

# DESIGN OF ROBOT ON THE ROOF



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Abstract

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This thesis is a concept design of a robot on the roof which is a mounting system for industrial collaborative robots to do roof jobs. The paper includes research about flat roof type, lifecycle, maintenance works, risks, and suitable robots for the tasks. The design process follows the Ullman design process with four phases: discovery, definition, conceptual design and evaluation. The expected outcome of the thesis is the concept illustration with 3D CAD model of the robot platform, Arduino control programme and Solidworks motion study simulation of the platform working on the flat roof.

The final concept design is developed using four stepper motors and winches to control the movement of the robot mounting platform as assigned. Within a limited scale, this study also indicates the challenges during the design process and provides further development suggestions.

Keywords 3D design, Arduino, Collaborative Robot, Flat Roof, Ullman Design Process, Winches.

Pages 51 pages and appendices 10 pages

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## 1 INTRODUCTION

Roof work is always a challenge due to the high level of the work area, on top of buildings. Many aspects can affect the lifespan of the roof, especially with Finnish weather, which drives the needs for roof jobs. Manual installation or maintenance takes time, effort, and many workers, depend on the size of the building, which could increase the risk of unexpected accidents or affect the durability of the roof. Finding the solution for this job is the key point in this thesis paper.



Figure 1. Roof manual installation (Next Insurance , 2020)

Developments in industrial technology field bring a lot of advantages for mechanical engineering for the last decade. Workplaces and factories are now equipped with modern machines and compartments and developed technologies in manufacture, maintenance and sustainability. Robot and automation have made an enormous step of humankind which were applied in many forms and application to enhance work efficiency, precision and process time reduction, especially with extraordinary amounts.

Generally, robots are created to simulate the human work which requires precise method, heavy load or repetitiveness and so on. In mechanical manufacture, they are usually used for material processing, assembly, palletizing and inspection thus certain types will be applied to different needs. Thousands of collaborative robots are working with workers around the world in the recent years, which brought the idea of implying the usage of cobot into roof works as a support or replacement for workers. For the rooftop area, mounting the robot to perform tasks is a challenge because of the height of the working area. Roof also has many varieties, such as steep, low-pitch and flat, which will need detailed research of each, so this study only focused on flat roof type.

Other modern technologies are used to develop a working system these days, for instance microprocessor, programming software and 3D printing. Arduino boards, which is an open-source microcontroller including both hardware and software, can

be used for the control system with the programmable processor and many compatible components available commercially.

This thesis aims to create a solution concept to install and carry the UR3 in order to apply its usages for flat roof type jobs. Theoretical studies on flat roof features, maintenance, hazards, and design process, future development suggestions will be carried out thoroughly in this thesis paper. Furthermore, the goal is to have an idea illustration with 3D design, control operation and working simulation in the virtual environment of CAD software.

## 2 PROBLEM IDENTIFICATION

### 2.1 ROOF TYPE

Roof is the uppermost component of a building which prevents weather status from affecting building's inner structures. Due to complicated climate condition in Finland with significant high range of temperature changing between lowest and highest temperature, heavy snow falling and laden and strong wind etc affect much to the roof structure, durability, and lifetime. Therefore, most of building roof was designed and constructed with decline roof to allow snow slip off from the roof avoiding heavy load of snow accumulate on the roof. An example of different components of the roof are illustrated in Figure 2, including shingles, attic ventilation, roof deck protection and leak barrier.

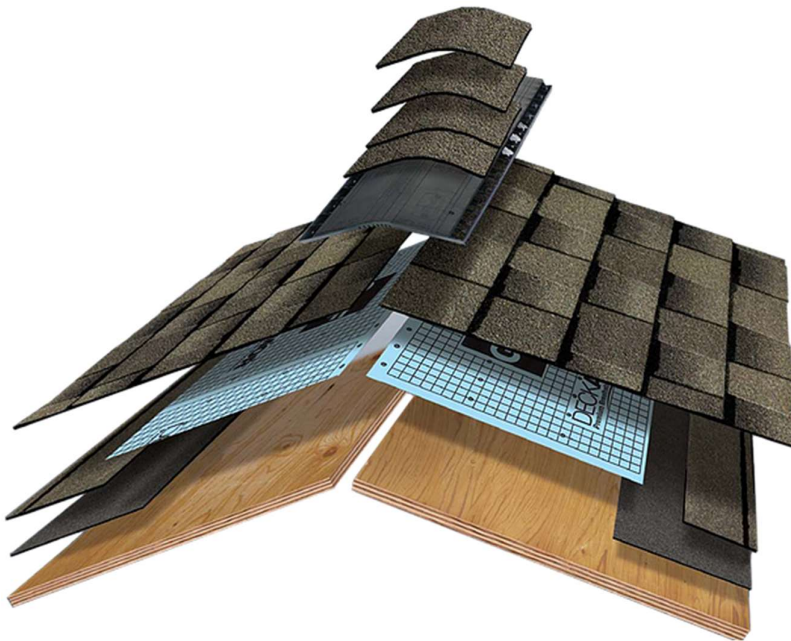


Figure 2. Roof components (fletcherroofs.com, 2021)

Roof shapes can be categorized into four groups: low pitched roof, high pitch roof, flat roof and curved roof.

Low pitched roof has pitch ( $Pitch = \frac{Rise}{Span}$ ) ratio between 1:10 – 1:80. High pitched roof has pitch ratio of 1:20 or higher (pitch ratio 1:10 – 1:20 can be varied with different systems to be specified as low or high pitched). Meanwhile, flat roof obviously has pitch ratio of 0 and curved roof has curves, so pitch ratio is irrelevant to calculate with this type. (Kattoliitto, 2010)

Nowadays materials used for roofs are bitumen and metals. Other materials such as clay, wood and thatch will not be introduced in this thesis as additional or heavyweight equipment cannot be installed with those material types.

Bitumen or asphalt is distilled low-grade crude oil and known for its waterproof and adhesive properties so this substance in construction industry is mainly used for paving and roofing applications. (Energy Education, 2018)

There are two common roofing procedures for bitumen: built-up and polymer modified. Built-up method consists of stacking layers of oxidized bitumen and bitumen membranes and on top of them all is a coating.

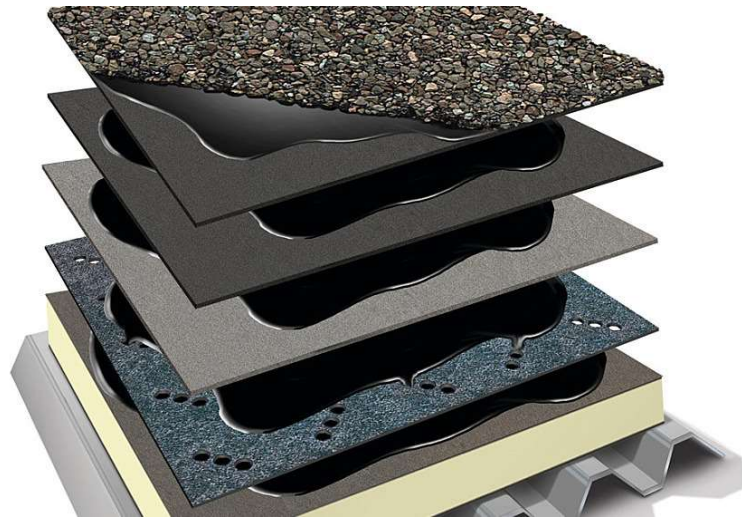


Figure 3. Built-up method (Edwards, 2020)

Modified polymer bitumen roofing is a more advanced method of built-up method as the layers of modified bitumen does not need hot melted tar and gravel because modified bitumen can self-sticking together in normal temperature. Commercially, APP (Atactic Polypropylene) and SBS (Styrene-Butadiene-Styrene) polymers are widely purchased for buyers who use this roofing method.

The bitumen roof systems have long life span (more than 20 years), high waterproof capability, high tensile strength and weather durability. However, bitumen absorbs heat a lot due to its black colour so the building can be superheated if proper installation was not done correctly. (SPRI, 2019)

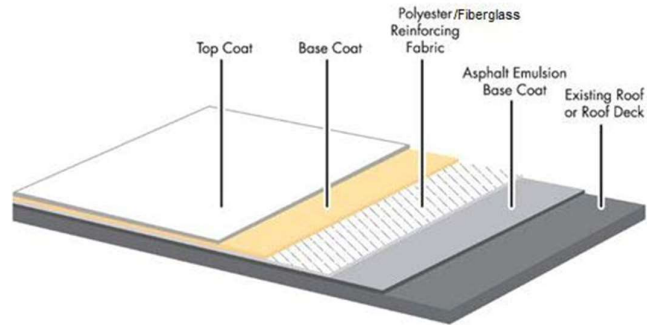


Figure 4. Modified polymer bitumen (Champion Roofing, 2019)

Secondly, metal can also be used for roofing e.g., steel, zinc, aluminium and copper. Metals can be formed as sheets, shingles, tiles, panels and then locked together by seams and joints to create the roof.



Figure 5. Steel roof (Abcseamless, 2020)

Metal roof lasts long (40-50 years) is lightweight, can be installed easily and reflects heat. However, initial installing cost is higher than bitumen roof and cracks can appear if extreme weather conditions start. (Vandervort, 2021)

## 2.2 PHASES OF ROOF LIFE CYCLE

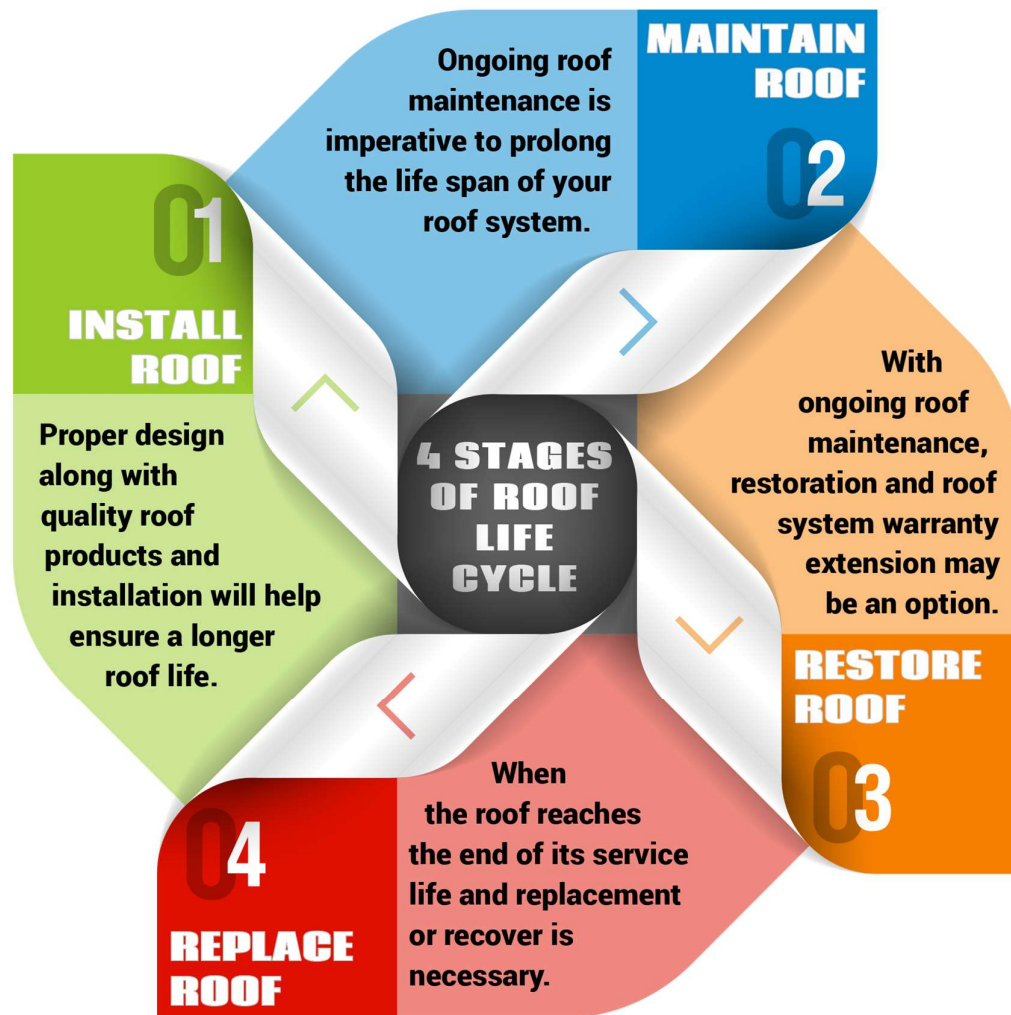


Figure 6. Phases of roof life cycle (Mullen, 2021)

Figure 6 above is the 4 stages of roof life cycle flowchart. In real life there is not a definite way to calculate the lifespan of any roof structure, but usually construction company guarantees for 15 to 30 years of usage. This is because many affected factors vary in every building, area, and country, such as local climatic, material usage, design, etc.

