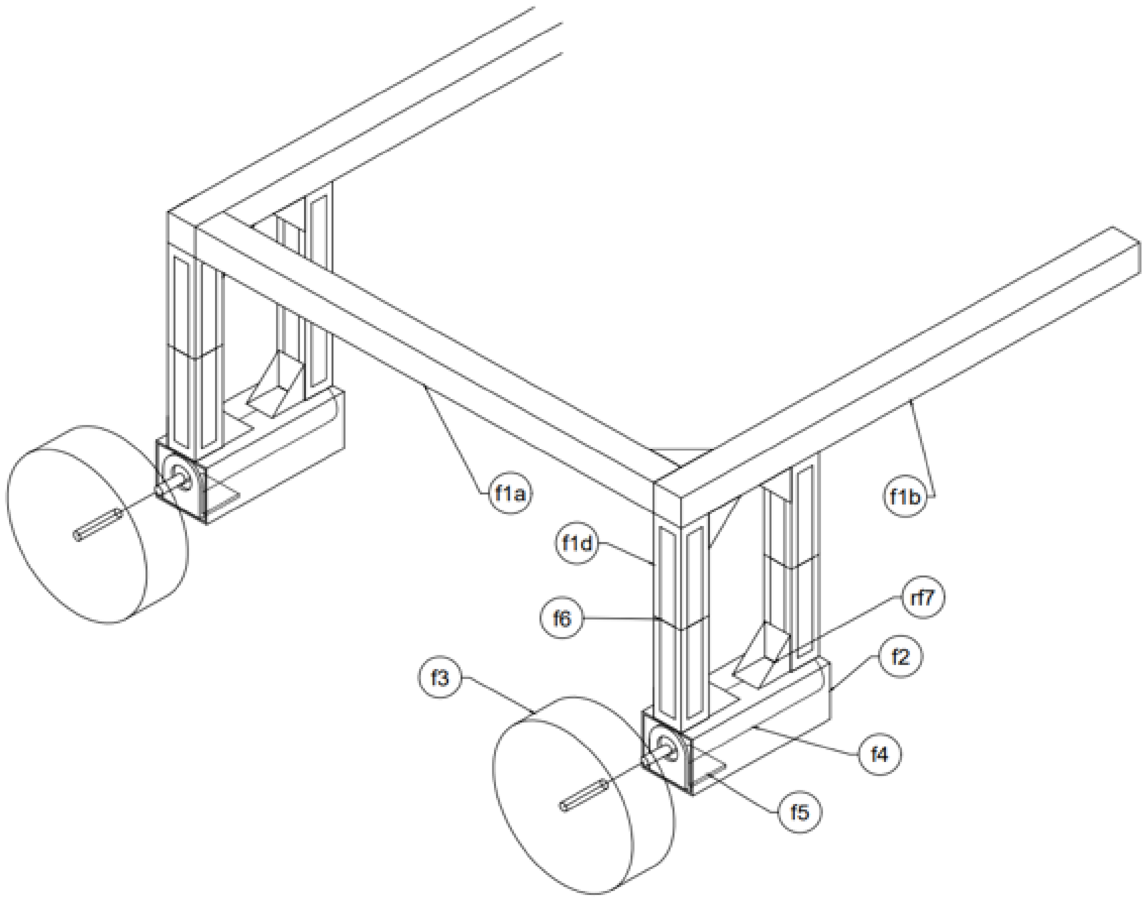
Drawing A-2: Moving Frame Orthographic Drawing - Top and Side View



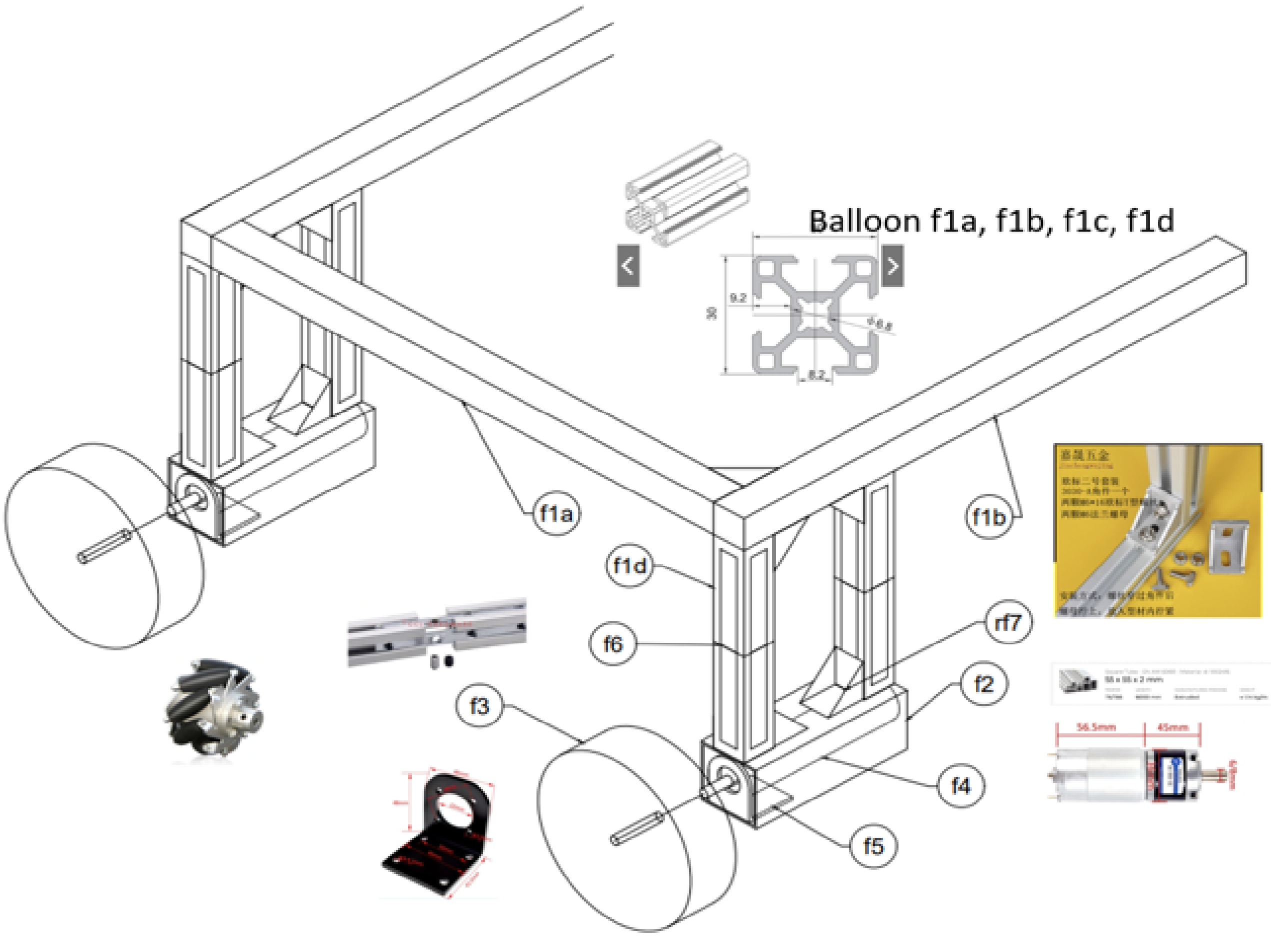
Drawing A-3: Moving Frame Orthographic Drawing - Front View



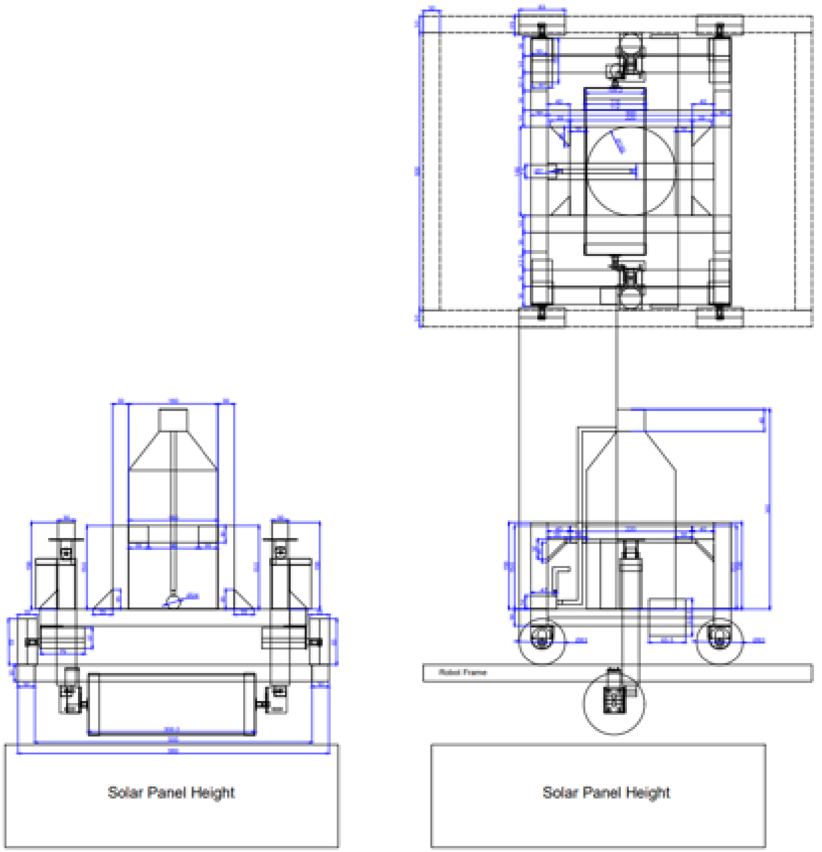
Drawing A-4: Moving Frame Orthographic Drawing - Side View Details



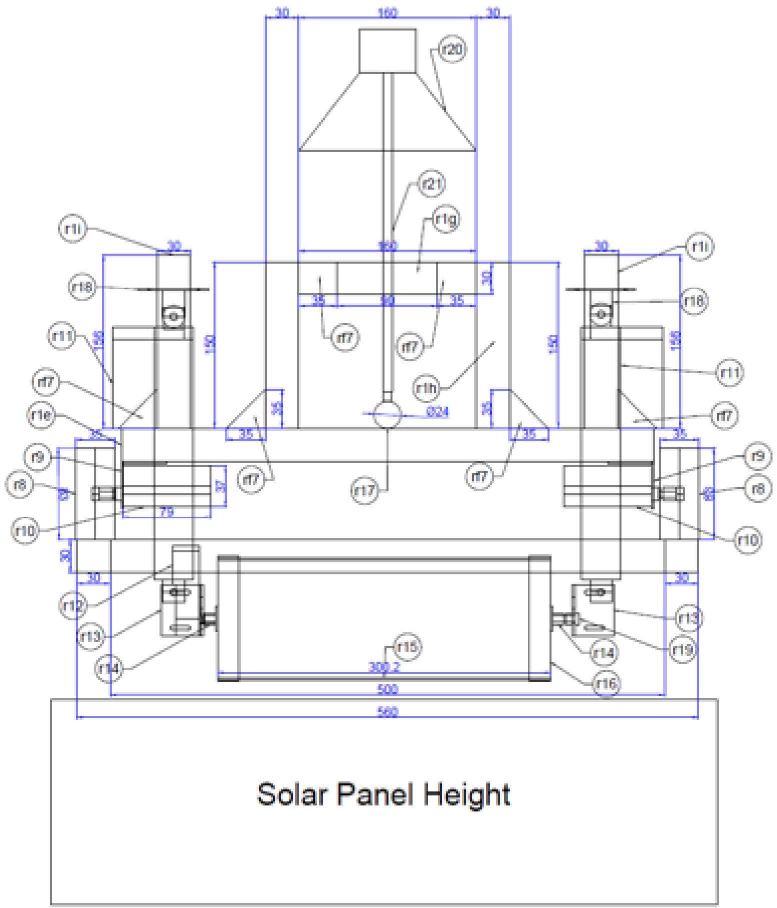
Drawing A-5: Moving Frame Isometric Drawing - Full View



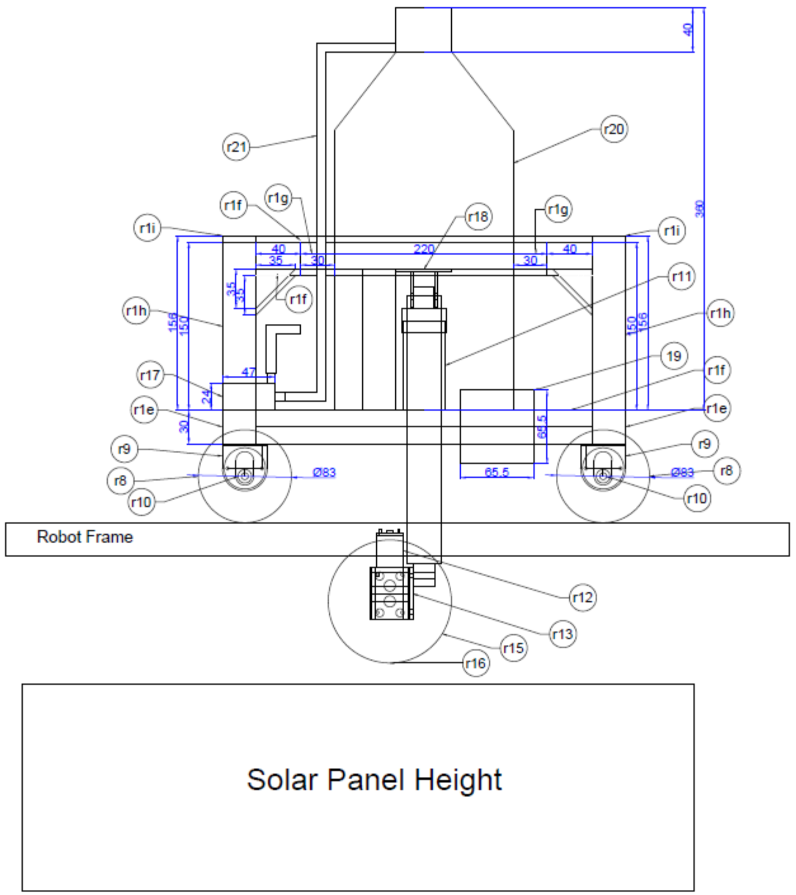
Drawing A-6: Moving Frame Isometric Drawing – Full View with Components



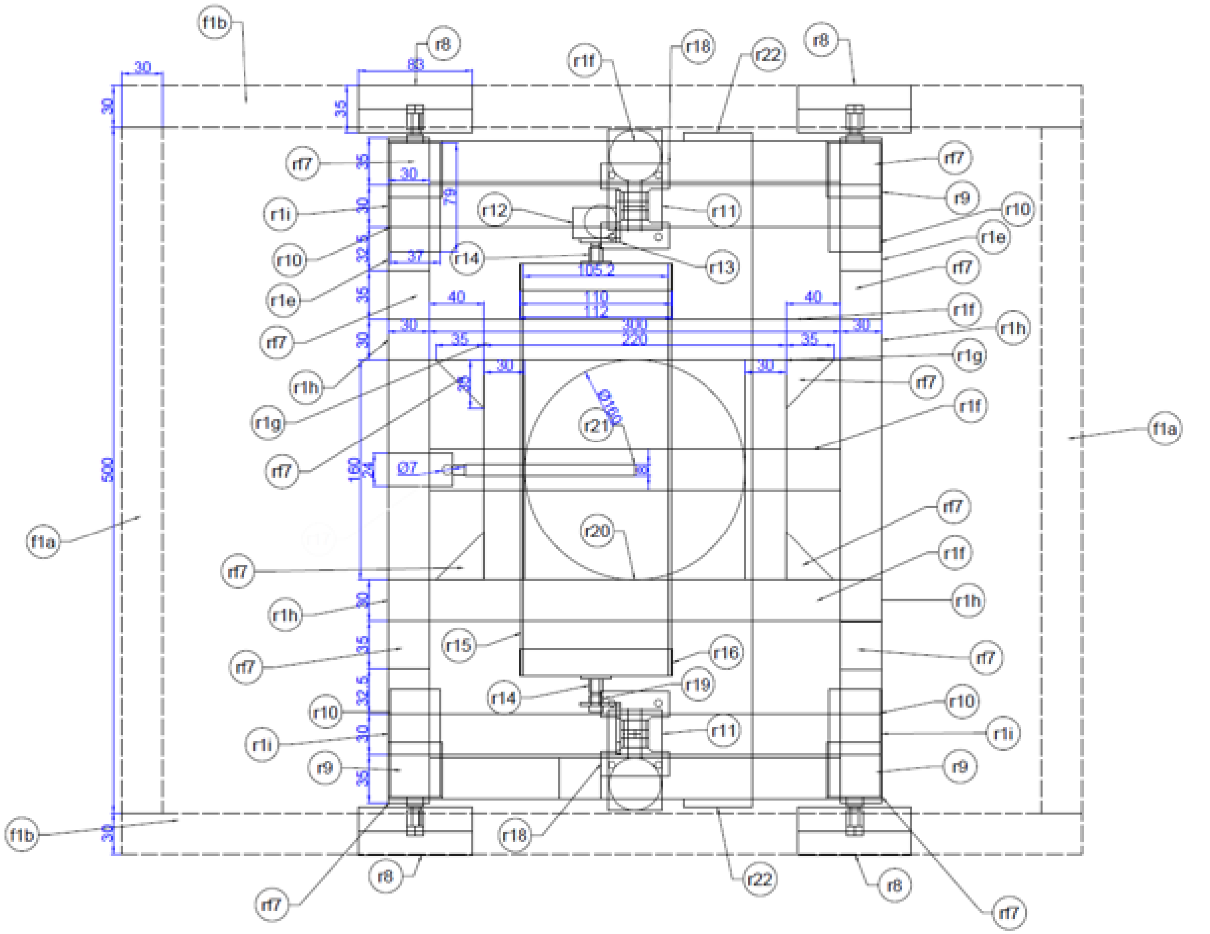
Drawing A-7: Cleaning Robot Orthographic Drawing – Full View



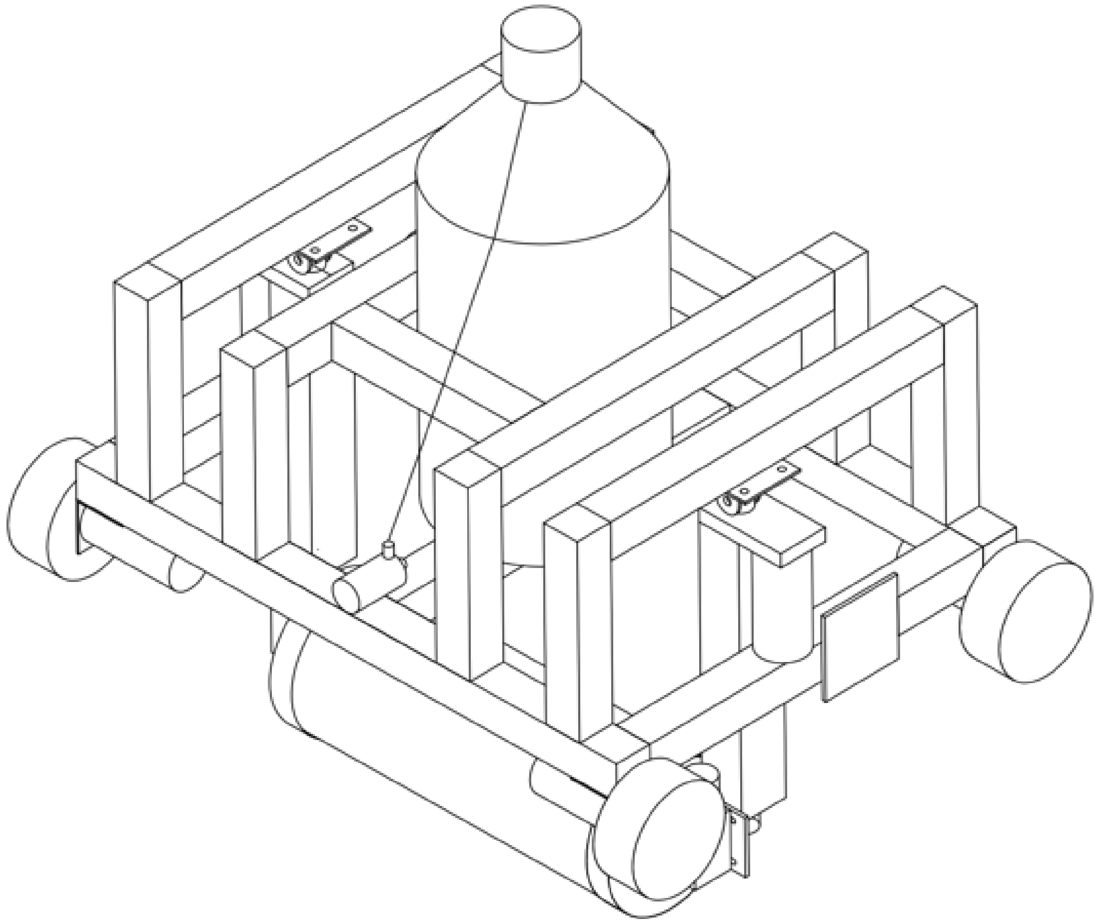
Drawing A-8: Cleaning Robot Orthographic Drawing – Front View



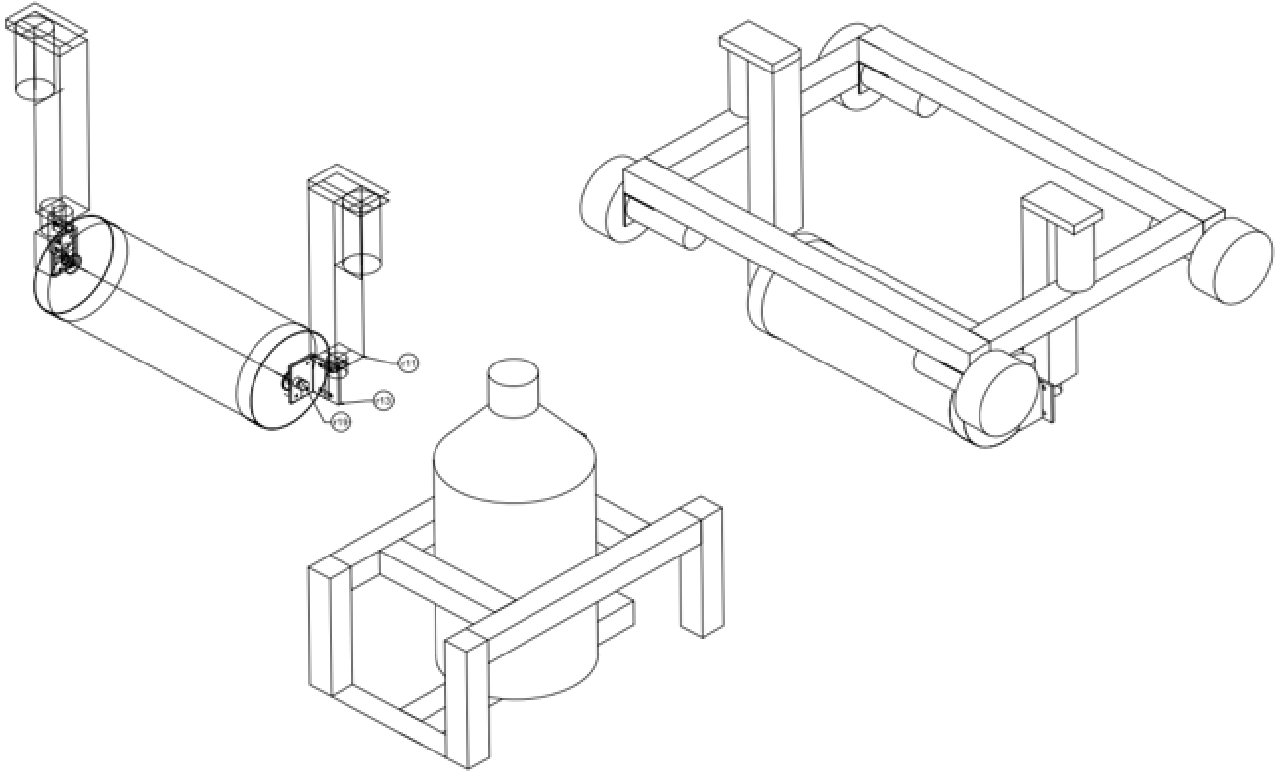
Drawing A-9: Cleaning Robot Orthographic Drawing – Side View



Drawing A-10: Cleaning Robot Orthographic Drawing – Top View



Drawing A-11: Cleaning Robot Isometric Drawing – Full View



Drawing A-12: Cleaning Robot Isometric Drawing – By Parts

Appendix B: Arduino Codes

Arduino Code of Moving Frame

```
// Solar Panel Cleaning Robot - Moving Frame Final 05-Apr2023

#include <nRF24L01.h>
#include <RF24.h>
#include <RF24_config.h>
#include <SPI.h>

// Wheels
#define FWFL_PWM 3    // Frame Wheel Front Left
#define FWFL_DIR 2
#define FWBL_PWM 6    // Frame Wheel Back Left
#define FWBL_DIR A3
#define FWFR_PWM 5    // Frame Wheel Front Right
#define FWFR_DIR 4
#define FWBR_PWM 9    // Frame Wheel Back Right
#define FWBR_DIR A2

// Radio Transceiver
#define CE_PIN 7
#define CSN_PIN 8
const uint64_t pipe1 = 0xE8E8F0F0E1LL;    // Writing Pipe Moving Frame
