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Final Report

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TORONTO METROPOLITAN UNIVERSITY
FACULTY OF ENGINEERING, ARCHITECTURE AND SCIENCE

DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING

MEC 825 – Mechanical Design
Final Project Report

Friday, April. 5th, 2024

Gutter Done

Loose Screw Design

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Abstract

Maintaining gutters is imperative for homeowners to protect their properties from water damage and prevent potential health hazards caused by water stagnation. Routine cleaning is the most crucial aspect of gutter maintenance. However, traditional cleaning methods are often time-consuming, physically demanding, and pose risks of injury. To address these challenges, LSD Engineering is undertaking the development of a gutter-cleaning robot capable of remote control or autonomous operation. The engineering team will employ a comprehensive top-down design approach, which includes studying existing interventions, identifying target markets, iterative design, prototyping, programming, 3D printing, and conducting failure mode and effect analysis. The objectives of LSD Engineering encompass producing a final CAD assembly, detailed testing reports, material and motor specifications, cost analysis, and a fully functional prototype.

The design process began with two main systems of the gutter-cleaning robot: debris removal and movement. Through a heavy emphasis on iterative development and rigorous testing, LSD Engineering explored multiple movement and debris removal designs to refine the product. Control mechanisms for both systems underwent iterative design to enhance overall performance. The final design emerged in a compact form, meeting predetermined dimensions. The control system includes components like TB6612FNG for motor control, ESP32-CAM for remote connectivity, and Arduino as the central controller. Movement is facilitated by two N20 DC motors, while debris removal utilizes a 3D printed hub with zip ties and a robust DC motor. Despite challenges, such as meeting size requirements and executing precise maneuvers, LSD Engineering persevered through iterative design processes to achieve a final design that met spatial constraints and demonstrated satisfactory performance. The final cost for the prototype came to be $114.88 with an overall cost of $279.99 for the entire developmental period.

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Chapter 1 - Conceptualization and Feasibility Study

1. Introduction

Throughout most of recorded history, rain gutters have been used to divert rainwater and are still a very important feature in any and all houses. Gutters are essential for directing rainwater away from buildings to protect their foundation and structure. Regular cleaning ensures proper drainage, preventing issues like erosion, mold, and structural damage. Well-maintained gutters also deter pests and enhance the appearance of a property, contributing to its longevity and value. Recognizing and maintaining gutters is crucial for preserving the integrity of any home or building. Considering this, it is of utmost importance to have the gutters cleaned whenever there is any debris build up. Unfortunately current methods are simply not safe enough or effective enough.

When addressing clogged roof gutters, two primary concerns emerge. Firstly, the task of gutter cleaning at elevated heights exposes individuals to various hazards, notably slips, trips, and falls. Statistics reveal that ladder fall injuries occur at a rate of 2.13% per 1000 inhabitants annually, with a significant portion affecting older males in domestic settings [1]. Given that gutter cleaning typically involves being on a ladder and utilizing extensions, which can disrupt one's center of gravity, the likelihood of falling and sustaining injuries escalates significantly. Moreover, certain gutter cleaning methods necessitate climbing onto the roof, which, while arguably providing more stability than ladders due to the larger surface area, presents risks of dislodging shingles and encountering slippery surfaces, especially after storms [2]. Overall, traditional gutter cleaning approaches entail substantial risks of injury.

Simultaneously, the threat of water stagnation within clogged gutters only worsens the situation, making it a health risk for inhabitants. As debris, such as leaves or twigs, obstructs the flow of rainwater, standing water becomes a breeding ground for mold, mildew, and harmful bacteria [3]. This not only accelerates the decay of the gutter system but also poses health hazards. Airborne contaminants from stagnant water may get into living spaces, leading to respiratory issues and other ailments. The stagnant water not only compromises the integrity of the property but also attracts pests, creating an additional layer of concern as mosquitoes and other insects thrive in these stagnant environments [4].

The amalgamation of these risks necessitates a comprehensive approach to gutter maintenance—one that not only addresses the immediate dangers of working at heights but also confronts the subtle perils of water stagnation. Proactive strategies, innovative technologies, and heightened awareness are imperative to safeguard both the physical well-being of those engaged in gutter cleaning activities and the overall health and resilience of the property.

A secondary concern would be the impact to the surrounding environment in the cases of clogged roof gutters. Certain gutter and roofing materials intended for corrosion resistance pollute the water flowing through. This problem is made worse when the gutters are clogged and flow cannot be achieved. By neglecting gutter maintenance, blockages are more likely to occur leading to increases in concentrations of contaminants in the rainwater runoff [5].

Considering the risks associated with working at heights to clean gutters and the health hazards posed by neglecting gutter maintenance, it becomes evident that a solution addressing both these concerns is imperative. Various methods are currently employed for gutter cleaning, each with its own advantages and drawbacks. Traditional manual cleaning, though cost-effective and accessible, is labor-intensive and potentially hazardous. Using gutter cleaning tools on extendable poles offers a safer alternative but may lack thoroughness. Existing automated solutions like robotic gutter cleaners provide convenience and almost completely eliminate risk of injury but may struggle with certain challenges such as dealing with compacted leaves or thicker residue. With that being said, it is clear that the currently available solutions, while better than cleaning out a gutter by hand, don't make the action of cleaning the gutter particularly easy or convenient. The goal of LSD engineering is to provide a better solution. A solution that makes the task more convenient than using a long pole with an attachment on the end of it in order to scrape or flush out dirt. A solution that is more robust and thorough than using the currently existing “iRobot”. A solution that is safer and doesn't need the user to climb up a ladder or the roof. In order to achieve this goal and produce an adequate solution, LSD Engineering will take inspiration from all existing solutions while also attempting to leverage newer technology. To simplify and streamline the process, LSD will be employing design roadmaps adapted from Professor Salustri's MEC 325 road map [6] along with the Simplified Design Process introduced by Professor Sajad Saeedi. Using these tools, a comprehensive and complete solution will arrive within the provided time frame.

The deliverables are to produce comprehensive CAD design drawings along with part models and assemblies, stress analysis calculations for key points throughout the structure, material and design choice justifications, and expected data values with regards to dimensions, weight, performance, cleaning efficiency, and costing to name a few. A full scale model will be produced in order to provide an interactive physical representation of what the final design might look like.

2. Literature Review and Background Research

In the progression towards innovative gutter maintenance solutions, it is important to build a foundation of specialized knowledge and an understanding of the current market landscape. This section is dedicated to a comprehensive examination of relevant literature and an analysis of the existing market for gutter cleaning technologies.

Background Research

2.1 Understanding Gutters

To develop an effective gutter cleaning robot, the purpose of roof gutters and design parameters which the robot will be designed for must first be established. An introduction to gutter functions and specifications will ensure the goals of the project stay aligned with the priorities of the consumer. This section will also determine the most popular configuration of gutter used in residential roofs. By designing for the most common and generic gutter type, size, and material, the product will be usable for the largest market.

The primary objective of roof gutters is to prevent mold growth by minimizing the rainwater trickling down along walls and into foundations. Without roof gutters, the stormwater runoff would penetrate the porous building material comprising the walls and floors, accumulating moisture over time and leading to mold spores [7]. These resultant mold spores pose a clear potential for harm to human health. Simultaneously, having an installed roof gutter in place that is not properly maintained carries its risks as well which ultimately defeat its purpose. Gutters which are clogged with various debris pose separate but equally potent risks. Gutter cleaning is an essential component of ensuring that the initial objective of this tool is upheld.

The functions of the interfacing components should also be considered while designing a gutter cleaning solution. The gutters specifically are designed to collect and direct water toward a downspout. The higher the water holding capacity, the more effective the system is. The end caps close off the ends of each section of gutter, preventing flow of rainwater in undesired directions and helping retain the collected water while it flows. The downspout is a vertical receptacle where all the collected water flows into, ultimately directing it away from the foundation. Downspouts could also be designed for irrigation by directing and distributing water across the lawn, or directly toward storm drains. All of the above components are secured against the side of the building using brackets and hangers [8] which are capable of holding large amounts of water, but its load carrying capacity should also be considered for the design of a gutter cleaning robot. If the robot is cleaning while the gutter is empty or dry, this is less of a concern. If the robot is cleaning while the gutter is clogged and flooded, the weight of the robot and the forces imparted on the system during cleaning should be considered.

Gutters are classified based on their cross-sectional profile. The most commonly used roof gutter types are the K-style and the half-round. K-style gutters are the most commonly used type of gutter, where there is a flat bottom and a distinct “K-shape” comprising the wall. Half-round gutters have a circular cross-section with the top half of the circle removed, leaving a round semi-circle at the bottom to catch water. K-style gutters are capable of carrying twice as much water as half-round gutters per linear foot. Half-round gutters are often selected because they are seen as more aesthetically pleasing. Generally, these gutters measure 5-6 inches across the top [8].

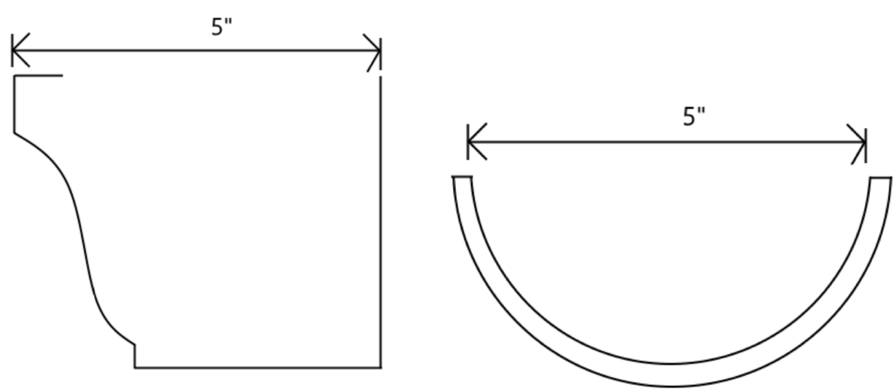


Figure 1: Cross-sectional profile of 5” wide K-style (left) and half-round (right) gutters respectively.[drawn by Raymond Wu].