The new phase typically last for 2 years after the roof is installed, all the considerations and choices of material from here will affect the whole life of a roof. The next phases would be the next 15 years of usage when damages and aging start to affect the roof more serious. At this stage, annual inspection and ongoing maintenance needs to be carried out to ensure the good condition of the roof and prevent it from breaking down. Proper maintenance also helps the owner save additional cost because warranty is likely not covering every aspect. Finally, the last stage is re-cover and replace the whole roof. For the last decade, good quality material, manufacturing and maintenance in the previous phases could give an average 15 to 30 years, some even run up to 50 years of lifespan to the roof. After that

point most of the roofs would reach the end of their usage and it is time to consider replacement possibilities. Cracked, broken or missing shingles, exposed bald spot and staining are some of the aspects to determine for a renewal of rooftop area. Depending on the condition of the remains, a re-cover or rebuild is needed in order to not corrupt the lifespan of the building. (Meza, 2015)

## 2.3 ROOF MAINTENANCE

### 2.3.1 Maintenance tasks

To maintain a fine condition rooftop, check-ups and repairs need to be taken regularly. A list of common roof works is included and explained below:

- Inspection

An inspection is carried out to identify the problems occur with the roof, by throughout spectate, capture with infrared or other special cameras. In some cases, uninstalation of roof parts is needed for underneath roof damages.

- Cleaning

Tree branches, leaves or other elements could fall on the roof and stack up through time. Cleaning the area before any further maintenance task is required to prevent additional damage.

- Renovating hole

Drainpipe hole could be clogged overtime, due to high water pressure surround the area, leading to seepage. Fixing can be done by open up the exit hole.

- Painting

Roof surface can get damage over time from corrosion, moisture seepage. Painting done with waterproof; rust protection paint can extend the lifespan of the rooftop.

- Coating

Coating, which is carried out for older roof when renovating, used different materials, such as bitumen-based, has been done for a long time for flat roofs in Finland. This is also applied when re-paint is not possible for roof maintenance.

### 2.3.2 General maintenance process

Roof maintenance process includes mainly four phases: inspection, cleaning, repair, and recording. Firstly, the purpose of inspection is to detect debris, moss/mold, worn-down, rotten parts, or areas that affect the quality of drainage/gutter and coating features negatively of the roof. Secondly, the purpose of cleaning is to remove all the detected mentioned features and prevent the roof from decaying. Thirdly, the repair phase will replace the broken or missing parts to assure that the quality of the roof remains constantly good. Finally, recording phase means that all the actions that the robot did during the maintenance process will be archived for future cost-benefit references. For instance, in the next scheduled maintenance day, this roof area will not need coating inspection because the area was painted in the previous maintenance day. (angi.com, 2016)

## 2.4 ROOF WORK RISKS

Working on the rooftop area can lead to extreme dangerous situations if safety management is not performed carefully. This suggests a short list below it:

- Falling. This could happen and potentially heavily causes damage to workers, with extreme height buildings.
- Falling objects. This is one of the causes to construction workers' injuries as tools and materials can fall onto roofers.
- Heat exposure. This could be a problem when workers must work under hot weather for a significant amount of time, resulting in suffering dehydration, cold or sun stroke.
- Electrocution. This could happen with households with complex electrical wiring and equipment, which has higher risk from metal ladders contact with power lines, rains, or lightning.
- Weather conditions. This is an important aspect, as working environment is outdoor, extreme weather could lead to fatal accidents. (Hart, 2022)

Furthermore, flat roof has specific characteristic which could affect the working process, depending on the type. Bitumen roofing method consists of many layers and coatings, which would affect the procedure of inspecting cracks, leakage, shrinkage and later maintenance jobs. High temperature could increase health risks of workers, because bitumen can absorb a lot of heat. (Bituroll, 2020)

Since the popular forms of metal roof are tiles and metal sheets/plies, people or robot cannot move on the roof freely if they do not want to bend or break the roof. Furthermore, the expansion and tractions of metal in various temperature conditions create cracks unexpectedly. (Wisniewski, 2020)

Understanding the hazards of roof work in normal life, this thesis topic is to research for an alternative option and reduce the risk may cause for roofer employees. Working safety requirement advises from expert for flat roof jobs include:

- Assuring a safe access to the roof and establish a material handling setup.
- Using soft protective clothing.
- Avoiding heavy metal to prevent scratting, damaging the roof because of weight.
- Covering the layer underneath the working area with carton or sheet metal to prevent damage while working.
- Ensuring the weather within the safe condition during the working period.
- Preparing an escape option in case of fire or other unexpected accidents. (The Stationery Office, 2020)

## 2.5 ROBOT SELECTION

Depending on the size of houses or building roofs, different types of collaborative robot are required. From the roof study sections above, requirements for the robots are formed: the robot needs to be lightweight, can carry decent payload (for equipment, roof part) and can be programmed for maintenance tasks.

As shown in Figure 7, the Universal Robots (UR) UR3 is a versatile collaborative industrial robot with a high payload up to 3 kg and reachable work range of 500mm. The UR3 is also packed with secure features to avoid human working injury, easily programmed and has a fast setup procedure which is suitable to assign tasks. A detailed specification of the UR3 can be found in the appendix. This product is installed and used for various lab-testing, programming, and product manufacturing by HAMK Tech Robotics Research Group of HAMK University of Applied Sciences to carry out projects and studies on industrial robots.



Figure 7. Universal Robots UR3 rendered (universal-robots, 2021)

As for the mentioned features, the UR3 is fit to be chosen to be carried out for development of this virtual prototype design.

## 2.6 DESIGN IDEAS AND EVALUATION

In this section, the thesis provides various possible ideas of the design. The platform design should be able to mount and move the UR3 on the rooftop area and to create a workable environment and positioning system for the UR3. The design should also match the safety criteria and have a simple setup procedure for flat roof buildings.

### 2.6.1 Ideas generation

Option 1: Mounting frame covering the building

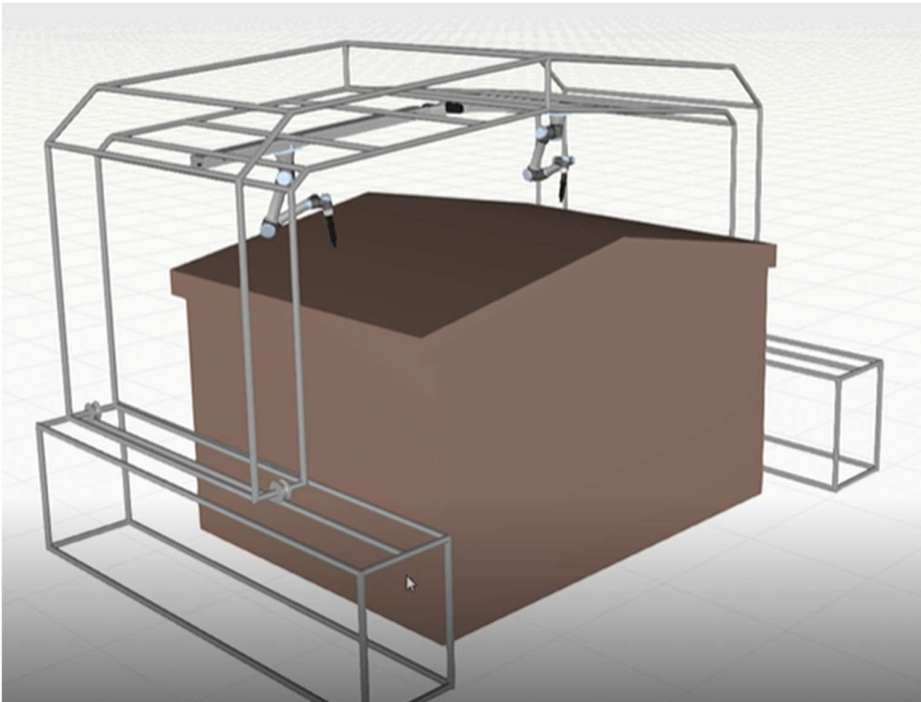


Figure 8. Scaffold frame (HAMK Robotic, 2021)

The first drafted concept is building a frame covering the house and roof area. The UR3 robot will be mounted on the top side as illustrated in Figure 8 and moving around by the frame and rail implanted of the system. There would be no contact between the frame and the roof, and the UR3 can travel to any spot of the roof area.

Option 2: Hanging frame

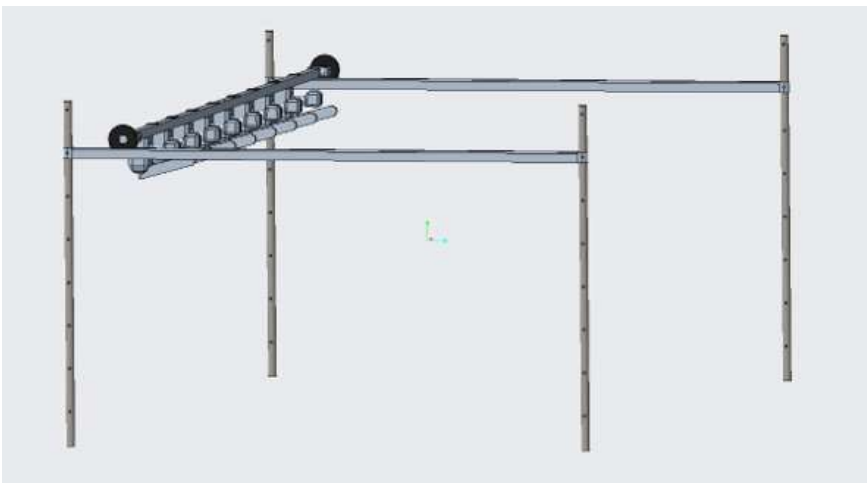


Figure 9. Hanging frame (HAMK Robotic, 2021)

The second concept is to build a frame mounted onto the rooftop with rails on both side and a middle axis to install the UR3 robot. As shown in Figure 9, the robot can operate easily around the area by running on 2-axis coordinate system.

### Option 3: Robot stand operated by rope winch

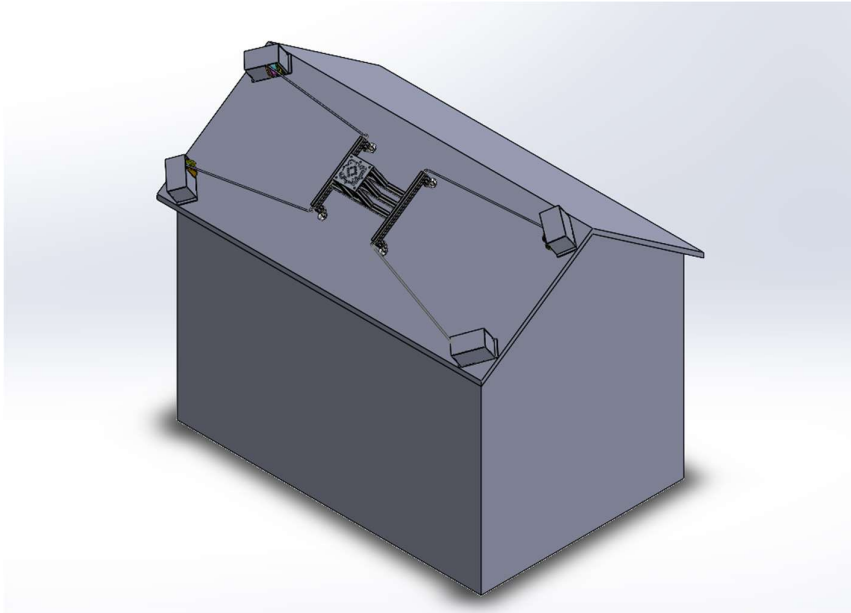


Figure 10. Robots stand with rope winch system

This concept, as previewed in Figure 10, uses four rope winches which are located at the corners of the roof area to drive the UR3 standing frame.

#### 2.6.2 Evaluation

In this section, all the concept ideas are analysed and compared to each other which is illustrated in the Table 1 below. All the information is based on the author's own assumptions and experiences.

Option 1 is the scaffold frame, of which seems to have a wide range of applications due to its design but needs more working hour and cost to manufacture because of the large-scale structure needs large quantity of construction material. Option 2 is the hanging frame, which is a moderation of the option 1 with light and simple design and it also has some of the advantages and drawbacks shared with the option 1. Lastly, option 3 is the rope winch system with module design so that it can be used for more variety of roof sizes, manufacturing is easier due to its small scale, and it is easier to install.

Concepts	Advantages	Disadvantages
Option 1	<ul style="list-style-type: none"> <li>- More applications</li> <li>- None contact with roof area; none roof extra load</li> </ul>	<ul style="list-style-type: none"> <li>- High cost of materials</li> <li>- High cost of manufacture</li> <li>- Only use for specific house design</li> <li>- Complicated design process</li> </ul>

		- Take lots of space
Option 2	- Lighter version of option 1 - Easy programming	- High cost of materials - High cost of manufacture - Need modification for different house design
Option 3	- Easy manufacture and installation - Use for different roof size - Easy storage	- Put extra loads on roof - Difficult applying for certain roof (with chimneys, skylight, ventilation holes)

Table 1. Idea comparison

As result indicating in above comparison table, the author finds that option 3 is the most practical to be applied as a virtual prototype in this thesis because of more advantages, and as it would be highly efficient to imply in real-life. The application would take less efforts to install and can be applied to any kind or size of roof with reasonable investment.