const uint64_t pipe2 = 0xE8E8F0F0AALL;    // Reading Pipe Moving Frame
RF24 radio(CE_PIN,CSN_PIN);

char output_pin[] =
{FWFL_PWM,FWFL_DIR,FWBL_PWM,FWBL_DIR,FWFR_PWM,FWFR
_DIR,FWBR_PWM,FWBR_DIR};

int max_speed = 30;       // Wheel Motor Max Speed
```

```
int start_delay = 2;      // Acceleration Delay
int stop_delay = 2;       // Deceletation Delay
char msg[25] = "STOP";    // Store Incoming Message

void setup() {
    Serial.begin(9600);
    radio.begin();
    radio.openReadingPipe(1,pipe2);
    radio.openWritingPipe(pipe1);

    for(int i = 0; i< (sizeof(output_pin)/sizeof(output_pin[0])); i++) {
        pinMode(output_pin[i], OUTPUT);
        digitalWrite(output_pin[i], LOW);
    }

    Serial.println("Done Setup");
}

void loop() {
   radio.startListening();
   do{
      if(radio.available()) {
          radio.read(msg, sizeof(msg));
      }
      Serial.println((String)"Pending Ori Posi: "+ msg);
      delay(500);
   } while(strcmp(msg, "Ori Posi") != 0);

   Serial.println("Frame Front 5 Seconds");
   Frame_Front();
   delay(5000);      //only move 5 seconds = 300 mm
   Frame_Stop();
```

```
radio.stopListening();
strcpy(msg,"Check_SP");
radio.write(&msg, sizeof(msg));
Serial.println(msg);
delay(500);

radio.startListening();
do{
  if(radio.available()) {
    radio.read(msg, sizeof(msg));
  }
  Serial.println((String)"Pending SP...: "+ msg);
} while(strcmp(msg,"SP_Yes") != 0 && strcmp(msg,"SP_No") != 0);

if(strcmp(msg,"SP_No") == 0) {
  Frame_Back();
  Serial.println("Frame Moving Back...");
  delay(1000);
  do{
    if(radio.available()) {
      radio.read(msg, sizeof(msg));
    }
    Serial.println((String)"Pending Reach Initial: "+ msg);