Commonly used gutter materials include aluminum, vinyl, steel, copper, and zinc. Each of these materials have their respective pros and cons. Aluminum is a lightweight material which does not rust, but develops a thin protective film of aluminum oxide. Vinyl is the cheapest material, is lightweight, does not rust or corrode, but has poor durability. Steel is durable, but is heavier, costs more, and requires measures to be taken to prevent or treat rust over time. Copper is an expensive material that won't rust, but oxidizes and develops a green color over time that to some is considered aesthetically pleasing. Zinc is also expensive, but very durable and develops a patina over time [9]. The most common material used for gutters is aluminum due to its low weight, relatively low cost, durability, ease of installation, and corrosion resistance.

To finally determine the specific type, size, and material of the gutter to be used in the project, data from existing products on the consumer retail market will be aggregated and the most common configuration will be selected. The following table was created using data collected from The Home Depot's and RONA's websites under their respective "gutter" categories. Data was collected on the store, supplier name, gutter type/style, material, width in inches, length in feet, total cost, and an index comparing the cost per foot.

Table 1. Existing gutter products on the market for retail consumers using data from The Home Depot and RONA. [10] [11]

Store	Supplier Name	Type	Material	Gutter Width (in)	Gutter Length (ft)	Total Cost ($)	Cost per Foot ($)
Home Depot	Amerimax Home Products	K-style	Aluminum	5	10	12.98	1.298
Home Depot	Gibraltar Building Products	K-style	Aluminum	5	10	12.98	1.298
Home Depot	Amerimax Home Products	K-style	Aluminum	5	16	28	1.75
Home Depot	Spectra Metals	K-style	Aluminum	5	16	28	1.75
Home Depot	Amerimax Home Products	K-style	Vinyl	5	10	6.58	0.658
Home Depot	Amerimax Home Products	K-style	Aluminum	5	10	12.98	1.298
Home Depot	Amerimax Home Products	K-style	Aluminum	6	16	38	2.375

RONA	Kaycan	K-style	Aluminum	5	10	25.99	2.599
RONA	Plastmo	Square	Vinyl	2.5	10	17.49	1.749
RONA	Plastmo	Half-round	Vinyl	4	10	11.49	1.149
RONA	Euramax	Half-round	Vinyl	4	10	8.19	0.819
RONA	Euramax	K-style	Aluminum	5	10	21.39	2.139
RONA	Euramax	K-style	Vinyl	4.5	10	10.99	1.099

Table 2. The average cost and most common gutter configuration as derived from Table 1.

Mean Cost/Ft	1.537
Width Mode	5
Material Mode	Aluminum
Type Mode	K-style

By looking at existing gutters on the market, it was ultimately determined that the most common gutter configuration is a 5” wide aluminum K-style gutter. The gutter cleaning robot designed in the following project will be made specifically for gutters of this specification.

An often overlooked but critical component of gutter systems is the hanger. Hangers play a pivotal role in maintaining the integrity and functionality of gutters by providing the necessary support. There are two primary types of hangers: those that support the gutter from below and those that are mounted inside the gutter to offer an 'invisible' support system. This distinction is potentially crucial in the design of gutter cleaning robots, as the type of hanger used can affect the robot's ability to navigate and clean efficiently. External hangers might provide more clearance and ease of movement for the robot, whereas internal hangers offer a sleeker appearance but might introduce constraints in terms of space and accessibility for cleaning mechanisms.

The installation process of gutters has seen significant advancements, with the shift towards seamless gutters marking a notable improvement in both aesthetic appeal and functionality. Seamless gutters are custom-formed on-site from a coil of sheet metal, a process facilitated by portable machines that allow for a tailor-made fit to the building's roofline. This method, as informed by a foreman from The Dalton Company, is increasingly preferred in new constructions for its ability to reduce joints, thereby minimizing potential leak points and debris accumulation. The seamless nature of these gutters not only enhances their durability and longevity but also presents a more streamlined appearance.

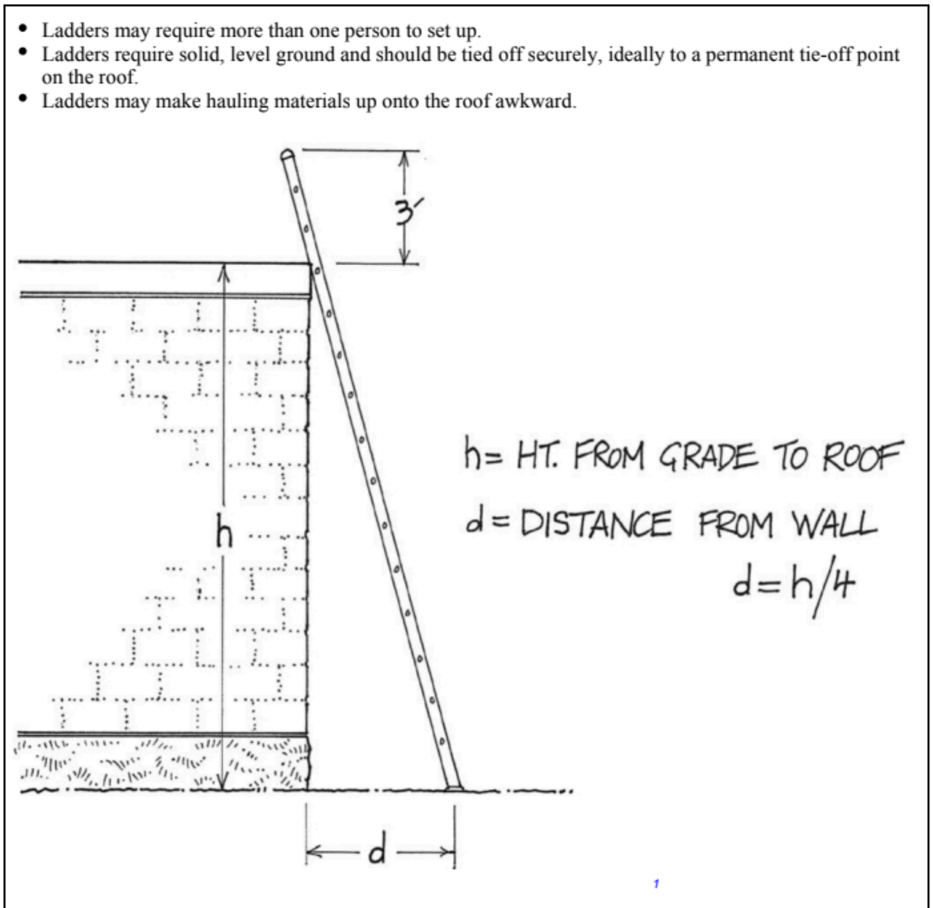


Fig. 4.1 *How to accurately distance the extension ladder feet from the base of the wall.*

Figure 2: Diagram of safe ladder configuration [12].

Adjacent to the innovation in gutter installation is the imperative of ladder safety. The proper setup and use of ladders are non-negotiable factors in preventing accidents. As shown in the provided diagram and table, the 1:4 ratio rule is a cornerstone of ladder safety, dictating that the ladder's base should be placed one foot away from the building for every four feet of height to where the ladder contacts the building [12]. This ensures stability and minimizes the risk of the ladder tipping backward or sideways. For instance, a ladder reaching a height of 20 feet should be situated five feet away from the wall, according to the safety table. These guidelines are not only essential for the safe installation of gutters but are also significant in the context of deploying gutter cleaning robots. Ensuring that robots can be safely placed or controlled from the ground can substantially reduce the need for ladder use, thereby enhancing safety protocols. Moreover, the gutter cleaning robot's design must account for these safety measures, considering the additional weight it represents and the interaction with the ladder during the cleaning process.

Table 3. How High Extension Ladders Can Reach Based on Safe Set-ups* [12]

Extension Ladder Height	Maximum Reach of Extension Ladder	Distance of Base Placement from Wall	Highest Point Ladder Will Touch
16 foot	15 feet	4 feet	9 to 13 feet
20 foot	19 feet	5 feet	13 to 17 feet
24 foot	23 feet	6 feet	17 to 21 feet
28 foot	27 feet	7 feet	21 to 25 feet
32 foot	31 feet	8 feet	25 to 29 feet
36 foot	34 feet	9 feet	28 to 32 feet
40 foot	37 feet	10 feet	31 to 35 feet

2.2 Current market solutions

Table 4: Current market options for residential gutter cleaning

Category	Robot	Power tool		Manual
Product	iRobot Looj 330 [13]	Pressure Washer + Attachment [14]	Leaf Blower [15]	Scoop [16]
Image				
Dimensions	2.25 (in) x 3.25 (in) x 15.63 (in)	Total length 102 (in)	11.42 (in) x 7.68 (in) x 46.06 (in)	3 (in) x 7 (in) x 14.6 (in)
Weight	2.77 lb	N/A	5.29 lb	0.2 lb
Power A/C /output	7.2V	4000 psi	60V	N/A
Type of Control	Remote control	Manual controls/nozzle attachments	Manual (button/switches)	Manual
Battery Capacity	2600 mAh	N/A	4000mAh	N/A
Battery Type	Lithium-ion (rechargeable)	N/A	Lithium-ion (rechargeable)	N/A
MSRP	399.99 CAD	46.50 CAD + cost of pressure washer	349.99 CAD	5.95 CAD

Additional Details	Battery powered, remote operated gutter cleaner. Inserted into gutters via ladder.	- The gutter cleaning tool consists of 6 straight rods, a curved rod - extension wands have M22 14mm male thread end and it can change to 1/4” quick connect	blowing force of 130 MPH max air speed and 610 CFM max air volume, 20% lighter than comparable gas-powered models	- Manual shovel, user needs to climb a ladder to reach and shovel the gutters - Lightweight and durable - Ergonomic design, however prolonged use can lead to fatigue

The table above displays the current gutter cleaning solutions offered to consumers. For the power tools and manual sections various brands and models using the same cleaning method exist, the options were narrowed down and imputed into the table. Each cleaning method has its advantages and disadvantages which will be discussed in this section of the report.