### 3 DESIGN PROCESS

Breaking down the design process into different phases will give a clearer view on the topic needs and approaches to obtain the final design of the product. As shown below in Figure 11 are the main 4 stages of the process, which are Discovery, Definition, Conceptual Design and Evaluation.

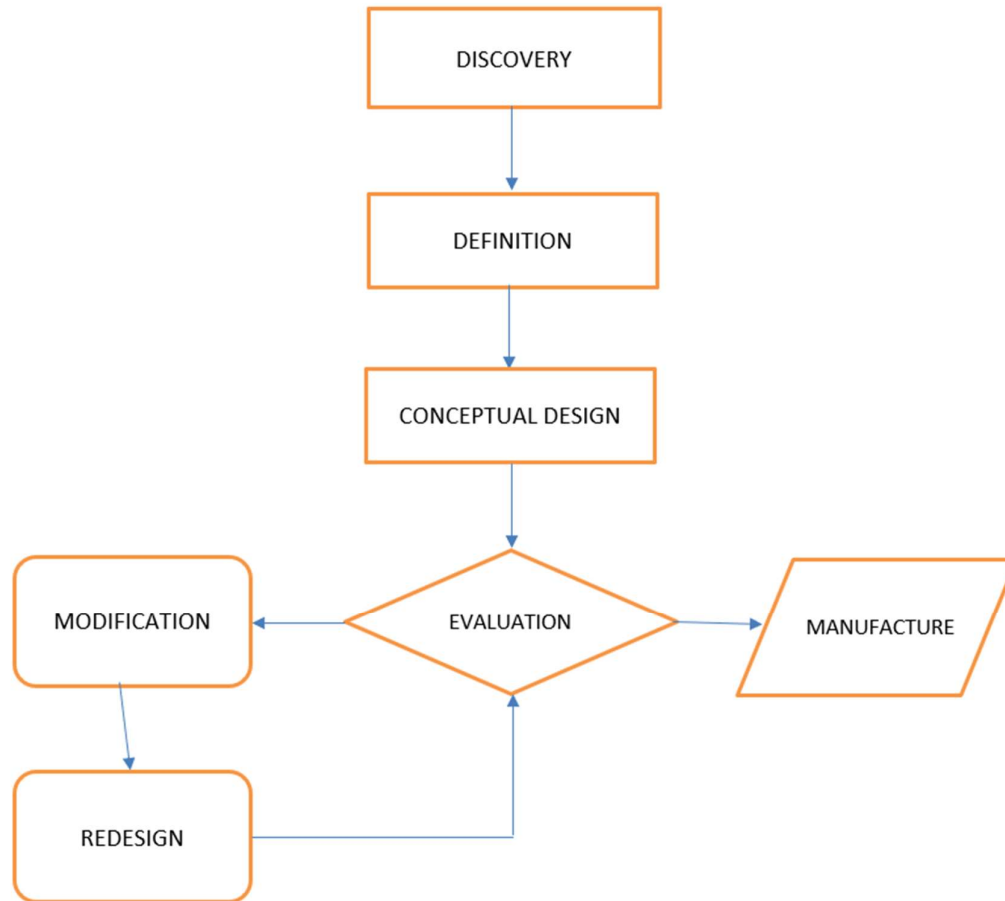


Figure 11. Product design process in different stages  
(Ullman, 2010)

Setting requirements and checkpoints of each phase to archive is very helpful to understand about the idea of the project and eliminate mistakes at earlier stage.

### 3.1 DISCOVERY

In this early stage, the design ideas are researched and analysed. Taking every aspect under consideration at the beginning in order to lower the risk of missing out possible solutions, saves time redesigning later on.

Roof load mostly consists of dead load and live load. Dead load is the constant load of the structure's weight itself and depending on the size and material it will vary and be calculated when installing the roof. Live load is the temporary weight of any equipment, workers, or environment matters such as snow or leaves on the rooftop after the roof is in used for a significant period of time, for instance 6 months to 1 year. In this case, the load will be the weight of the whole system and the UR3 mounted.

Robots, especially UR products, have a wide range of related parts and accessories available on the market with variable usages and applications.



Figure 12.  
2016)

Commercial Universal Robot stations (Vention,

As shown in figure 8, most of the available stands, tables made for UR are made using aluminium material, usually used at a fixed spot or with wheels to be moved indoor on a flat floor. Machine-powered platforms are also customized specifically for customers' order, with axis and rails or conveyors for the transition of the mounted robots. Those types can hold the robot in place and move it in different directions, depending on their techniques, on the installed platform which has the disadvantage that only the designed workplace can use and not flexible. Figure 9 illustrates an example of the multi axis transition platform (Vention) for the UR3.

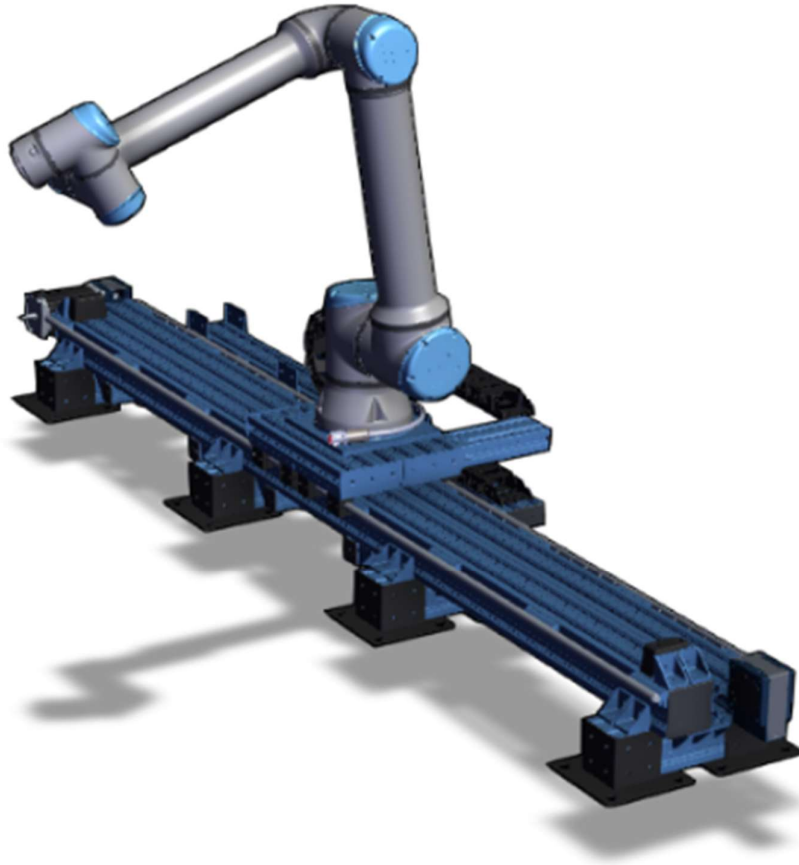


Figure 13. Heavy-duty 7-axis for UR3 (Vention, 2016)

The idea of this thesis is to imply the system on top of a roof, which may not be feasible to use the transition platform due to the instrument installation would take more time and the size of the system is cumbersome.

Rope winches are used widely in many fields such as lumberjack, fishing and building, which run by a motor or manually with a basic toward-back control. Rope winch is used for lifting, pulling at a distance or height due to installation easiness, heavy loads and adjustable covered length depends on the rope. Drawbacks of this system is: Since it is manually controlled, which requires human operation and lack of precision, implication would be a challenge.



Figure 14. KDJ 300KG AC Winch 240V (warriorwinches, 2004)

As for the controlling component, microcontroller boards such as Arduino or Raspberry Pi are often used in Automation, Mechanical Engineering system due to their open-source hardware and programming software. Especially, setting up an Arduino as a digital controller with simple input, output and component arrangement, connection was a part of the Mechanical Engineer degree's compulsory studies. Arduino UNO board (as shown in Figure 11) applications are various from LED lighting, digital clock to sensors, motors control, etc. Furthermore, because of its widely usage, accessories and compatible components are also available which enhance the ability of the microprocessors on the board.

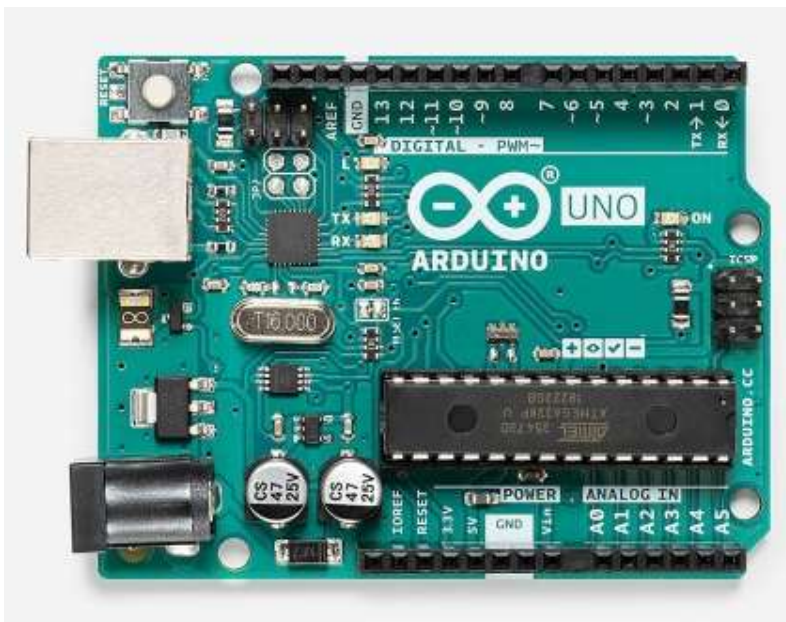


Figure 15. Arduino UNO board (Arduino, 2021)

Driver Carrier like the one shown in Figure 16 is an example of a controller for motors which has additional functions and provides extra connection to the mainboard.

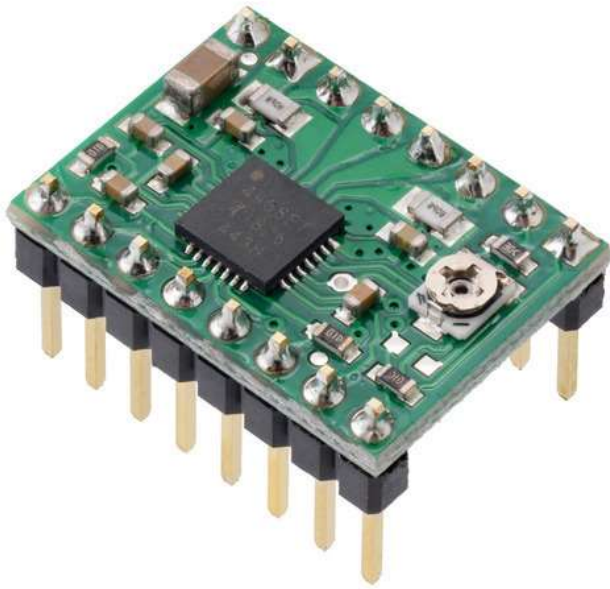


Figure 16. A4988 Stepper Motor Driver Carrier  
(pololu.com, 2000)

Universal Robots also have a wide variety of add-on components on the market. Figure 17 shows the Wrist Camera from Robotiq which would come in handy for the overall inspection and enhance the precision of the robot. With the camera, the operator can check the roof condition thoroughly and control the work properly.



Figure 17. Robotiq Camera UR Installation Kit (Robotiq, 2016)

Figure 18 is the TiX580 Infrared Camera from Fluke, which can be used for roof leak inspection. The physics used for thermal roof inspections is that dry roof insulation heats up and cools down faster than wet roof insulation. Infrared inspection goes beyond simply finding a leak by locating the extent of the moisture invasion of the insulation. A bright day with solar heating is required and then at night, after the sun goes down and the roof surface begins to cool, the dry roof insulation cools faster than wet roof insulation. This temperature difference detected will be used for analysing the moist area.



Figure 18. TiX580 Infrared Camera (Fluke, 2021)

### 3.2 DEFINITION

After looking through all the general commercial components, in this phase, all the aspects will be taken under consideration to pick out the possible solutions. HAMK Robotics Lab has provided specifications for the project which were listed and analysed as below.

- *Function*: The platform is able to mount and move the UR3 on the rooftop area controlled by the rope winches system and an operating program.
- *Dimensions*: The platform design shall be parametric and able to withhold the payload. The size and weight of the design shall not exceed the live load of the roof.

- *Components:* Various parts needed for the platform, for instance wheels, mount plates, winches, which are available as commercial products. Designed parts can be 3D printed.
- *Control system:* The system must be able to receive input coordinates and give output commands to move on the roof area and report platform position.
- *Manufacture and Assembly:* The design shall utilize the usage of commercial parts to reduce the time and costs. Also, assembly needed to be easy and simple.

### 3.3 CONCEPTUAL DESIGN & EVALUATION

In this phase the design ideas will be formed as conceptual sketches according to the requirements formed in the previous part of the project. Each concept will be broken down with details, specifications which will be used to compare advantages, drawbacks, and manufacturing possibility.