    //delay(500);
  } while(strcmp(msg,"Reached Initial") != 0);
  Frame_Stop();
  delay(1000);
  Frame_Front();
  delay(2500);
  Frame_Stop();
  Serial.println("Frame Returned to Initial Position");
}
```

```
  radio.stopListening();
  strcpy(msg,"Clean");
  radio.write(&msg, sizeof(msg));
  Serial.println(msg);
  delay(500);
}

void Frame_Stop() {
   deceleration(FWFL_PWM, FWBL_PWM, FWFR_PWM, FWBR_PWM);
}

void Frame_Front() {
  digitalWrite(FWFL_DIR,HIGH);
  digitalWrite(FWBL_DIR,HIGH);
  analogWrite(FWFR_DIR,255);
  analogWrite(FWBR_DIR,255);

  analogWrite(FWFL_PWM, max_speed);
  analogWrite(FWBL_PWM, max_speed+32);
  analogWrite(FWFR_PWM, max_speed+31);
  analogWrite(FWBR_PWM, max_speed+32);
}

void Frame_Back() {
  digitalWrite(FWFL_DIR,LOW);
  digitalWrite(FWBL_DIR,LOW);
  analogWrite(FWFR_DIR,0);
  analogWrite(FWBR_DIR,0);

  analogWrite(FWFL_PWM, max_speed);
  analogWrite(FWBL_PWM, max_speed+30);
  analogWrite(FWFR_PWM, max_speed+33);
  analogWrite(FWBR_PWM, max_speed+32);
```

```
}

void Frame_Right() {
  digitalWrite(FWFL_DIR,LOW);
  digitalWrite(FWBL_DIR,HIGH);
  analogWrite(FWFR_DIR,255);
  analogWrite(FWBR_DIR,0);

  analogWrite(FWFL_PWM, max_speed);
  analogWrite(FWBL_PWM, max_speed+32);
  analogWrite(FWFR_PWM, max_speed+31);
  analogWrite(FWBR_PWM, max_speed+32);
}

void Frame_Left() {
  digitalWrite(FWFL_DIR,HIGH);
  digitalWrite(FWBL_DIR,LOW);
  analogWrite(FWFR_DIR,0);
  analogWrite(FWBR_DIR,255);

  analogWrite(FWFL_PWM, max_speed);
  analogWrite(FWBL_PWM, max_speed+30);
  analogWrite(FWFR_PWM, max_speed+33);
  analogWrite(FWBR_PWM, max_speed+32);
}

void deceleration(int *pwm_fl,int *pwm_bl,int *pwm_fr,int *pwm_br) {