Robot

A company named iRobot has designed, manufactured and sold the only commercially available gutter cleaning robot named Looj 330. The Looj 330 operates inside the rain gutter. It can comfortably be placed in a gutter that has approximately 2 inches of clearance from the base of the gutter to the gutter hanger. Affixed to the robot's front is a pliable four-part auger rotating at 500 rpm. The foremost component, termed the breaker, is tasked with dislodging obstructions. Two rubber flaps, referred to as ejectors, expel debris from the gutter. Positioned between each ejector are two breaker bars, aiding in clog breakdown. The final element comprises two sweeper brushes, complemented by a scraper blade beneath the Looj, facilitating the removal of debris from the gutter's bottom. The robot moves with a rubber track on either side of its body. The user carries the Looj 330 up a ladder by holding onto its handle or attaching it to the hip via a hip/belt attachment. The handle can be removed once the robot is placed inside the gutter and acts like a remote control for the robot's movements.

The iRobot Looj 330 offers plenty of advantages to traditional cleaning methods. For starters the robot is waterproof and made with durable materials. The remote control offers intuitive controls with minimal interaction. The robot's compact size allows it to easily fit in the gutter, and its high spinning auger assembly jets out debris. The device has a few disadvantages, mainly that it can’t turn within the gutters as it's long. This means that after cleaning a segment of the gutter on one side of the house, the user has to climb a ladder and manually position the device onto the next side. Furthermore, it's difficult for the Looj 330 to clean large dense piles of wet leaves and debris, and can require multiple passes and possibly manual intervention by the user.

Power tools

Pole Attachment (pressure washer)

The Agiiman gutter cleaning tool is a pole attachment for a regular pressure washer. Many types of pole gutter cleaners consist of segments of shorter rods that connect to each other via a quick connect option, in this case ¼” connections. Once fully assembled the pole’s length can reach the rain gutters of a standard home, in the case of the Agiiman its total length is 102 inches. The end of the pole is also bent at an angle of 45 degrees to allow the outflow of water to be aimed at the gutter. The product also comes with various nozzle heads that adjust the spray pattern of the water by angle. The water inlet of the pole is connected to a pressure washer, thus making it a power tool operating at 4000 psi. The device works by spraying a pressurized stream/spread of water aimed at the gutters. The force of the water dislodges the debris, ejecting out of the gutter while at the same time the remaining debris gets washed away via the downspout. The user standing on the ground by the side of the house operates the pressure washer and pole. They walk around the house holding the pole attachment facing the gutter and clear out the debris. The system is safer as the user does not need to climb a ladder to clean out the gutters, they can stay on the ground and accomplish the task. Moreover, the force of the water provides a thorough cleaning and the debris disposal via the downspout saves on clean up time. The system does use large amounts of water, and requires the user to have a pressure washer which is an additional cost. Furthermore, the once pressurized water is flowing through the pole, its control can be difficult, potentially causing damage to gutter straps and the side of the house.

Leaf Blower

Leaf blowers are generally used for lawn care to collect fallen leaves for removal. They also serve another purpose, cleaning gutters. The model above is a fairly lightweight and powerful leaf blower. Its 4000mAh and 60V battery allows it to be more compact compared to traditional gas powered blowers while still maintaining a strong blowing force. Generally, the user would carry the leaf blower up a ladder near the gutter, aim it towards the gutter base and turn it on and in a sweeping (back and forth) motion would blow the debris out of the gutter. This method provides thorough cleaning and can be faster than a traditional scoop method. However, it poses many challenges, the most important being safety. Operating a leaf blower on a ladder can result in injury, when the blower is turned on the force from the air can disbalance a person causing them to fall and injure themselves. Moreover, if the user doesn't have someone supporting the ladder at its base that can increase their chance of falling. This is why it is common for many homeowners, elderly people, people with disabilities, people living alone, to hire landscaping/maintenance services to perform this task. Other challenges include fatigue from carrying the blower overtime. Also the user must move the ladder to various points along the gutter as the blower has a limited range and would not be able to blow leaves that are far away. There is also the difficulty in blowing away wet debris, compared to dry debris, that tends to clump and stick together which can also cause a mess on the roof. Leaf blowers can be costly and electric leaf blowers can have a short use time before needing a battery swap.

Manual tools

Currently there are multiple different types of manual tools that can be used to effectively clean roof gutters. In this instance, the product that shall be the focus is the scoop. The scoop is a handheld, small, and manual tool which allows the user to spoon out waste from within the gutter and toss it, either into a bag or onto the floor. The tool is effective and what it is meant to do and also benefits from very affordable pricing with costs generally being under 10$ at most locations selling a variation of it. Besides this, due to the simplicity of the piece and ease in manufacturing, virtually any and all stores that pertain to home maintenance would have some variation of the tool making it very easily accessible and almost always available. With all these positives, it is a fairly popular option, however it does also have a reasonable number of negatives that weigh heavily on its overall effectiveness. Due to the nature of the tool, the user needs to climb onto a ladder to use it, which automatically puts them at risk of falling. Besides this, the object also can only be used by hand and does not come with pole attachments. This would mean the user would only have access to the gutter that is within their reach, which in turn means the user would either have to climb up and down the ladder multiple times over and over in order to complete the task of cleaning, or it incentivises overreaching and shifting your weight off the ladder in order to increase your effective range. This would likely make the task of cleaning quicker to complete but would also significantly increase the risk of the user falling off the ladder and suffering an injury.

2.3 Current Market Takeaways

After conducting the analysis of the current market solution for gutter cleaning it was determined a few key takeaways that should be considered for the gutter cleaner design. Firstly, to ensure safety the device should be lightweight and easy to carry up a ladder (eg: iRobot Looj 330 waist clip). For mobile robots specifically, to avoid repositioning the device in the gutter/on the roof, the device should be able to turn corners and be operated via a remote. This would reduce the number of ladder trips a user would need to take thereby reducing the chance of injury. Furthermore, it was determined that leaf blowers and the Looj 330 are better suited for cleaning dry leaves and debris than wet leaves. For wet leaves the pole attachment pressure washer tool or the scoop is more effective, however the pole tools have limited visibility and require the user to own a pressure washer (costly). On the other hand, manual scoop tools can be more laborious, require more ladder trips to reposition and can lead to overreaching making it unsafe. Scoop tools are the only method that offer visibility of the gutter while cleaning, allowing the user to clean more thoroughly. It was determined that visibility of the gutter while cleaning should be a factor to consider when designing the solution.

Literature Review

2.4 Biomechanical Modeling and Design Considerations for Gutter Debris Removal

Understanding gutter debris characteristics is crucial for designing an effective cleaning mechanism. Gutters collect various materials, such as leaves and compost, which behave differently under stress. This behavior must be considered to design mechanisms that can efficiently clear debris. Key references like "Plant Biomechanics" by Karl J. Niklas and principles from “Physics Plants” provide a basis for modeling these materials. These references provide a framework for approximating the behavior of plant-based debris, enabling the modeling of leaves and compost as either elastic solids or ideal fluids, depending on the duration of the applied force [17].

The viscoelastic nature of plant debris adds complexity to mechanism design [17][18]. Under rapid, instantaneous stresses, such as those encountered by fast-moving components of a cleaning mechanism (e.g., brushes or blowers), debris can be effectively modeled as elastic solids. This approximation helps in designing components that can effectively dislodge and remove debris without causing blockages. However, for slow-moving mechanisms or the gradual accumulation of debris, the visco behavior becomes significant. Here, the design must account for the slow deformation of debris, ensuring the mechanism can handle these materials without malfunctioning.

The behavior of plant matter as nonlinear viscoelastic materials introduces further design challenges. Unlike simple viscoelastic materials, nonlinear viscoelastic debris, such as wet leaves and compacted compost, do not follow predictable patterns under stress and can behave more like non-Newtonian fluids [18]. This irregular behavior, characterized by significant deformation, makes it difficult to predict and model the interaction between the debris and the cleaning mechanism. The absence of comprehensive models for nonlinear viscoelastic materials means that standard design assumptions may not always apply, especially under conditions of large strain [17][18]. Furthermore as plant debris has high deformations without fractures, clogging is potentially a major challenge. Developing a model is outside the scope of this project, as it would likely involve training a neural network to find the nonlinear behavior.

Moisture plays a critical role in altering the physical properties of gutter debris. When leaves absorb water, they become more pliable and tend to adhere to surfaces, complicating the removal process [18]. This effect requires design adaptations to ensure the cleaning mechanism remains effective in wet conditions, which are common in gutters. For instance, mechanisms might need to be designed to apply greater force or to incorporate features that reduce adherence to facilitate debris removal. Designing for these worst-case scenarios ensures that the cleaning mechanism can operate effectively across a range of conditions, from dry leaves to wet, matted debris.