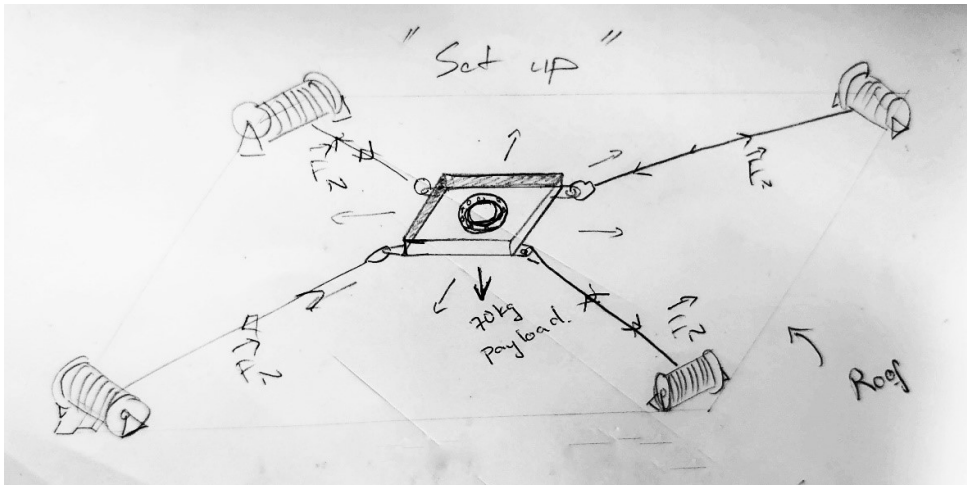


Figure 19. System setup concept sketch

The components setup is briefly illustrated as sketch in figure 13. As seen on the drawing, the platform will be located on the surface area of the rooftop with 4 rope winches installed at the corners and attached to the mounting platform. An Arduino UNO board is used to control the 4-winch with 4 addition drivers for each motor which will be installed in a separate container and connected to other components by wiring.

Wheels are implicated to the design to help the platform to move smoothly on the surface. There are a few options for the type of wheel, for instance swivel, mecanum.

Swivel type caster wheel is suitable for the platform due to its durability, heavy-load and 360-degree range of movement. Wheel with brake is also available, although not needed because of the winches system already taken care of the movement and positioning.

Mecanum wheel, as shown in Figure 20, is a special designed wheel which allow it to be able to run in any direction. This would help the platform move easily to any desire spot on the rooftop.



Figure 20.

Mecanum wheel

For the rope winch system, there are two possible options:

Option 1: Using electric rope winch as shown in figure 6.

- *Advantages:* Build-in motor with winch rope, high-powered output, long last durability, and addition parts not needed
- *Disadvantages:* Inaccurate precision control which would be difficult and complicated to programme a control system.

Option 2: Using stepper motor connect to a hand winch by coupling.

- *Advantages:* Stepper motor has a greater precision, wider range of programmability
- *Disadvantages:* Separated parts needed, custom made coupling in order to imply to the system, calculation for the motor torque, power.

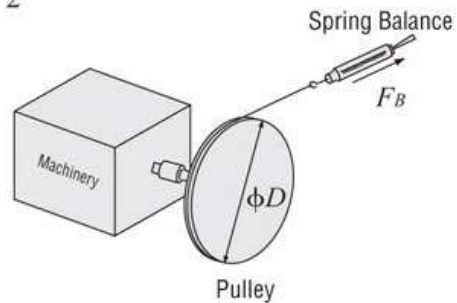
Calculation of motor holding torque:

Polyethene	Steel	.2
Polystyrene	Polystyrene	.50
Polystyrene	Steel	.30 - .35
Rubber	Rubber	1.15
Rubber	Asphalt	.9
Rubber	Concrete	.6

Table 2. Rolling Coefficient Chart (engineersedge.com)

Friction = Coefficient of friction x Normal force =  $0.2 \times 70\text{kg} \times 9.81\text{m/s}^2$   
 $\approx 137.34 \text{ N}$

$$T_L = \frac{F_B D}{2}$$



$F_B$  : Force when main shaft begins to rotate  
 ( $F_B = \text{value for spring balance} \times g$ )  
 $D$  : Final pulley diameter  
 $g$  : Gravitational acceleration

$$\text{Torque}_w = \frac{137.34\text{N} \times 0.0165\text{m}}{4} \approx 0.5665 \text{ Nm}$$

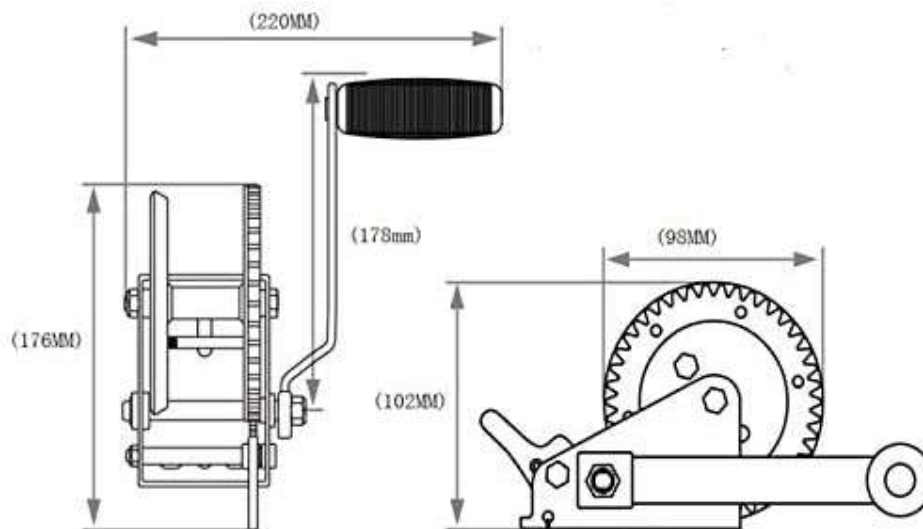


Figure 21. TradeDrive 270kg rope winch diameters  
 (TradeDrive, 2016)

As calculated above, a suitable stepper motor for this system should have holding torque with the minimum of 0.5665Nm. The motor shown in Figure 22 below is the 29SM-K250-00V model from NMB Technologies Corporation which has torque rating at 0.580Nm.



Figure 22. 29SM-K250-00V Stepper Motor (NMB Technologies Corporation) (Electronics, 1977)

## 4 COMPONENT DESIGNS

In this section, the details of the design are broken down in categories with 3D models, technical drawings, and commercial parts. After evaluation of all the ideas in the previous part of the design process, results are taken in place to optimize product modelling, minimize risks of incompatible materials, parts while maintain its efficiency.

### 4.1 VIRTUAL PROTOTYPE

3D design is an essential piece of most mechanical engineering and also other product creations. With modern software, designs, appearances, working mechanisms and assembly processes can be created, modified, and analysed at ease with immediate responding time.

The models in this topic are created using SolidWorks 2020, which is reliable with helpful features and high compatibility.

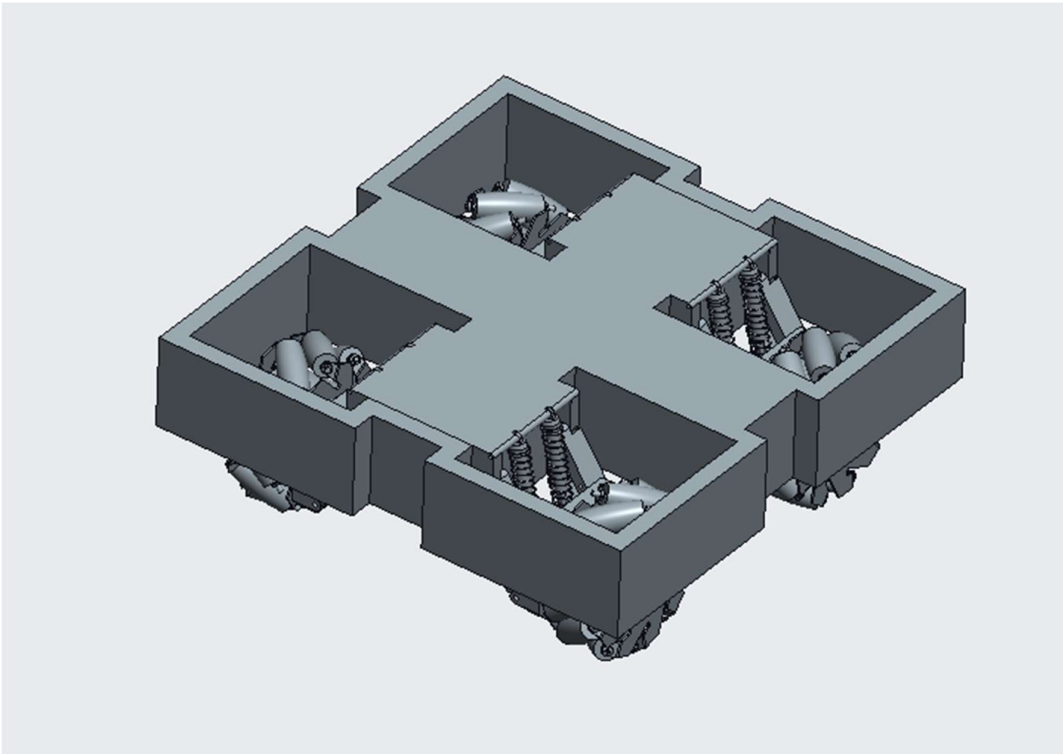


Figure 23. 3D model of the virtual prototype

As shown in Figure 23 is the 3D model rendered in CAD software. The virtual prototype will be manufactured by 3D printing with spring suspensions and mecanum wheels.

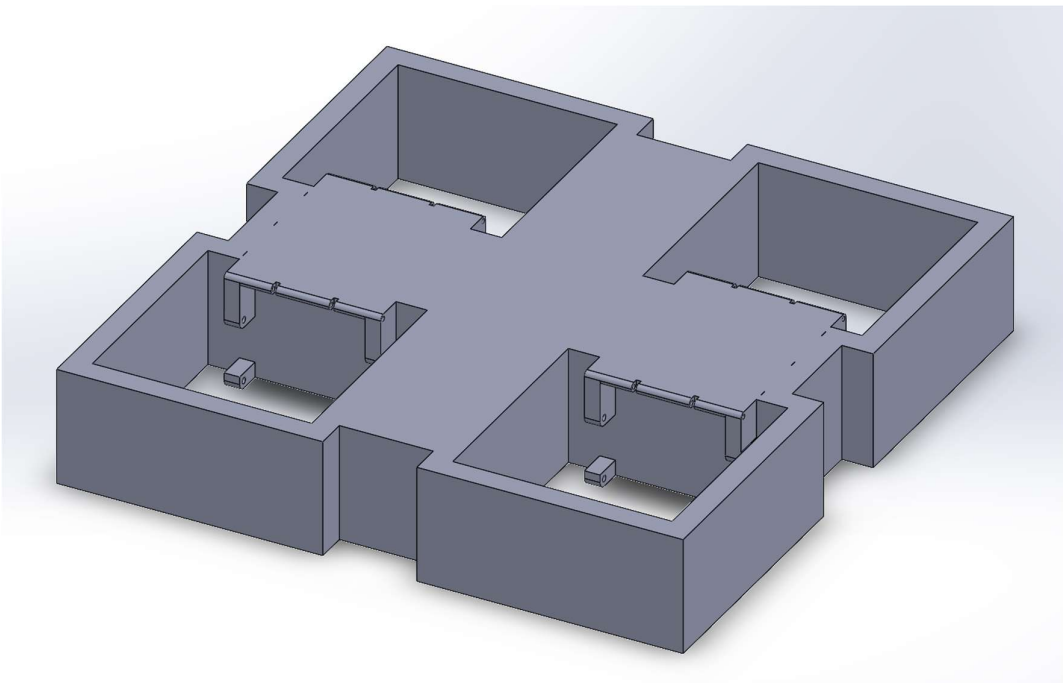


Figure 24. Main body part

The main body will be made in one piece with connections to assemble mecanum wheels on the side. The technical drawing with detail dimensions is attached in the appendix.

Spring suspensions are used to reduce shock from the movement of the platform and roof surface.



Figure 25. Spring shock absorber 80mm

Wheel mount parts are shown in Figure 26 and Figure 27 below.