 for(int pwm_value = max_speed; pwm_value > 0; pwm_value--) {
    analogWrite(pwm_fl, pwm_value);
    analogWrite(pwm_bl, (pwm_value/2));
    analogWrite(pwm_fr, (pwm_value/2));
    analogWrite(pwm_br, (pwm_value/2));
    delay(stop_delay);
```

```
  }
  analogWrite(pwm_fl, 0);
  analogWrite(pwm_bl, 0);
  analogWrite(pwm_fr, 0);
  analogWrite(pwm_br, 0);
  return;
}

void acceleration(int *pwm_fl,int *pwm_bl,int *pwm_fr,int *pwm_br) {
  for(int pwm_value = 0; pwm_value <= max_speed; pwm_value++) {
      analogWrite(pwm_fl, pwm_value);
      analogWrite(pwm_bl, (pwm_value/2));
      analogWrite(pwm_fr, (pwm_value/2));
      analogWrite(pwm_br, (pwm_value/2));
      delay(start_delay);
  }
  return;
}
```

Arduino Code of Cleaning Robot

```
//Solar Panel Cleaning Robot Final Version 05-Apr2023
//Remember:
//1. The CE Pin = 49, CSN Pin = 48
//2. Check the connections on the arduino

#include <nRF24L01.h>
#include <RF24.h>
#include <SPI.h>
#include <Wire.h>
#include <Servo.h>

// define the pin number
// Sensors
#define RobotStopFront 19     // Robot Stop Sensor Front
#define RobotStopBack 20      // Robot Stop Sensor Back
#define LAS_echo 40           // Linear Actuator Stop URSensor
#define LAS_trig 42
#define SPCHECK_echo 38       // Solar Panel Checking Sensor
#define SPCHECK_trig 36

// Radio Receiver
#define CE_PIN 49
#define CSN_PIN 48

// Motors
#define RWFL_PWM 8        // robot wheel front left
#define RWFL_DIR 25
#define RWBL_PWM 9        // robot wheel back left
#define RWBL_DIR 24
#define RWFR_PWM 7        // robot wheel front right
#define RWFR_DIR 23
```

```
#define RWBR_PWM 2        // robot wheel back right
#define RWBR_DIR 27