The unpredictable nature of nonlinear viscoelastic materials necessitates empirical testing for validating design assumptions and refining the cleaning mechanism. Given the limitations in modeling the complex behaviors of gutter debris, especially under varying conditions of moisture and compaction, physical testing becomes essential. This involves experimenting with the mechanism in controlled conditions using debris in different states—dry, wet, and partially decomposed—to observe its performance and adaptability. Such empirical testing allows for the identification of any discrepancies between theoretical models and real-world behavior, enabling adjustments to the design that enhance effectiveness and reliability.

2.5 Exploring Academic Concepts Relevant to Design

This section will document the exploration into academic research potentially relevant to the design. Understanding the literature will provide insights on feasibility, and existing models which can be translated into this project. Literature on technologies that were originally intended for other applications or similar purposes such as pipe cleaning and duct cleaning will also be reviewed to derive a novel mechanical design which may not have previously been considered in gutter cleaning.

The first challenge is to find a method of placing the robot into or onto the gutter system. The conventional method of achieving this, as done in the iRobot Looj, is by carrying it up a ladder and manually placing it into the gutter. This is a very reliable method, but offers limited advantages of using the robot. The dangers of climbing a ladder are still ever present. If a ladder is required to begin with, then the user may as well use a manual method of gutter cleaning using any regular tool. It can save some effort in terms of repositioning the ladder but it would be significantly cheaper and offer a more thorough clean to use a non-robot method instead. Another option to be considered is using a pole to mount the robot onto the gutter system with an attaching/detaching mechanism. This method requires physical strength, dexterity, and coordination to be able to move the robot at the end of the pole. A pole-based system would thus impose weight restrictions for the robot to minimize the physical forces required by the user. On the other hand, it eliminates the risks of deploying ladders. If a property lacks a flat, stable surface on the ground for the ladder to rest or if the user is uncomfortable with climbing a ladder, a pole may be a safer alternative. The user would also not be required to work at heights, eliminating the falling hazard. Since both these options do require a respectable amount of strength and dexterity, ideas were sought which were purely autonomous in its method of reaching the gutter. One potential solution involves magnetic adhesion within the robot's locomotion system. This concept is derived from robotic applications in structural inspection where devices scale metallic bridges as outlined by Nguyen and La [19]. By embedding magnets into the robot's treads, the unit could autonomously navigate ferromagnetic surfaces such as a downspout, adhering firmly and mitigating the risk of detachment during operation. While the feasibility of this method depends on the magnetic properties of the gutter materials, it could also be coupled with a one-time installation of a magnetic track on non-metallic surfaces, thus broadening the applicability of this approach. Similarly, emulating the grip mechanisms found in the clothes climbing robot designed by Liu et al., a friction-based system could be employed [20]. The robot would harness this principle to ascend the downspout, leveraging the contact friction between two counter-rotating wheels or treads and the spout surface. This method, while necessitating a delicate balance between the frictional force and the material integrity of the downspout.. Finally, a quadcopter drone could be considered as an option to deploy the robot. The drone attaches to the robot, flies above and into the gutter, detaches from the robot, and returns to the user. This system could be autonomous or remote-controlled. Drones are relatively complicated devices requiring many electronic components, adding to the cost and user requirements to operate the device. Assuming most of the target market does not already possess drones, this would add significant cost to the project and make it uncompetitive in the market.

The next design decision involves determining how the robot will navigate the gutter system. A challenge within this decision is the unique profile of K-style gutters and the presence of gutter hangers spaced across the system. The hanger spans across the top of the gutter width to hold the entire system in place against the side of the home. This is a design challenge, as this will restrict the vertical size and certain methods of motion. The most primitive method of locomotion can be achieved using a regular motorized wheel system. However, with the debris expected to be present within the gutter, it may not achieve sufficient traction to move in the desired manner. To be able to grip the surfaces of the gutter, a deep-treaded tire may be considered. To maximize traction, a tracked system such as that used in the iRobot Looj design could be used. During research, examples were found of existing rescue and solar panel cleaning robots using tracked treads. These applications are quite similar to gutter cleaning. In a modular linked rescue robot design by Zang et al., the tracks aid in natural disaster debris and rubble traversal [21]. In the context of gutter cleaning, the masses of debris, leaf litter, branches, and more accumulate within and could most definitely benefit from this tracked design to move through. As for the solar panel cleaning robot designed by V. A et al., a tracked design is also used to maximize surface contact with the ground surface to have grip while cleaning under wet or dry conditions. Similar conditions can be expected for gutters which are in need of maintenance, where it may be entirely dry, filled with semi-solid debris, or immersed in rainwater due to a clog [22]. A novel method of locomotion could be achieved through peristalsis. A pneumatic rotary mechanism designed for in-pipe robots emulates this behavior well. This design by Yamamoto et al. uses pneumatics to expand and contract sections to establish traction along the pipe walls in conjunction with a forward propulsion mechanism to move forward [23]. This method grips the sides with enough frictional force to enable forward traversal through debris. This design conveniently conforms with the internal geometry and develops a large contact patch, which is adaptable for the unusually-shaped K-style gutter wall. The design was additionally adapted to work in open spaces, which would further benefit the gutter geometry, since it is open to the atmosphere at the top. Unfortunately, the gutter geometry consists of a very inefficient middle compromise where it is not fully enclosed but also not fully open which would not be ideal for the robot. Another novel mechanism could be using a series of robotic legs to traverse the gutter. A robot using 6 legs to coordinate can easily step over and around obstacles, and provide superior maneuverability. A proposed design which will be shown in the upcoming morphological dubbed the “Gutter Crab” leverages this idea to be positioned on the roof and reach into the gutter to perform cleaning. This design easily bypasses the problem of gutter hangers, but is complicated to design mechanically and electronically. It requires separate motors and sensors for each leg and an innovative method of coordinating them to achieve simple linear motion.

Turning corners of the gutter system was also something that could be considered. Some homes have simple gutters where gutters only comprise one straight section but for more complex gutters with multiple sections, a corner turning capability on the robot will save the consumer time and effort. The K-style gutters in particular have their width measured across the top, but the flat bottom is narrower which makes it slightly more difficult to turn. From research, one of the potential designs to navigate corners is to take inspiration from a zero-radius steering autonomous amphibious vehicle as designed by Tee et al. [24]. The design emphasizes navigation in narrow spaces, in amphibious environments, and autonomy, all of which are to be considered for the design of the gutter cleaning robot. The design consists of 2 front wheels and 1 rear wheel located at the center. The robot moves forward into the corner, with all wheels pointing forward. When the turn begins, the rear wheel turns perpendicular and begins driving the device to orient itself with the new direction. As the namesake suggests, this is a zero-radius turn. A tracked robot could establish a similar function by moving the left and right tracks in different directions, but would generally require a longer wheelbase.

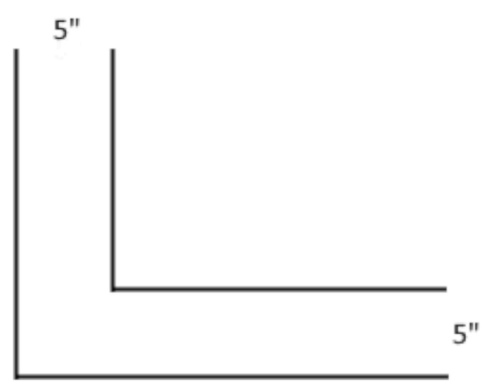


Figure 3: Gutter corner limitations for a 5” wide gutter system.

Designs for gutter cleaning mechanisms can be drawn from existing products on the market or analogous tools in similar applications. The cleaning mechanism on the iRobot Looj is a motorized rubber paddle sweeping unwanted objects up and out of the gutter, intended for removing medium to large pieces of debris. Bristles located immediately behind it loosen smaller particles such as silt accumulation. In the plumbing industry, snaking tools are often used to unclog pipes and ducts and those same principles could be applied to the case of gutter cleaning. In a study performed by Tanihira et al., a double helix pipe cleaning snake robot was designed. This design adopted a plumbing snake-like design while adding brushes to clean material stuck to the pipe wall while propelling itself forward [25]. This design could also be adopted for use in unclogging gutter systems. Disadvantages of this design are that it would not be able to turn corners and that it may not be compatible with the K-style gutter. It has only been proven to work in closed circular pipe systems. An alternative design to consider is a solution proposed by Hitomi et al., where rotating brushes are attached to a planetary gearset which conforms to the square profile of the duct [26]. The design could be adapted to the K-style gutter in particular to loosen and remove debris stuck to the walls of the gutter and used in conjunction with another mechanism to remove large debris such as rubber paddles.

3. Problem Definition

Gutter cleaning stands as a crucial component for effective home maintenance playing a pivotal role in preserving residential infrastructure. The core challenge lies in balancing the need for unobstructed water flow through gutters with the inherent risks of conventional cleaning methods. Annually, numerous homeowners grapple with the unsafe chore of ascending ladders to clear debris from their gutters, exposing themselves to the potential dangers of falls and injuries. Furthermore, the accumulation of stagnant water in clogged gutters presents notable health hazards, effectively turning these essential water management systems into breeding grounds for mold, pests, and bacteria. The goal of this project is to create a device that can solve this problem while not hindering the functionality of the gutters.