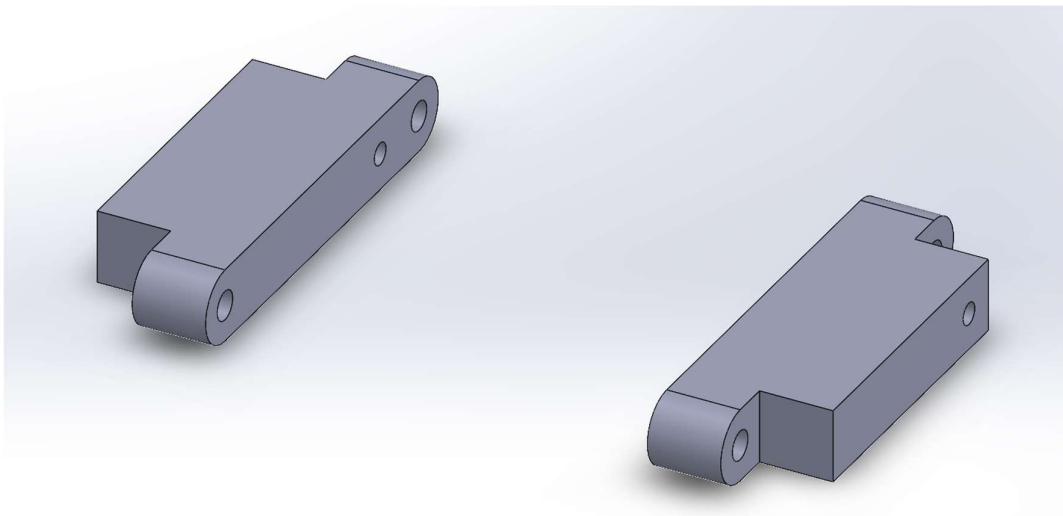


Figure 26. Wheel handle

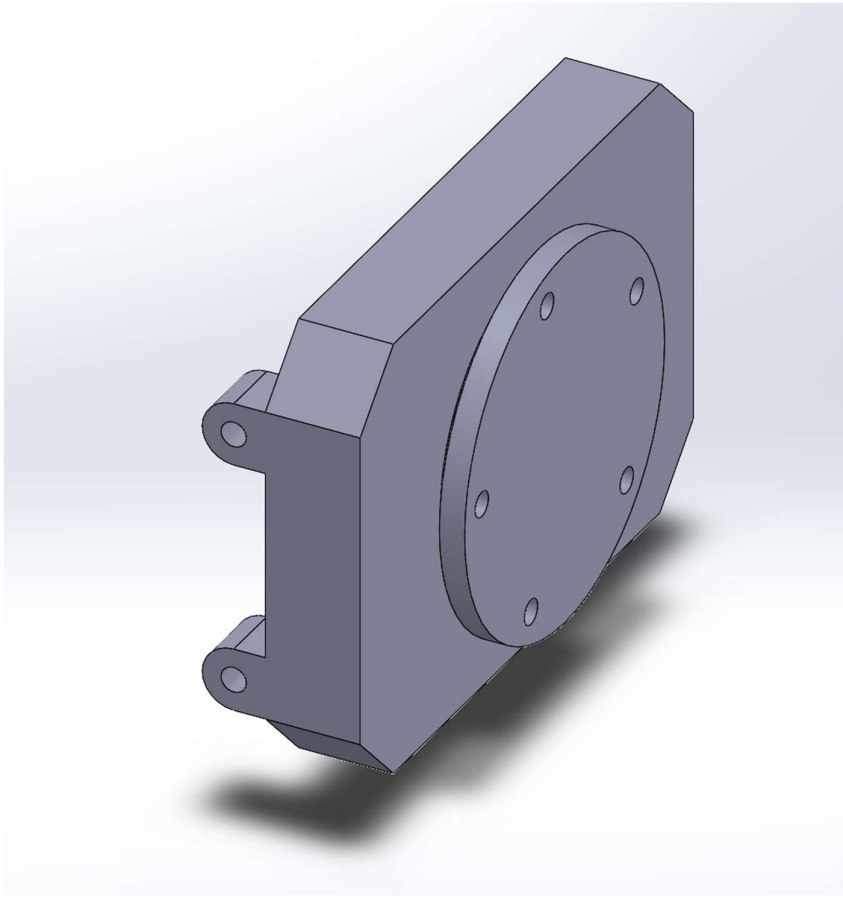


Figure 27. Wheel mount plate

## 4.2 WINCH SETUP

### 4.2.1 Coupling

Coupling is required to transfer the stepper motor torque to the rope winch system. The motor used to power the movement operation, as shown in Figure 28, has the shaft outer-diameter of 7.5mm

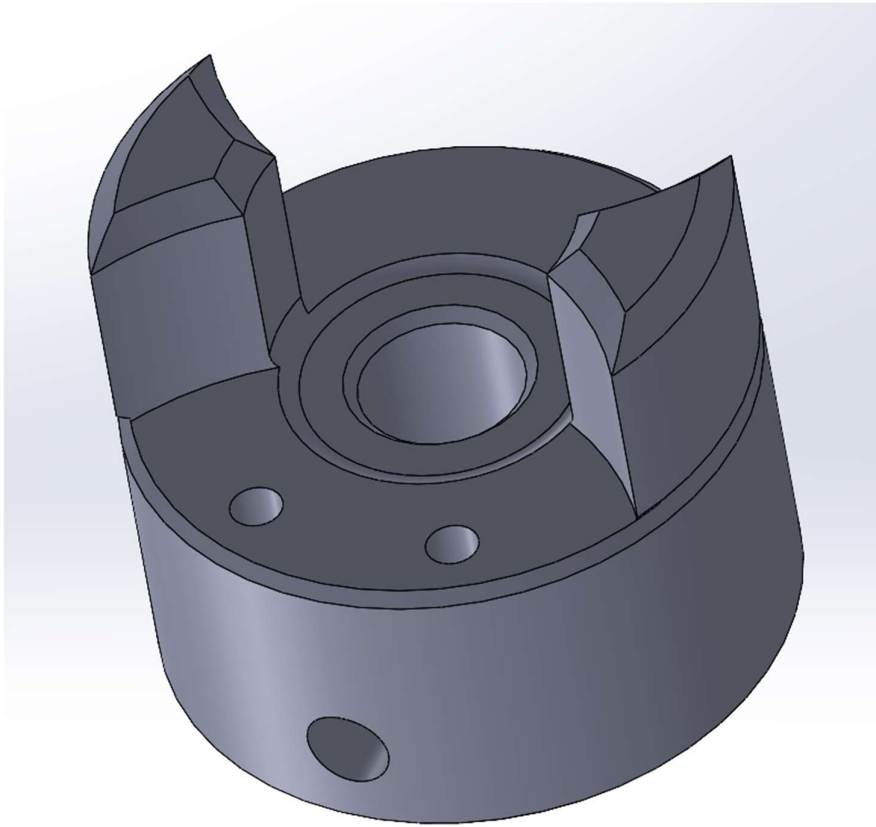


Figure 28. Ruland Jaw Coupling Coupler (MJC19-5-A)  
(Ruland, 1937)

The coupling for the hand winch handle Figure 29 is designed to be compatible with the motor coupling above. The part will be manufactured with Stainless Steel SS314, and the detail technical drawing is attached in the appendix. Figure 30 below illustrated the connection and installation.

The coupling for the hand winch will be custom made as it is specially designed for this system. The process includes drilling, turning, and milling with the G-code program attached in the appendix.

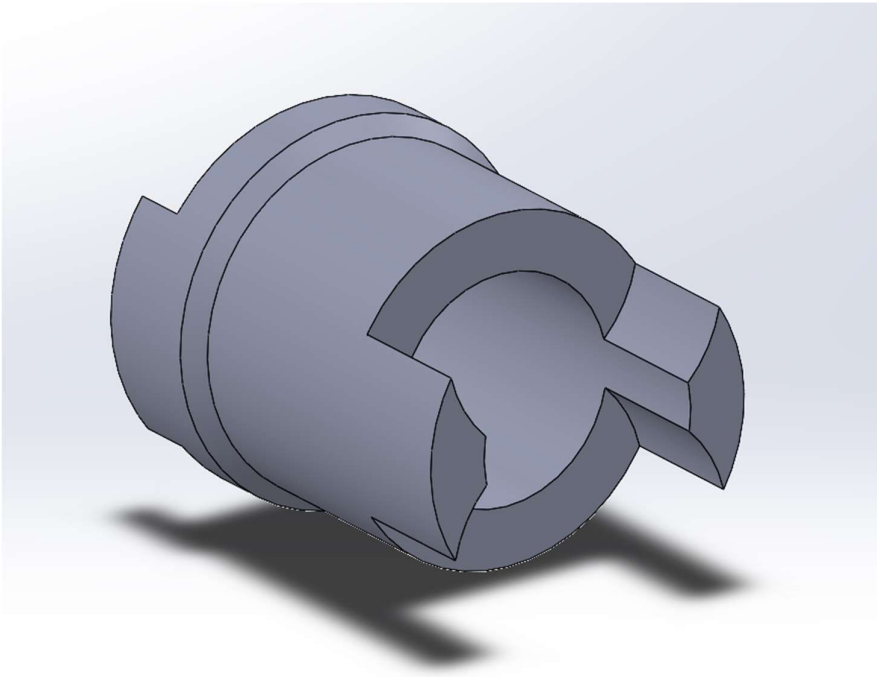


Figure 29. Winch Handle Coupling

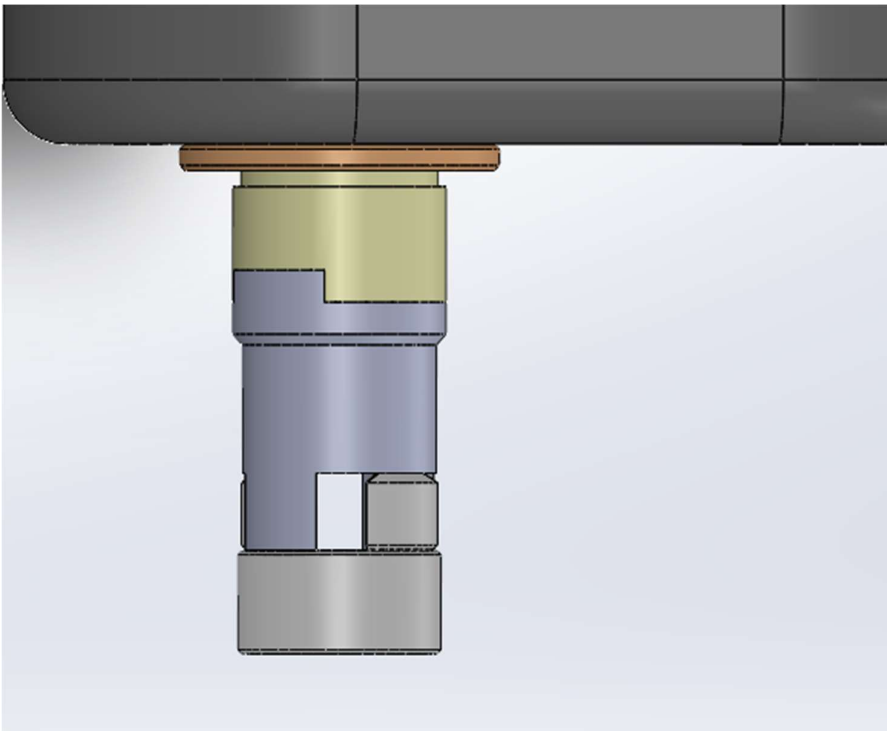


Figure 30. Coupling Assembly

#### 4.2.2 Winch box

In order to mount the system on to the rooftop area, a container is needed to arrange the rope winch and motor in place. Figure 31 shows the winch box design, which will be manufacture by 3D printing.

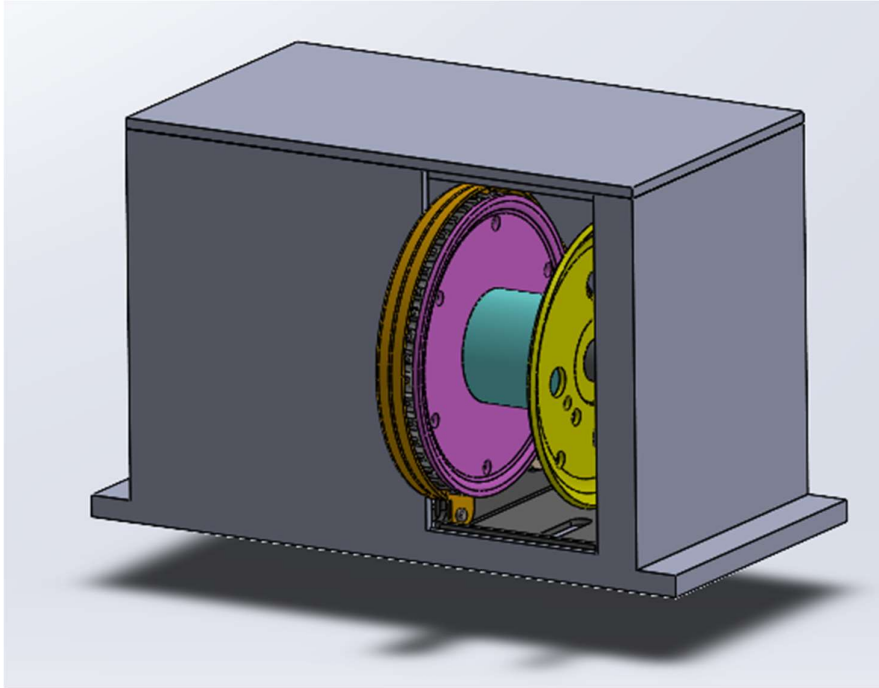


Figure 31. Winch system assembly

## 5 CONTROL SYSTEM

### 5.1 SET UP

The control system will be built on Arduino platform, using microprocessor to calculate variables, storing data. The component placement will be set up as in Figure 32 with the dimension variables illustrated.