#define LAL_PWM 4         // linear actuator left
#define LAL_DIR 28
#define LAR_PWM 3         // linear actuator right
#define LAR_DIR 26
#define CLBM_PWM 5        // cleaning brush motor
#define CLBM_DIR 29
#define WPM 53            // water pump motor

// define the variables

int distance;                   // Store Distance Calculated by Ultrasonic Sensor
long duration;                  // Used for Ultrasonic Sensor
int dum = 0;                    // Dummy Variable
const int brush_offset = 7;     // Cleaning Brush Offset
const int wheel_speed = 255;    // Wheel Motor Max Speed
const int brush_speed = 255;    // Brush Motor Max Speed
const int start_delay = 2;      // Acceleration Delay

const uint64_t pipe1 = 0xE8E8F0F0E1LL;        // Reading Pipe of Cleaning
Robot
const uint64_t pipe2 = 0xE8E8F0F0AALL;        // Writing Pipe of Cleaning
Robot
RF24 radio(CE_PIN,CSN_PIN);
char msg[25] = "";              // Store Incoming Message

int output_pin[] =
{RWFL_PWM,RWFL_DIR,RWBL_PWM,RWBL_DIR,RWFR_PWM,RWF
R_DIR,RWBR_PWM,RWBR_DIR,LAL_PWM,LAL_DIR,LAR_PWM,LAR
_DIR,CLBM_PWM,CLBM_DIR};

void setup(){
```

```
    Serial.begin(9600);
    radio.begin();
    radio.openReadingPipe(1,pipe1);
    radio.openWritingPipe(pipe2);

    for(int i = 0; i< (sizeof(output_pin)/sizeof(output_pin[0])); i++) {
        pinMode(output_pin[i], OUTPUT);
        digitalWrite(output_pin[i], LOW);
    }

    pinMode(WPM,OUTPUT);
    digitalWrite(WPM,HIGH);     //Water Pump Relay "HIGH" to switch off
    pinMode(LAS_trig, OUTPUT);
    pinMode(LAS_echo, INPUT);
    pinMode(SPCHECK_trig,OUTPUT);
    pinMode(SPCHECK_echo,INPUT);
    pinMode(RobotStopFront,INPUT_PULLUP);