3.1 Scope Refinement

In defining the scope of the project, the primary consideration is the identification and understanding of the end users. The scope of the project is centered around the development of a gutter cleaning solution tailored for residential use. It was decided to design a product that accommodates a wide range of homeowners, from the elderly to individuals in their 20s, ensuring that the solution is not limited to industrial or expert use. The design aims to be intuitive and user-friendly, requiring minimal technical knowledge for operation. By focusing on residential applications, the product is intended to address the specific challenges and needs of this user group, ensuring broader accessibility and ease of use without compromising on efficiency.

3.2 Design Requirements, Constraints and Performance Metric

After conducting literature review & background research the products requirements and metrics were revised for success from the RFP Proposal. The adjustment can seen below in Table #. As part of this revision selectins of the requirements were moved into a separate table, Table #, which include additional requirements which will be nice to have but not necessary. One of these constraints is mechanical novelty imposed by the supervisor Dr. Bill Lin. Thus it would be preferred to integrate mechanical novelty into the design but not essential.

Table 5. Problem Definition Chart

Product Characteristics	Functional Requirements	Constraints	Performance Metric
Cleaning Efficiency	Robot must remove at least 30% of debris in one pass by weight	Cannot damage gutters during operation.	$P_1 = \frac{Efficiency}{30\%} \times 100\%$
Energy Usage	Clean 60 linear meters of gutter on a single charge	Cannot charge midway through gutter cleaning.	$P_2 = \frac{Actual\ distance\ traversed}{60\ m} \times 100\%$
Durability	Withstand 1 cleaning cycles without general upkeep	Must operate in diverse weather conditions.	$P_3 = \frac{Actual\ cycle}{1\ cycles} \times 100\%$
Survivability* (Mobile Robot Requirement)	Can withstand a fall from a height of 3 meters onto a grass lawn.	There must be no effect on system functionality after.	$P_4 = \frac{Number\ of\ falls\ survived}{1\ fall} \times 100\%$
Connectivity	Offer wireless operational range of at least 15 meters.	Connection must be secure.	$P_5 = \frac{Actual\ Range}{15\ meters} \times 100\%$
Maintenance and Reliability	Mean time between failures is at least 50 hours.	Parts must be easily replaceable and easily cleaned.	$P_6 = \frac{Actual\ MTBF}{50\ hours} \times 100\%$
Cost-effectiveness	Total cost under $500 for 2 years of operation.	Cost includes purchase and maintenance.	$P_7 = \frac{500}{Actual\ Cost\ (2\ years)} \times 100\%$

Some requirements and constraints are dependent, thus refined will be made as necessary. The following is a summarized list of the product characteristics by solution category.

All solutions will require:

- The ability to prevent or remove debris
- The ability to detect debris - Potentially for closed loop - other human advisor

A mobile robot additional requires:

- Localization | Pose of the Robot: The robot's position and orientation, measured as displacement and angles from the start origin.
- Mapping | Awareness of Surroundings: The robot's ability to map its environment, measured by the relative distance from itself to surrounding elements.
- Odometry | Effectiveness of Actuation Input: The impact of actuator commands on the robot's motion, assessed through angular displacement.

Table 6. Non-essential requirements and performance metric

Product Characteristics	Functional Requirements	Constraints	Performance Metric
Navigation Capability	Navigate autonomously across various gutter layouts.	Must fit standard residential gutter sizes.	$P_{s1} = \frac{Navigation\ Success}{90\%} \times 100\%$
User Interaction	Require no more than 5 actions to start a complete cleaning cycle.	Interface must be intuitive.	$P_{s2} = \frac{5\ (actions)}{Actual\ Action\ to\ operate} \times 10$
Innovation		Find an innovative way to have mechanical novelty	

3.3 Foreseeable challenges

Solving this problem poses many challenges and considerations. For starters, the average household rain gutter is 5” wide and 3.5” tall, a small space with periodic supports called hangers. For a mobile robot solution there are a few challenges to consider. When placed inside of the gutter it will face difficulty to make tight, 90 degree, corners. Even roof centered mobile robots could face issues with incline and obstruction from the hangers. The debris removal mechanism also poses a challenge as the composition of organic debris varies and holds different physical properties when wet and dry. Thus the removal mechanism needs to be able to expel all debris regardless of the amount of moisture it holds. Another major challenge is the delivery system for the device, many injuries occur when making ladder trips to and from the roof for cleaning purposes. Therefore the solution should try to reduce, if not entirely eliminate, the use of ladders by the user. Thinking outside the box, having a preventative maintenance system installed into new/pre-existing gutters is also possible. That idea has its own challenges, specifically with the prevention of collecting debris and the high costs for design, manufacturing, installation and maintenance of such a system.

4. Methodology Overview

4.1 Project Management Strategy

The project will follow an agile, iterative approach, leveraging the diverse expertise to address the complexities of designing a gutter cleaning robot. This approach will ensure flexibility, efficiency, and adaptability throughout the project lifecycle. The team lead is Mr.James, due to he has the most experience with gutter cleaning and robots. This role includes organizing and assignment tasks, lead point of contact with supervisor, final review. The Project manager for this project is Mr.Saherwala, who will be responsible for keeping tasks on schedules and ensuring notes and documentation is completed. The project methodology was revised from the RFP into the following:

Conceptualization and Feasibility Study:

- Establish System Requirements: In consultation with stakeholders, clear specifications for the gutter cleaning robot will be defined, considering factors like debris type, gutter dimensions, and environmental conditions.
- Feasibility Study: Led by Mr. James, whose background in robotics and landscaping provides practical insights, technological constraints, risks, and the feasibility of the proposed solution. Literature review will be conducted to gain a deeper understanding of the problem. Once the best solutions are identified the top two designs will be explored.

System Design and Modeling:

- Mechanical and Electronic Subsystem Design: Mr. Wu will spearhead the design process, utilizing his proficiency in 3D printing, CAD, and design, to develop detailed models of the mechanical and electronic subsystems. The deliverables will be CAD models, and electrical schematics. This stage will be vital for designing the debris removal / prevention system.

Simulation and Prototyping:

- System Simulation: Mr. James will apply his skills in microcontroller programming, SPICE, and ROS2/Gazebo simulation to create accurate models of the robot's behavior and operational capabilities. This will be important for testing out electric circuits and the maneuverability on roof or inside the gutter.
- Physical Simulation: Mr. Saherwala's experience in 3D printing and CNC machining will be instrumental in creating accurate physical prototypes for testing.

Component Acquisition and System Assembly:

- Procurement and Assembly: The necessary components like sensors, motors, and controllers must be acquired. Mr. Boriyawala's experience with Arduino, ESP 32 Cams, and DC motors will be crucial in integrating these components into a cohesive system. Potentially designing as PCB to ensure the electronics can fit in a confined space.

Integration and Control System Development:

- Control Architecture: Development of the digital control architecture will be managed by Mr. James, leveraging his extensive knowledge in microcontroller programming and networking.
- Subsystem Integration: Ensuring seamless communication and functionality among all subsystems will be a collaborative effort, with each team member contributing their specific expertise.

Testing and Validation:

- Extensive Testing: Mr. Wu's experience in test design will guide the testing process, ensuring the robot meets quality and performance standards under various conditions.
- Iterative Improvement: Based on testing results, iterative improvements will be made, involving all team members in the refinement process to leverage their diverse skills and insights.

Testing Procedures:

1. Cleaning efficiency test
    1.1. Place a measured weight of debris into the gutter
    1.2. Weigh the gutter
    1.3. Move the robot through 2.5 ft gutter in 1 minute
    1.4. Weigh the gutter again
    1.5. Cleaning effectiveness = (Total weight after cleaning - gutter weight)/(Total weight before cleaning - gutter weight)
2. Energy usage test
    2.1. Place robot on treadmill/on clear path
    2.2. Turn on robot so it moves in cleaning mode
    2.3. Measure the distance it travels
    2.4. Energy Usage = (actual distance traversed)/(distance required) x 100
3. Durability test
    3.1. Device shouldnt require maintenance before 200 ft
    3.2. Should be water-resistant
4. Survivability test(Only for a mobile robot)