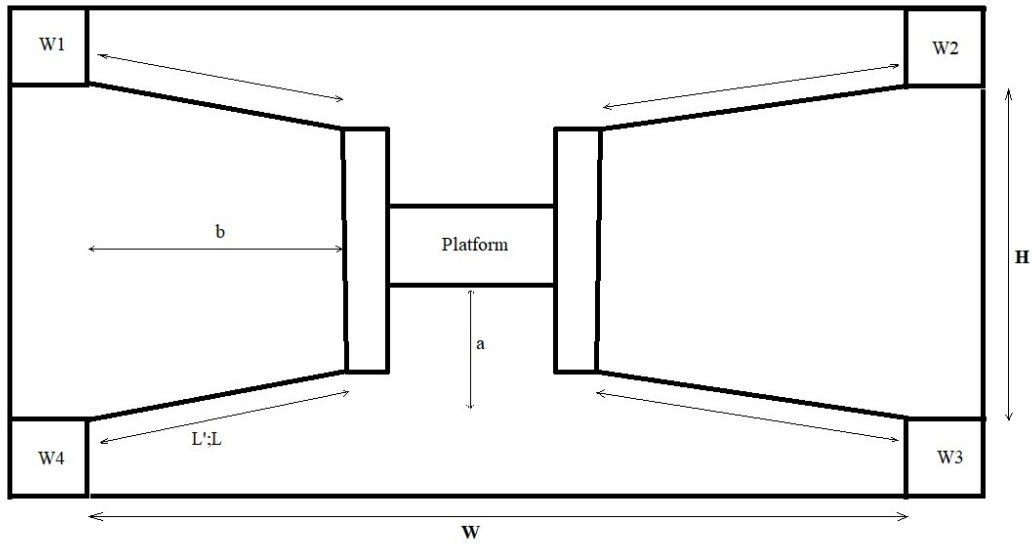


Figure 32. Working process diagram

The platform will be located in the centre of the roof at the beginning, which is also the zero-position.

## 5.2 PROGRAM

The program processing is illustrated as flow chart which is shown in Figure 33 below. Detail Arduino code can be found in the appendix.

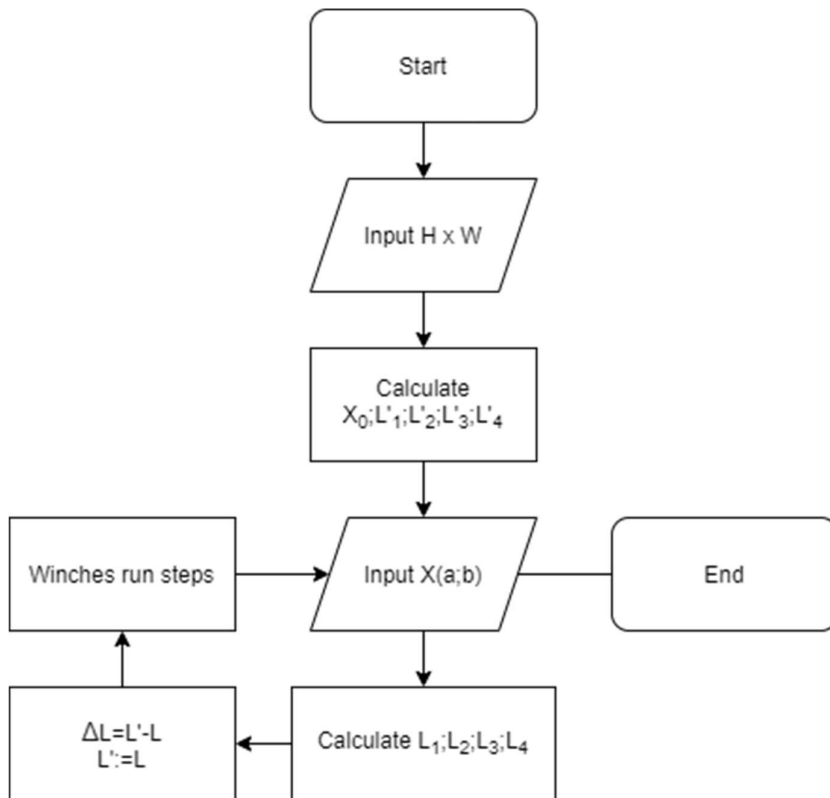


Figure 33. Processing flow chart

The process starts with inputs of the roof (working space) diameters and zero-position, diagonal is calculated from the input. The system then waits for destination input  $X(a;b)$  and calculates destination diameters which steps of each motor based on. The motor then acts on the output of the process and robot is now in place.

### 5.3 SIMULATION

A demonstration of the platform movement is simulated using SolidWorks Motion Study. The platform can be moved in the area between 4 winches, control by adjusting the length of the ropes. Figure 34 and Figure 35 illustrates the movement in simulation environment. A short video of the simulation can be found [here](#).

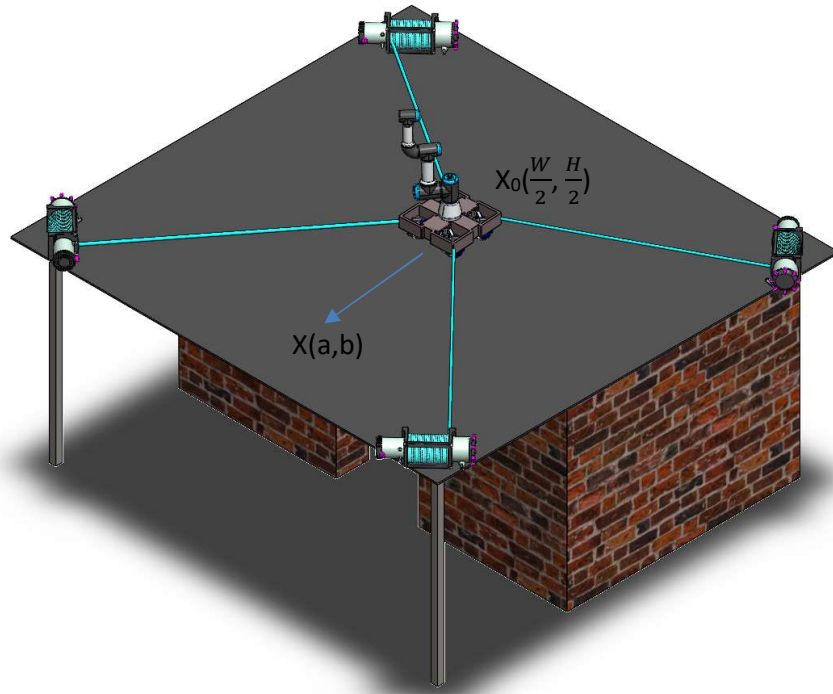


Figure 34. Platform at starting point

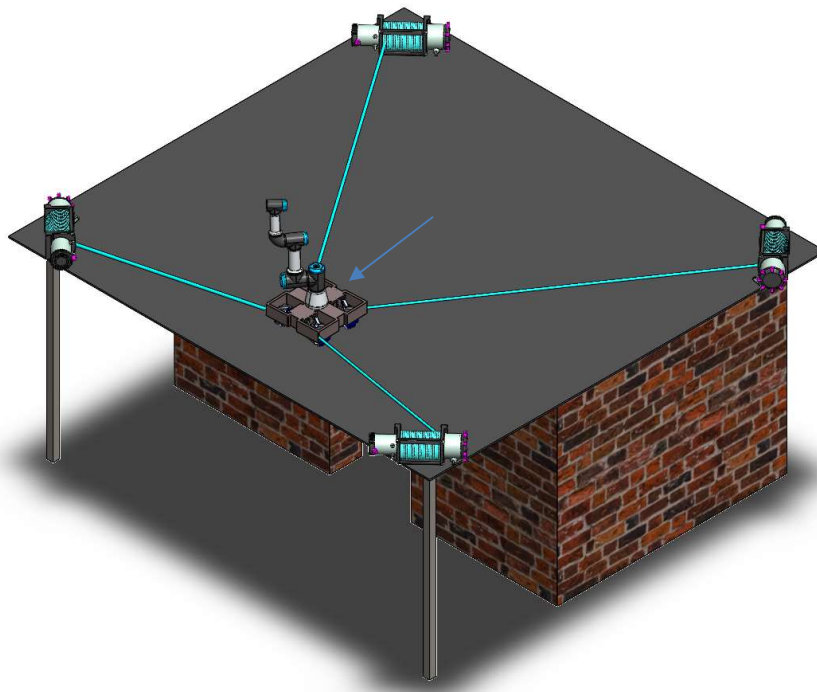


Figure 35. Platform moves to designated point

## 6 CONCLUSION

This thesis focused on finding out the design concept for automatizing roof maintenance with collaborative robot. The study included research on flat roof characteristics as well as risks in roof work to identify the problems. Different concepts were brought up and compared in order to find out which version is the most optimal one.

The design process followed the Ullman design process with four phases: discovery, definition, conceptual design, and evaluation. The design was then formed in the virtual environment with the 3D model indicating the setup for the robot mounting on the roof. The study also researched and developed a control system with Arduino processor and programme. A simulation illustrating how the control system operated the virtual prototype working on the roof is included in the thesis paper.

Although the chosen version satisfies the requirements of roof maintenance process, there are some difficulties that could not be overcome at this moment: the robot cannot operate comfortably in the four corners of the roof where the winches are installed, the platform cannot be used effectively in the snowy weather and the platform works best in flat roof but not entirely in sloped or steep roof.

To improve the design, it is recommendable to figure out better positioning for the winches so that the robot can cover more roof area, especially in the corners. Additionally, a whole new design concept should be discovered and compared to this design for optimizing purposes.

Overall, the thesis provided a solution for using collaborative robot to work on the flat roof area, located and controlled the movement of the robot.

## REFERENCES

- Abcseamless. (2020). *abcseamless.com*. Retrieved from abcseamless.com: <https://abcseamless.com/seamless-metal-roofing>
- angi.com*. (2016, 5 18). Retrieved 8 31, 2021, from <https://www.angi.com/articles/what-can-i-do-maintain-my-roof.htm>
- Anson Machines. (2021). *ansonmachines.com*. Retrieved from <http://www.ansonmachines.com/uploads/allimg/Mobile-Traction-Scissor-Lifts.jpg>
- Arduino. (2021). *Arduino.cc*. Retrieved from [https://cdn.shopify.com/s/files/1/0506/1689/3647/products/A000066\\_03.front\\_970c6014-61ab-4226-a20f-14cc6d8d682c\\_763x573.jpg?v=1629816078](https://cdn.shopify.com/s/files/1/0506/1689/3647/products/A000066_03.front_970c6014-61ab-4226-a20f-14cc6d8d682c_763x573.jpg?v=1629816078)
- Association, T. F. (1964). Roof System Manual. Finland. Retrieved 8 31, 2021
- Bituroll. (2020). *bituroll.com*. Retrieved from bituroll.com: [https://bituroll.com/bitu\\_advantages](https://bituroll.com/bitu_advantages)
- Brown, D. (2014, June 20). *dylanbrowndesigns.com*. Retrieved from dylanbrowndesigns.com: <http://dylanbrowndesigns.com/resources/roof-type-guide/>
- Champion Roofing. (2019, October 18). *championroofing.com*. (Champion Roofing) Retrieved from <https://championroofing.com/modified-bitumen-roofing-systems/>
- Edwards, K. L. (2020, 10 20). *gaf.com*. Retrieved from gaf.com: <https://www.gaf.com/en-us/blog/what-is-a-built-up-roof--281474980000809>
- Electronics, D. (1977). *digikey.fi*. Retrieved 08 04, 2021, from <https://media.digikey.com/pdf/Data%20Sheets/NMB-MAT/34KM-K.pdf>
- Energy Education. (2018, June 25). *energyeducation.ca*. Retrieved from energyeducation.ca: <https://energyeducation.ca/encyclopedia/Bitumen>
- fletcherroofs.com*. (2021). Retrieved 2021, from <https://www.fletcherroofs.com/roofing-process>
- Fluke. (2021, August 4). Retrieved from Fluke Website: <https://www.fluke.com/en-us/learn/blog/thermal-imaging/infrared-roof-inspection>
- HAMK Robotic. (2021). *Construction robots*. Riihimaki.