    pinMode(RobotStopBack,INPUT_PULLUP);
    Serial.println("Done Setup");

    //Robot Return Original Position
    original_position();
}

void loop(){
    cleaning_operation();
    radio.stopListening();
    strcpy(msg,"Ori Posi");
    radio.write(&msg, sizeof(msg));
    delay(5000);

    radio.startListening();
    do{
```

```
    if(radio.available()) {
        radio.read(msg, sizeof(msg));
    }
    Serial.println((String)"Pending Check SP: "+ msg);
    delay(500);
} while(strcmp(msg, "Check_SP") != 0);

radio.stopListening();
if(check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
    strcpy(msg,"SP_Yes");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
} else {
    strcpy(msg,"SP_No");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    //Wait for frame to return into SP
    //So that I could read SP_no when the Frame is moved out SP
    delay(8000);
    while (check_URsensor(SPCHECK_trig, SPCHECK_echo) <= 24) {
        strcpy(msg,"Return Initial");
        radio.write(&msg, sizeof(msg));
        Serial.println(msg);
    }
    strcpy(msg, "Reached Initial");
    radio.write(&msg, sizeof(msg));
    Serial.println(msg);
    delay(500);
}

radio.startListening();
do{
    if(radio.available()) {
```

```
      radio.read(msg, sizeof(msg));
      Serial.println((String)"Pending Clean: "+ msg);
    }
    delay(500);
  } while(strcmp(msg, "Clean") != 0);
}

void cleaning_operation() {
  Linear_Actuator_Down();
  do {
   distance = check_URsensor(LAS_trig,LAS_echo);
  } while (distance > brush_offset);
  Linear_Actuator_Stop();
  Brush_On();
  Water_Pump_On();
  Robot_Front();
  while(digitalRead(RobotStopFront) == HIGH) {