4.1. Drop it from a height of at least 3 meters onto grass lawn

4.2. Test the device's function

4.3. Record the results

5. Connectivity test

5.1. Keep sending input signals (move forward/turn/clean/whatever) until it stops

5.2. Measure the distance

5.3. Perform the same test with a house in between yourself and the robot to test distance with an object in the way

6. Maintenance and Reliability test

6.1. Create a list of top 5 criteria to monitor

6.2. Watch for the presence of error along any of the 5 dimensions with a total -operation span of 50 hours

7. Cost-effectiveness calculation

7.1. Record costs associated with procuring and operating device over a two year period

7.2. Cost effectiveness = (Estimated operating cost for 2yrs)/(Actual costs operating for 2yrs) x 100

4.2 Revised Timeline & Gantt Chart

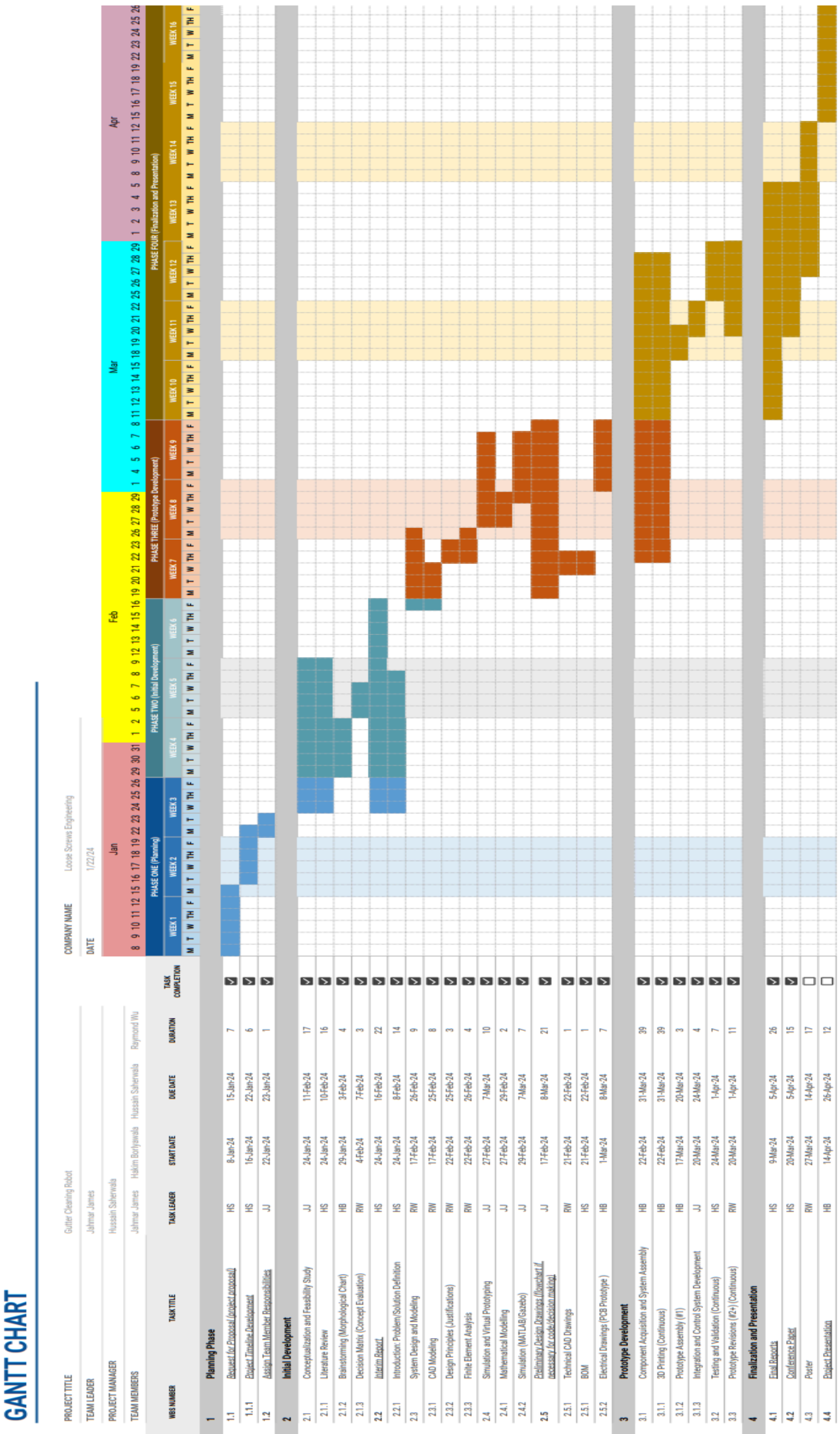


Figure 4: The most recent revision of the Gantt chart as of April 5, 2024.

While designing the Gantt chart, the deadlines were established with the intention of having some contingency to ensure that the timeline was realistic. As progression was made through each stage and updates were provided through frequent meetings, it became apparent that a few of the tasks required adjustment. During the February 5 meeting, the Gantt chart was updated to ensure it matched actual project progress and it was revealed that some tasks required deadline changes. The Problem/Solution Definition task deadline was moved from February 3 to February 8 since the Conceptualization and Feasibility Study task and its respective subtasks were taking more resources than expected to complete. The Literature Review prerequisite subtask deadline was also moved forward from February 11 to February 10 so that it could be completed prior to the Conceptualization and Feasibility Study task. The revised deadlines were adhered to and the tasks were completed on time. At the time of the submission of this report, the Gantt chart shown in the above figure and attached in the submission accurately reflects the progress of the project.

4.3 Guidelines for the Project

Design and modeling:

- Aim for the simplest model that meets all requirements to ensure efficiency and effectiveness.
- Incorporate human-focused design principles to enhance usability and safety.
- Employ system simulation and modeling to minimize component damage risks during assembly and testing.
- Design CAD model with manufacturability in mind

Software management:

- Utilize proven codebases to enhance system reliability.
- Implement hardware abstraction layers (HAL) to provide the flexibility to switch components
- Implement rigorous unit testing to identify and resolve issues promptly.
- Use GitHub for version control to track changes, facilitate collaboration, and ensure code integrity.

Teamwork and Risk Management:

- Conduct regular team meetings with detailed notes to track progress and adhere to weekly deadlines.
- Assign a lead for each subsystem to ensure focused expertise and accountability.
- Maintain flexibility for scheduling additional work, including weekends, to meet project timelines.
- Proactively identify potential risks and develop mitigation strategies, conduct FEMA
- Include contingency plans for critical components and milestones.

Stakeholder Engagement:

- Regularly update stakeholders on progress, challenges, and decisions to ensure alignment and gather feedback.

Documentation:

- Maintain comprehensive documentation for all aspects of the project, including design decisions, codebase, and meeting outcomes.

5. Design Conceptualization

5.1 Brainstorming & Embodiments

Table 7. Morphological Chart

SYSTEM	DESIGN 1	DESIGN 2	DESIGN 3	DESIGN 4	DESIGN 5	DESIGN 6
Debris Removal Mechanism	Scoop	Slide / Conveyor	Auger/Mulcher (mulch +* toss)	Rotary mechanism (Toss)	Snake/Worm (combine motion and removal)	Water /Air Jets (pressure washing)
Waste Collection and Disposal	Bag	Knock to the floor (None)	Waste Canister	Waste Ejection Hose / Chute/Impeller	Continually push debris until end	Incineration
Power Management Unit	Battery	Water (hydraulic pressure)	Engine (Gas/Diesel)	Semi Manual	Wall power (electrical outlet)	Wind-up spring
Motion	Wheel	Track	Snake / Worm	Drone (aerial)	Propeller (flooded gutter)	Robotic Legs (hexapod)
Turning system	Rotary Mechanisms	Flexible body	Compliant mechanism	Segment bodies	Mecanum wheels	Human turner
Mechanism to get onto the roof	Pole	Shingles type lift	Flight	Friction Climbing	Placed on via ladder	Magnetic Assisted tracks

Structural and Mechanical Housing	Recycled plastic (PLA)	Plexiglass (acrylic tube with epoxy resin)	Sheet Metal	Thermoplastic Polyurethane (3D printed TPU)	Pressure Treated Wood	Carbon Fiber

Based on the morphological chart above, team members created the following 8 designs with various embodiments.

Design 1:

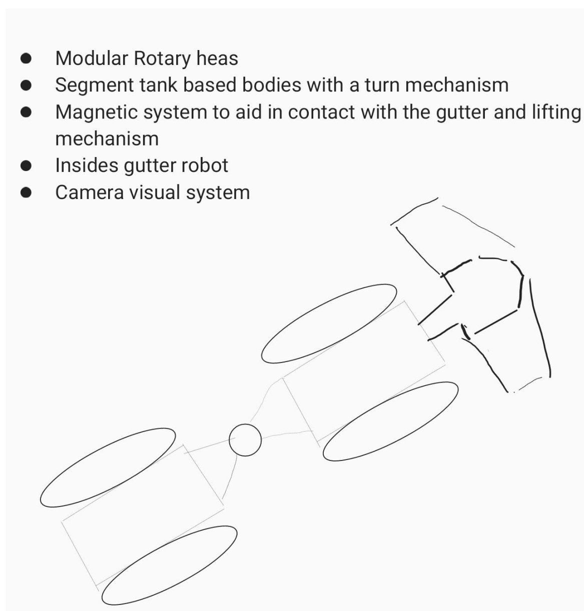


Figure 5: Design 1.

Design 1 as shown above in Figure 5 is similar to the iRobot Looj 330 device with some well needed modifications. To start, just like the Looj 330, design 1 is an inside gutter cleaning robot. It uses a modular rotary head to remove debris, uses a tank track style system to move, and has a segmented body to allow it to turn corners in the gutter. The rotary head can be swapped with different head attachments to suit the need of the gutter the robot is in (eg: longer, wider, shorter, smaller heads). The design also implements the use of a camera so the user can see obstacles and know the progress of the cleaning. The track motion system is also magnetic allowing the robot to potentially climb up the side of the gutter downspout and into the gutter, preventing the need of a ladder to place it in the gutter. The device is powered by a battery and is made from composite materials. Design 1 serves as a source of inspiration for practicality, with a low risk of loss while in operation. It is relatively easy to maintain, offering flexibility and modularity with the rotating head. However, there may be challenges in tight spaces, and uncertainty about the ability to turn. The system will require a substantial amount of energy for climbing up the gutter, but may not be sturdy enough to support the robot. The joint is a critical area prone to potential breakage. Additionally, the disposal of messy debris off the side of the roof poses an inconvenience as the user would still need to clean and dispose of it accordingly.