- Hart, D. (2022). *thhartlawfirm.com*. Retrieved from thehartlawfirm.com: <https://www.thehartlawfirm.com/library/5-common-causes-of-dangerous-roofer-accidents.cfm>
- Kattoliitto. (2010, January 25). *Kattoliitto.fi*. Retrieved from Kattoliitto.fi: [https://www.kattoliitto.fi/wp-content/uploads/pdf/Roof\\_systems\\_manual.pdf](https://www.kattoliitto.fi/wp-content/uploads/pdf/Roof_systems_manual.pdf)
- Meza, J. (2015, 12 30). *fibertite.com*. Retrieved from fibertite.com: <https://www.fibertite.com/blog/average-roof-life-stages>
- MiniTec. (2015). *minitec.fi*. Retrieved 08 01, 2021, from <http://www.movetec.fi/images/pdf/Profilesystem.pdf>
- Mullen, E. (2021, August 1). *roof-assets.com*. Retrieved from roof-assets.com: <https://www.roof-assets.com/wp-content/uploads/2015/08/Roof-Life-Cycle-Chart.png>
- Next Insurance . (2020, October 22). Retrieved from [www.nextinsurance.com](http://www.nextinsurance.com).
- Piristeel. (2020, May). *piristeel.fi*. Retrieved from piristeel.fi: <https://piristeel.fi/wp-content/uploads/2020/05/kattosilta-scaled.jpg>
- pololu.com*. (2000). Retrieved from <https://a.pololu-files.com/picture/OJ10065.180.jpg?b63f11341129426340f57ab54e30c6fb>
- Robotiq. (2016, June 21). *robotiq.com*. Retrieved from <https://robotiq.com/products/wrist-camera?301=%2Fproducts%2Fcamera%2F>
- Roof Hippie. (2020). Retrieved from <https://roofhippie.com/16-pros-cons-concrete-roofing-tiles/>
- Ruland. (1937). *ruland.com*. Retrieved 08 02, 2021, from <https://www.ruland.com/mjc19-5-a.html#>
- Safe Harbor Exteriors. (2019, February 7). Retrieved from <https://www.safeharborexteriors.com/4-important-benefits-of-installing-concrete-tile-roofing/>
- SPRI. (2019, January 15). *spri.org*. Retrieved from <https://www.spri.org/2019/01/bituminous-roofing-101/>
- The Stationery Office. (2020). *Health and safety in roof work (Fifth edition)*. Norwich: TSO (The Stationery Office).
- TradeDrive. (2016, 06 23). (TradeDrive) Retrieved 08 05, 2021, from amazon.co.uk: <https://www.amazon.co.uk/cable-winch-Strap-600lbs-270kg/dp/B01DKTEUHG>

Ullman, D. G. (2010). *The Mechanical Design Process*.

universal-robots. (2021). *universal-robots.com*. Retrieved from universal-robots.com:  
<https://www.universal-robots.com/products/UR3-robot/>

Vandervort, D. (2021, July 7). *Hometips*. Retrieved from  
<https://www.hometips.com/buying-guides/metal-roofing-drawbacks.html>

Vention. (2016, 07). *Vention.io*. Retrieved 08 03, 2021, from  
<https://vention.io/parts/225x225mm-UR3-mounting-plate-for-universal-robots-179>

Vention.io. (2020). *Vention.io*. Retrieved from <http://www.vention.io>

warriorwinches. (2004). Retrieved from warriorwinches:  
<https://www.warriorwinches.co.uk/products/Winches/kdj-300kg-ac-winch>

Wisniewski, J. (2020, November 16). *roofingcalculator.com*. Retrieved from  
roofingcalculator.com: <https://roofingcalculator.com/news/pros-and-cons-of-concrete-tiles>

yle. (2012, 6 9). *yle.fi*. Retrieved from Yle: <https://yle.fi/news/3-5298802>



## UR3 Technical specifications

Item no. 110103

## 6-axis robot arm with a working radius of 500 mm / 19.7 in

<b>Weight:</b>	11 kg / 24.3 lbs	
<b>Payload:</b>	3 kg / 6.6 lbs	
<b>Reach:</b>	500 mm / 19.7 in	
<b>Joint ranges:</b>	+/- 360° Infinite rotation on end joint	
<b>Speed:</b>	All wrist joints: 360 degrees/sec. Other joints: 180 degrees/sec. Tool: Typical 1 m/s. / 39.4 in/s.	
<b>Repeatability:</b>	+/- 0.1 mm / +/- 0.0039 in (4 mils)	
<b>Footprint:</b>	Ø128 mm / 5.0 in	
<b>Degrees of freedom:</b>	6 rotating joints	
<b>Control box size (WxHxD):</b>	475 mm x 423 mm x 268 mm / 18.7 x 16.7 x 10.6 in	
<b>I/O ports:</b>	Controlbox	Tool conn.
	Digital in	2
	Digital out	2
	Analog in	2
	Analog out	-
<b>I/O power supply:</b>	24 V 2A in control box and 12 V/24 V 600 mA in tool	
<b>Communication:</b>	TCP/IP 100 Mbit: IEEE 802.3u, 100BASE-TX Ethernet socket & Modbus TCP	
<b>Programming:</b>	Polyscope graphical user interface on 12 inch touchscreen with mounting	
<b>Noise:</b>	Comparatively noiseless	
<b>IP classification:</b>	IP64	
<b>Power consumption:</b>	Approx. 100 watts using a typical program	
<b>Collaboration operation:</b>	15 advanced adjustable safety functions	
<b>Materials:</b>	Aluminum, PP plastic	
<b>Temperature:</b>	The robot can work in a temperature range of 0-50°C*	
<b>Power supply:</b>	100-240 VAC, 50-60 Hz	
<b>Cabling:</b>	Cable between robot and control box (6 m / 236 in) Cable between touch screen and control box (4.5 m / 177 in)	

\*) At high continuous joint speed, ambient temperature is reduced.

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USA  
+1 631 610-9664

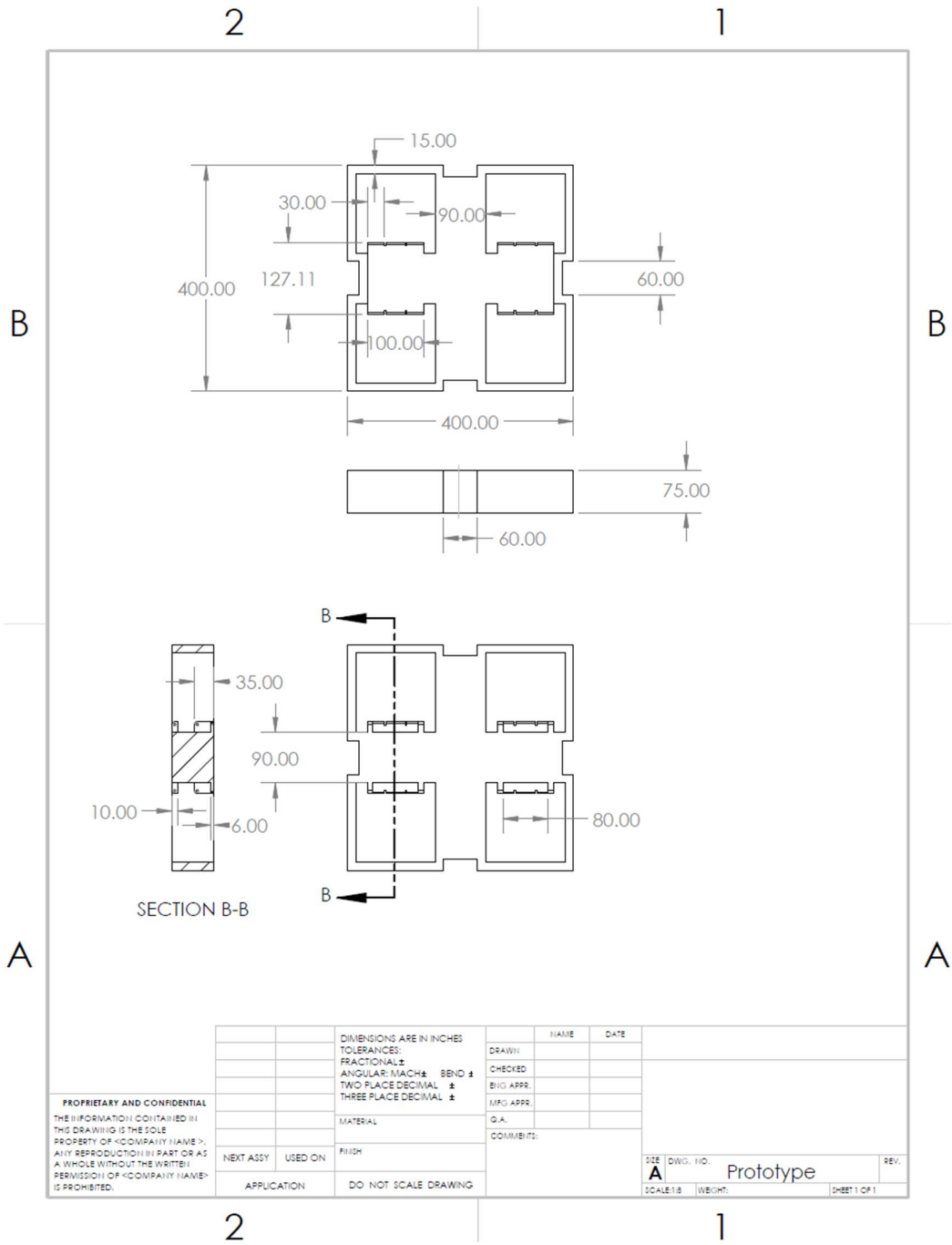
ur.na@universal-robots.com

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Denmark  
+45 89 93 89 89

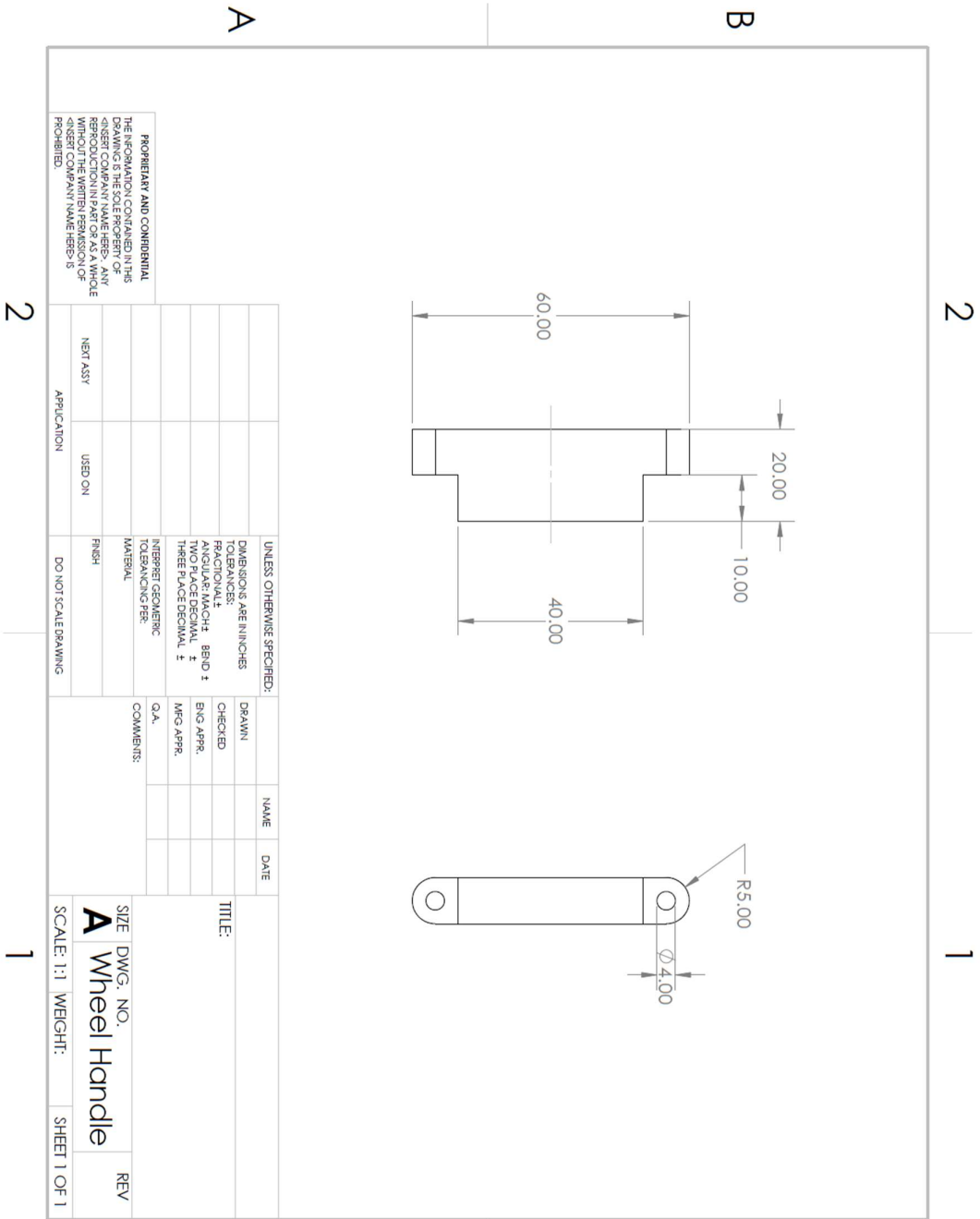
www.universal-robots.com  
sales@universal-robots.com