   Serial.println("Cleaning...");
   if(check_URsensor(LAS_trig,LAS_echo) > brush_offset) {
     Linear_Actuator_Down();
   } else if(check_URsensor(LAS_trig,LAS_echo) == brush_offset) {
     Linear_Actuator_Stop();
   } else if(check_URsensor(LAS_trig,LAS_echo) < brush_offset) {
     Linear_Actuator_Up();
   }
  }
  original_position();
}

void original_position() {
  Robot_Stop();
  Brush_Stop();
  Water_Pump_Stop();
```

```
  Linear_Actuator_Up();
  delay(1000);
  //Return Original Position
  Robot_Back();
  while(digitalRead(RobotStopBack) == HIGH) {
    Serial.println("Returning to Original Position");
  }
  Robot_Stop();
  Linear_Actuator_Stop();
  delay(2000);
}

int check_URsensor(int trigPin, int echoPin) {
  // Clears the trigPin
  digitalWrite(trigPin, LOW);
  delayMicroseconds(2);
  // Sets the trigPin on HIGH state for 10 micro seconds
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);
  // Reads the echoPin, returns the sound wave travel time in microseconds
  long duration = pulseIn(echoPin, HIGH);
  // Calculating the distance
  int distance = duration * 0.034 / 2;
  Serial.println(distance);
  return distance;
}

void Robot_Front() {
  digitalWrite(RWFL_DIR, LOW);
  digitalWrite(RWBL_DIR, LOW);
  digitalWrite(RWFR_DIR, LOW);
  digitalWrite(RWBR_DIR, LOW);
```

```
  acceleration(RWFL_PWM, RWBL_PWM, RWFR_PWM,
RWBR_PWM,wheel_speed);
  analogWrite(RWFL_PWM, wheel_speed);
  analogWrite(RWBL_PWM, wheel_speed-2);
  analogWrite(RWFR_PWM, wheel_speed-9);
  analogWrite(RWBR_PWM, wheel_speed-12);
}

void Robot_Back() {
  digitalWrite(RWFL_DIR, HIGH);
  digitalWrite(RWBL_DIR, HIGH);
  digitalWrite(RWFR_DIR, HIGH);
  digitalWrite(RWBR_DIR, HIGH);