Design 2:

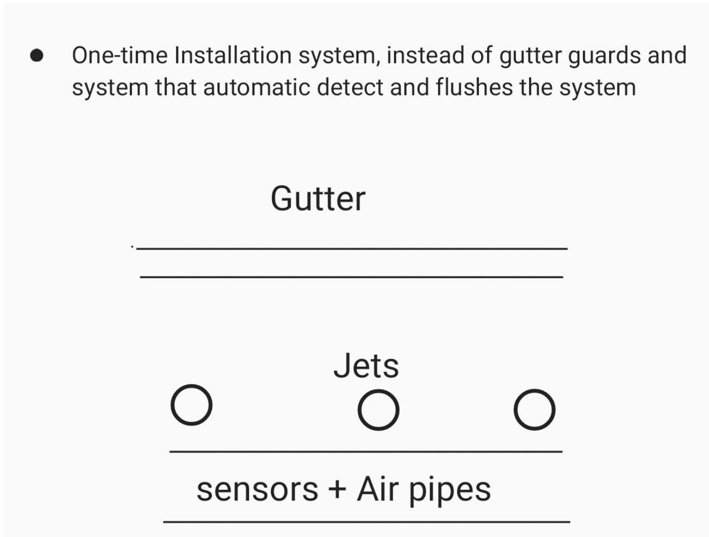


Figure 6: Design 2, self cleaning gutter system.

Design 2 is a unique solution which strays away from the mobile robot model and ventures towards a complete redesign of the rain gutter. The self cleaning gutter system as seen in Figure 6, would consist of a sheet metal rain gutter with sensors and air/water pipes that would detect the presence of debris. Once debris was detected the system would activate and high pressure air/water (powered by hydraulic pumps) would jet from the pipes and flood/flush out the debris from the gutter into the downspout. This would ensure a thorough cleaning of the gutter systems. The system offers a one-time installation, features few moving parts, requires minimal end-user involvement, and utilizes hot pipes to prevent the gutter freezing in winter similar to heated driveways. However, the system is costly, incompatible with existing infrastructure, and susceptible to weakening of pipes in cold areas.

Design 3:

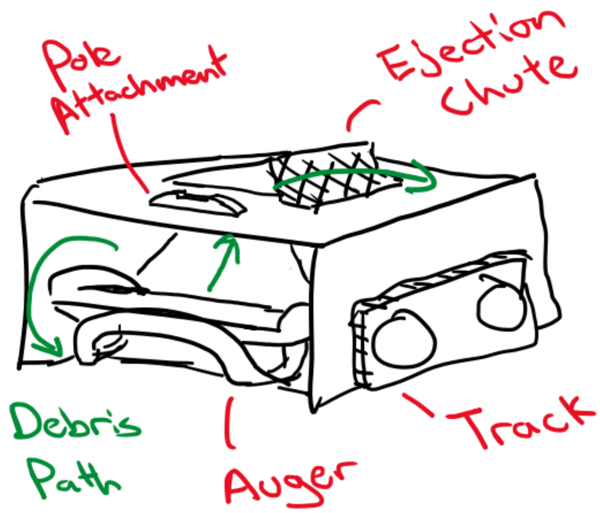


Figure 7: Design 3, mobile auger.

Design 3, shown above in Figure 7, is an in gutter design and uses the working principle of single stage snowblower auger to simultaneously sweep and eject debris out of the ejection chute. The design also features tracks for motion, a pole attachment so it can be placed in the gutter via a pole. The device is powered by a battery and is made from PLA. During operation, once the device reaches a corner, the user must climb and ladder and manually turn the device onto the other gutter. The system eliminates the need to climb a ladder, reducing the fall hazard. Its compact mechanism fits inside any gutter, and its simple, robust design allows for reinforcement. Good traction facilitates material pushing if removal is not feasible. However, manual placement with a pole demands physical strength. Manual turning is necessary on corners, and there's messy debris disposal off the roof's side. Objects exceeding the intake dimensions can only be pushed, not removed. There's also a potential for clogging due to the narrow chute.

Design 4:

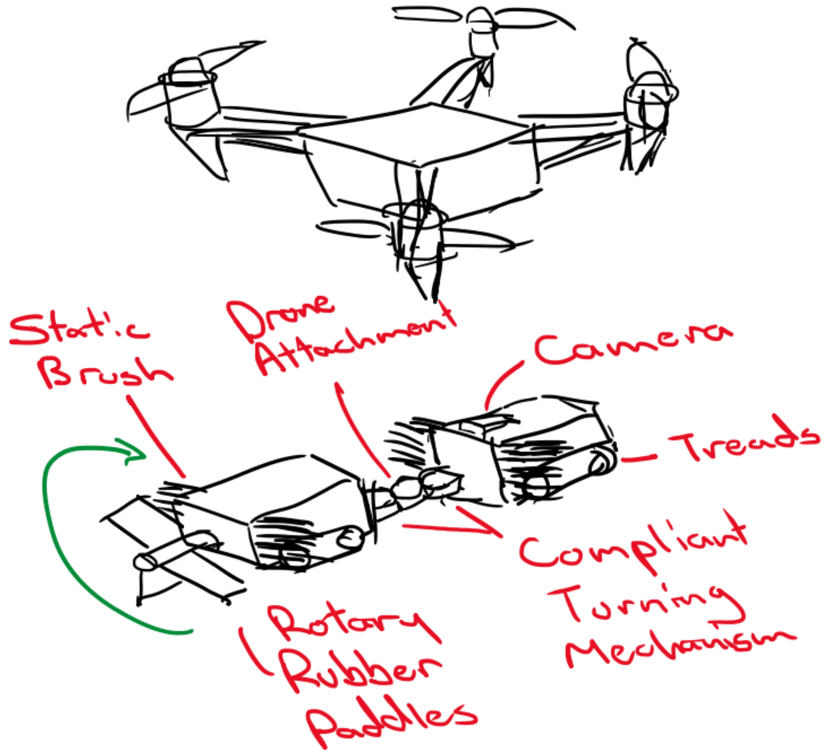


Figure 8: Design 4 uses a drone for deployment in the gutter.

Design 4 as seen in Figure 8 above, is an in-gutter device that's powered by a battery and made from PLA. The device shares similarity with the Looj 330 by having a high speed rotary paddle mechanism to knock the debris to the floor. The device is also unique in the sense that the body has a compliant mechanism and moves via a track system and allows for turning. The device would be deployed onto the roof (in the gutter) via a drone. It also has a camera to provide the user a visual status of the gutter. The design has a combination of rotary rubber paddles to remove large objects and static (non-moving) brushes to scrape the sediment from the sides. The system eliminates the need for physical strength or climbing. Its modular design allows for enhanced functionality with one or two modules, such as increased battery life, motor power, and a camera for remote job status monitoring. However, the higher complexity introduces more potential points of failure. Operation may require familiarity with quadcopter drone operation if not autonomous. Coordinating a powerful drone to lift and attach modules is necessary, making it an expensive build.

Design 5:

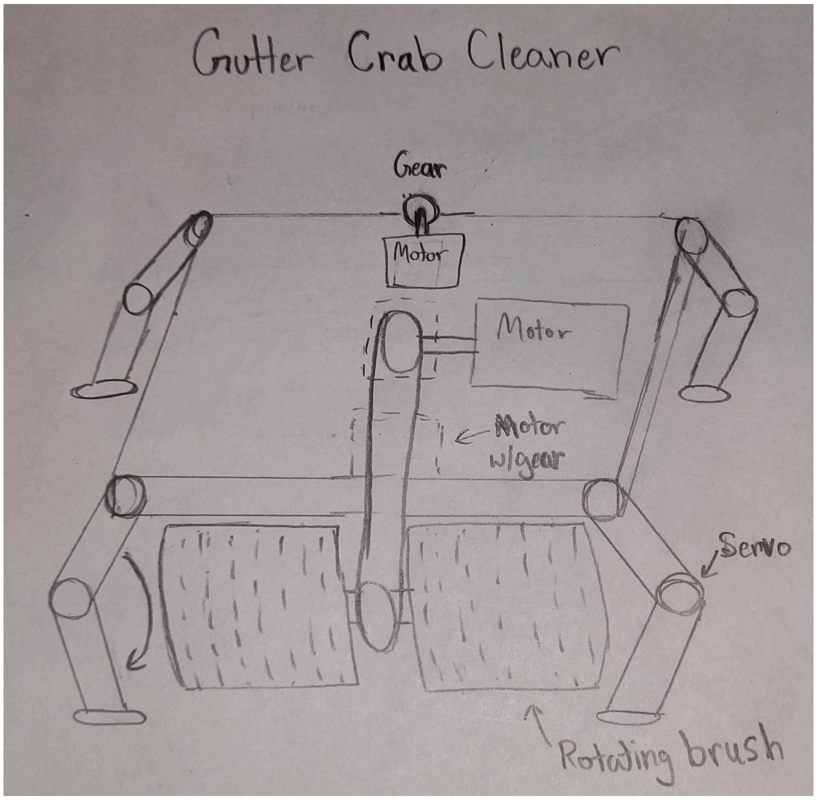


Figure 9: Design 5, Gutter Crab cleaner.

Design 5, known as the Gutter Crab, seen in Figure 9 above is an in gutter device, powered by a battery and made with recycled plastic. It consists of a flat base with a slot cut out the center to allow the a motor, and motor belt to go through to spin the brush (rotary mechanism) which removes the debris. The robots' legs are oriented sideways (like a crab's leg) operated by motors and a chain of gears. Legs can be orientated diagonally on the corners to allow for better turning. Device is placed in the gutter by the user via a ladder. The system features a novel motion design, with sideways legs that enhance maneuverability in narrow spaces, elevations, and turning. Additionally, a high-speed brush facilitates the disposal of gutter trash over the side. However, the motion mechanism is complicated due to the gear chain, additional motors, and servos, making it potentially fragile. The brush operated by a belt can be a point of failure, and the system is only compatible with certain gutter shapes. The use of a ladder is deemed unsafe, and there is a significant reliance on numerous motors, resulting in added weight and energy consumption. Additionally, despite the system's functionality, manual cleanup may still be required afterward.