Appendix 2  
Virtual prototype body drawing

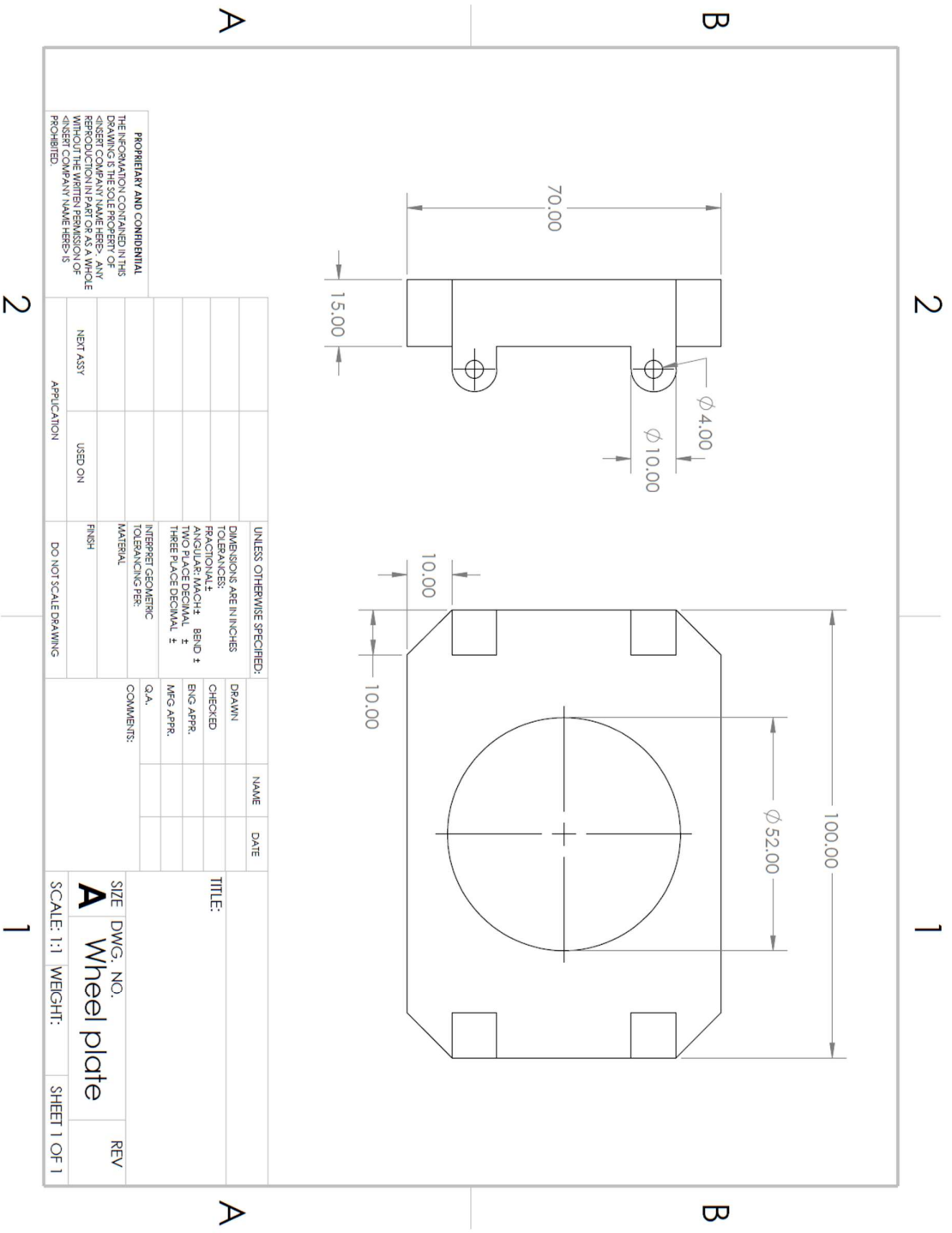


Appendix 3  
Wheel Mount Handle



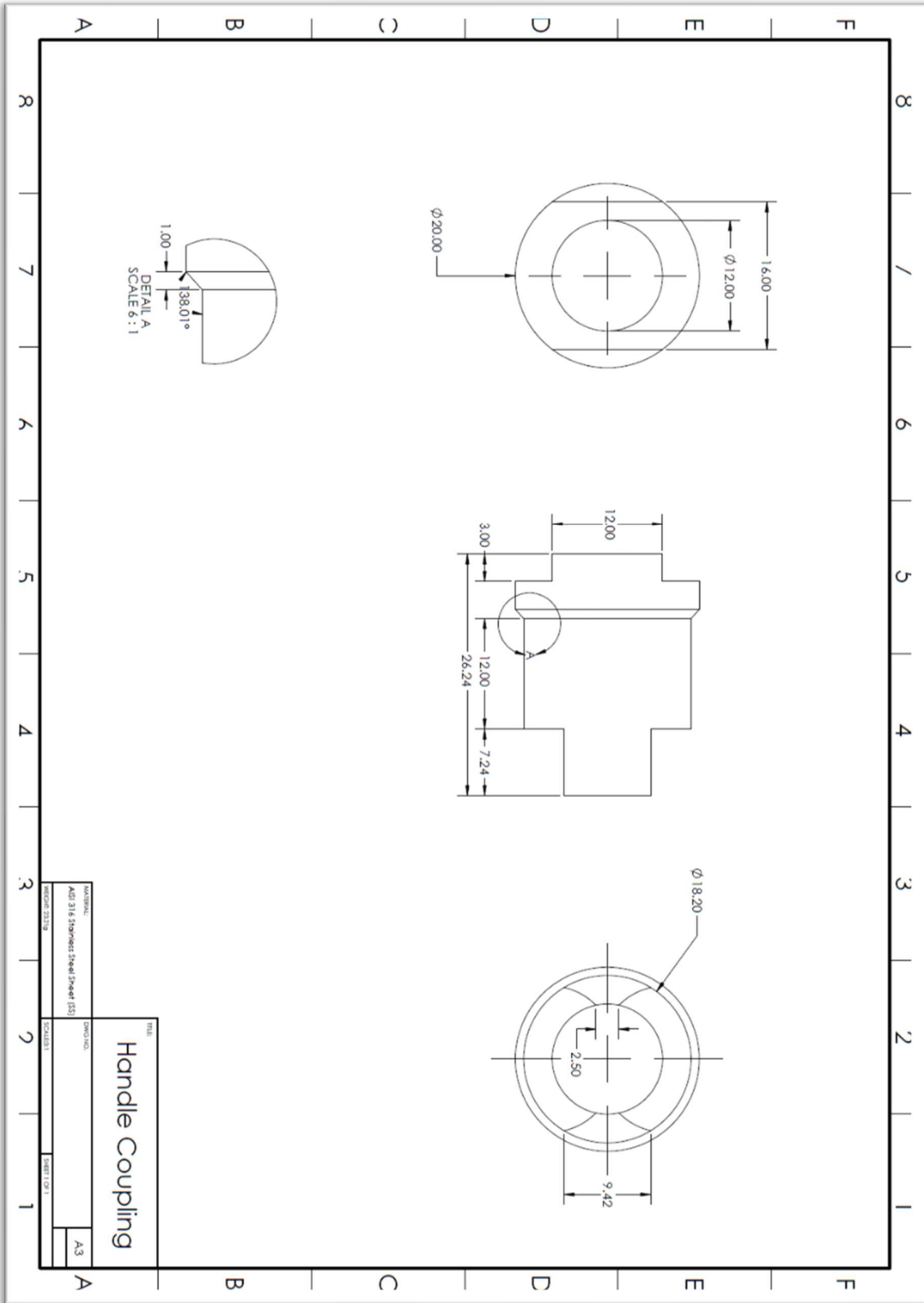
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Appendix 4  
Wheel Mount Plate



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Appendix 5  
Hand Coupling drawing



Appendix 6  
CNC G-code

```
%  
O0706  
N10 G54  
N20 G0 X30 Z10  
N30 G96 S400 M3  
N40 T0001 (drill, 12mm Hss)  
N50 G0 X0 Z5  
N60 G1 Z-27 R5 F0.2  
N70 X30 Z10 M5  
N80 T0002 (turning, 4mm tip same as milling)  
N90 G0 X18.2 Z10 M3  
N100 G1 Z-19.24  
N110 G1 X20 Z-20.24  
N120 G0 X 30 Z10 M5  
N130 T0003 (milling, 4mm tip, bigger end)  
N140 G0 X0 Y0 Z-3 M8  
N150 G02 X-2 Y-4 R8 F300  
N160 G02 Y-18 R8 F300  
N170 G01 X-14  
N180 G02 Y-4 R8 F300  
N190 G01 X-2  
N200 G0 X0 Y0 M9  
N210 T0004 (milling, smaller end, 3mm)  
N220 G0 X0 Y0 M8  
N330 G0 X-4.39 Y-1.31 Z-7.24 F300  
N340 G02 X-7.85 Y-3.23 R6.92 F300  
N350 G01 Y-14.97  
N360 G02 X-4.39 Y-16.88 R6.92 F300  
N370 G0 X0 Y0 M9  
N380 G0 X-13.81 Y-1.31 Z-7.24 F300  
N390 G02 X-6.89 Y-3.23 R6.92  
N400 G01 Y-14.97  
N410 G02 X-10.35 Y-16.88 R6.92 F300  
N420 G0 X0 Y0 M9  
M30  
%
```

```
#include "AccelStepper.h"

// AccelStepper Setup
AccelStepper stepper1(1, 2, 3); // 1 = Easy Driver interface
// UNO Pin 2 connected to STEP pin of Easy Driver
// UNO Pin 3 connected to DIR pin of Easy Driver

AccelStepper stepper2(1, 4, 5); // 1 = Easy Driver interface
// UNO Pin 5 connected to STEP pin of Easy Driver
// UNO Pin 6 connected to DIR pin of Easy Driver
AccelStepper stepper3(1, 6, 7);
AccelStepper stepper4(1, 8, 9);

int move_finished=1;

long h; // height of the roof
long w; // width of the roof
long D; // rope winch diameter
long s; // distance traveled each step
const float Pi = 3.141593;

long a; //
long b; //

long L1;
long L2;
long L3;
long L4;

long V1;
long V2;
long V3;
long V4;

// Stepper Travel Variables
int Travel1; // Used to store the motor1 travel value
int Travel2;
int Travel3;
int Travel4;

int move_done=1; // Used to check if move is completed

void setup() {
```

```

Serial.begin(9600); // Start the Serial monitor with speed of 9600 Bauds
Serial.println("Input coordinates");
Serial.println("a =");

// Set Max Speed and Acceleration of each Steppers
stepper1.setMaxSpeed(500.0); // Set Max Speed
stepper1.setAcceleration(500.0); // Acceleration

stepper2.setMaxSpeed(500.0); // Set Max Speed
stepper2.setAcceleration(500.0); // Acceleration

stepper3.setMaxSpeed(500.0);
stepper3.setAcceleration(500.0);

stepper4.setMaxSpeed(500.0);
stepper4.setAcceleration(500.0);
}

void loop() {

while (Serial.available()>0) { // Check if values are available in the Serial Buffer

move_finished=0; // Set variable for checking move of the Steppers
if (h == 0 || w == 0 || D == 0){

Serial.println("Enter Roof and rope winch diameters separated by a comma: h,w,D ");
Serial.print("Enter Values Now: ");

h= Serial.parseInt(); // Put First numeric value
Serial.print(h);
Serial.print(" Height , ");

w= Serial.parseInt(); // Put Second numeric value
Serial.print(w);
Serial.println(" Width ");

D= Serial.parseInt();
s= D*Pi*(1.8/360);
L1 = sqrt(sq(h)+sq(w))/2;
L2 = L1;
L3 = L1;
L4 = L1;
delay(100);}
else{
Serial.println("Input coordinates");
Serial.println("a =");
a= Serial.parseInt();
}
}
}

```

```

Serial.print("b =");
b= Serial.parseInt();

V1 = sqrt(sq(a-300)+sq(h-b))- L1;
V2 = sqrt(sq(w-a-300)+sq(h-b))-L2;
V3 = sqrt(sq(w-a-300)+sq(h-b-600))-L3;
V4 = sqrt(sq(a-300)+sq(h-b-600))-L4;

L1 = V1;
L2 = V2;
L3 = V3;
L4 = V4;
Travel1= V1/s;
Travel2= V2/s;
Travel3= V3/s;
Travel4= V4/s;
}
stepper1.moveTo(Travel1); // Set new move position for Stepper 1
stepper2.moveTo(Travel2); // Set new move position for Stepper 2
stepper3.moveTo(Travel3);
stepper4.moveTo(Travel4);

delay(500); // Wait 1 seconds before moving the Steppers
Serial.print("Moving...");
}

// Check if the Steppers have reached desired position
if ((stepper1.distanceToGo() != 0) || (stepper2.distanceToGo() !=0) ||
(stepper3.distanceToGo() !=0) || (stepper4.distanceToGo() !=0)) {

  stepper1.run(); // Move Stepper 1 into position
  stepper2.run(); // Move Stepper 2 into position
  stepper3.run();
  stepper4.run();}

// If move is completed display message on Serial Monitor
if ((move_finished == 0) && (stepper1.distanceToGo() == 0) &&
(stepper2.distanceToGo() == 0) && (stepper3.distanceToGo() == 0) &&
(stepper4.distanceToGo() == 0)) {
  Serial.println("Position reached!");
  Serial.println("");

  move_finished=1; // Reset move variable}}

```

### Appendix 8 Circuit Board Connection Diagram