  acceleration(RWFL_PWM, RWBL_PWM, RWFR_PWM, RWBR_PWM,
wheel_speed);
  analogWrite(RWFL_PWM, wheel_speed-12);
  analogWrite(RWBL_PWM, wheel_speed-10);
  analogWrite(RWFR_PWM, wheel_speed-2);
  analogWrite(RWBR_PWM, wheel_speed);
}

void Robot_Stop() {
    analogWrite(RWFL_PWM, 0);
    analogWrite(RWBL_PWM, 0);
    analogWrite(RWFR_PWM, 0);
    analogWrite(RWBR_PWM, 0);
}

void acceleration(int *pwm_fl,int *pwm_bl,int *pwm_fr,int *pwm_br, int
*max_speed) {
 for (int i = 0; i < max_speed; i++) {
    analogWrite(pwm_fl, i); //increase motor speed
    analogWrite(pwm_bl, i);
```

```
    analogWrite(pwm_fr, i);
    analogWrite(pwm_br, i);
    delay(start_delay);
  }
}

void Brush_On() {
  digitalWrite(CLBM_DIR, HIGH); //Change to "LOW" for opposite direction
  acceleration(CLBM_PWM, dum, dum, dum, brush_speed);
  analogWrite(CLBM_PWM, brush_speed);
}

void Brush_Stop() {
  analogWrite(CLBM_PWM, 0);
}

void Linear_Actuator_Up() {
  digitalWrite(LAL_DIR, HIGH);
  digitalWrite(LAR_DIR, HIGH);
  analogWrite(LAL_PWM, 255-12);
  analogWrite(LAR_PWM, 255);       //max_speed-12 is used for speed
difference
  //Serial.println("Linear Actuator Up On");
}

void Linear_Actuator_Down() {
  digitalWrite(LAL_DIR, LOW);
  digitalWrite(LAR_DIR, LOW);
  analogWrite(LAL_PWM, 255);     //max_speed-12 is used for speed
difference
  analogWrite(LAR_PWM, 255-12);
  //Serial.println("Linear Actuator Down On");
}
```

```
void Linear_Actuator_Stop() {
  analogWrite(LAL_PWM,0);
  analogWrite(LAR_PWM,0);
  //Serial.println("Linear Actuator Stopped");
}

void Water_Pump_On() {
  digitalWrite(WPM,LOW);
}

void Water_Pump_Stop() {
  digitalWrite(WPM,HIGH);
}
```