Design 6:

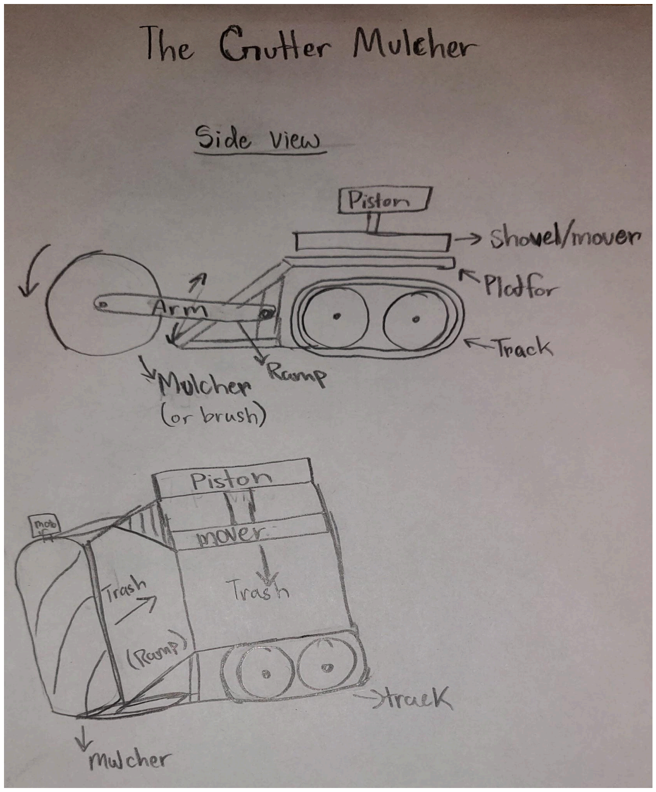


Figure 10: Design 6, Gutter Mulcher cleaner.

Design 6, known as the Gutter Mulcher, seen in Figure 10 above is a battery powered, in gutter/on roof device made from plexiglass. The design features a mulcher/auger (rotating) connected to a raising arm on a track driving base. The arm comes down onto the debris, mulches debris and moves it up the ramp onto the platform, a moving mechanism then pushes the debris off the side of the gutter (ejection). The ramp can have a conveyor belt to help debris move onto the platform. The device would be placed on the roof/in the gutter by the use via a shingles lift. The system offers the advantage of a raising arm, facilitating the cleaning of tall piles of debris. Its durable track provides better traction, and the move/push clearing mechanism efficiently removes large amounts of debris at a fast pace. However, the move/push operation requires significant power consumption. The addition of a raising arm introduces complexity and increases the potential for failure. Turning corners can be challenging with a wide mulcher, and manual cleanup is still necessary after operation.

Design 7:

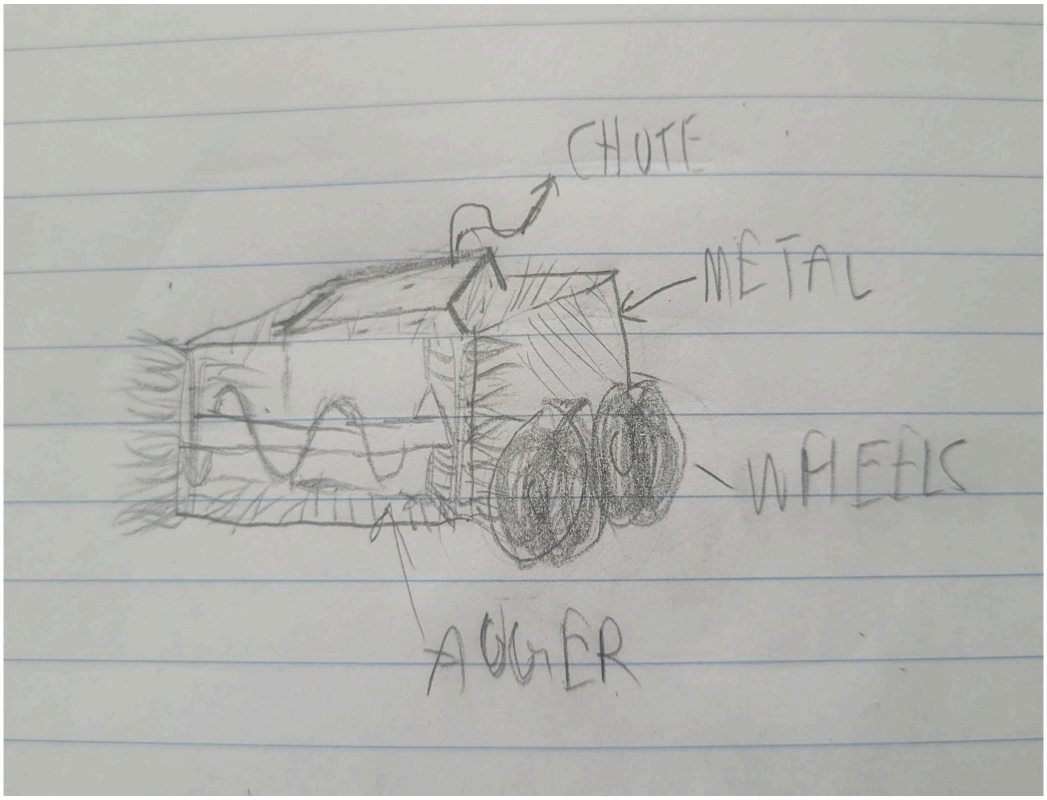


Figure 11: Design 7 sketch.

Design 7, as seen in Figure 11 above, is a wall outlet powered (plug in), in gutter device made from sheet metal. The design features a mulcher, crushing all materials passing through it. The mulcher's hair-like fins lead guide debris into its mouth, and the high spin speed crushes the debris which then gets ejected out the chute. The device is placed into the gutter by the user via a ladder, and requires the user to manually turn it at corners. The device moves with high traction wheels on either side. The system efficiently mulches debris, reducing the likelihood of blockages, and the resulting mulched material is easier to clean up. Its reliance on wall power ensures constant performance in the mulcher. However, the system is heavy and requires manual mounting. A constant connection via a wire is necessary, and manual turning is also required. There's a risk of damaging the gutter, and potential for clogging is present.

Design 8:

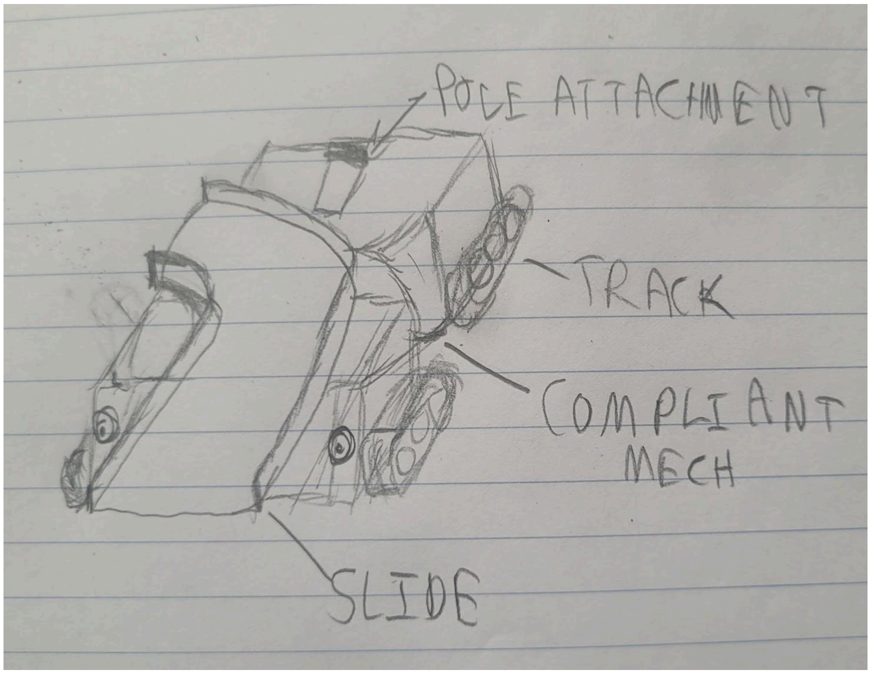


Figure 12: Design 8, slider sketch.

Design 8, known as the slider, seen above in Figure 12, is a gutter wall outlet powered device. The device consists of a slide that displaces debris from the gutter onto the ground below. It moves via tracks on either side which allows for maximized traction. The compliant mechanism reduces the likelihood of the turning mechanism being jammed. It gets mounted in the gutter by the user via the pole attachment. The device would be primarily made from carbon fiber. The sliding mechanism simplifies the gutter cleaning process, and the use of tracks ensures better contact, increasing motion reliability. However, the system requires a constant connection to wall power. It may not be as thorough in cleaning, and clearance with the gutter hangers could be problematic. Moreover the device needs to be oriented correctly to ensure proper functionality.

5.2 Decision Matrix

	Rating (0 Bad - 5 Good)					
	0	1	2	3	4	5
Cleaning Efficiency (Hanlde different types of debris)	0 (Ineffective): Struggles to remove even light debris like dry leaves; frequently leaves behind materials, requiring additional manual cleaning. Incapable of dealing with wet debris or compacted sediment.	1 (Limited Efficiency): Can remove some light debris such as dry leaves but fails to effectively handle twigs, wet leaves, or sediment. Often requires multiple passes or manual intervention for satisfactory cleaning.	2 (Adequate): Adequately removes dry leaves and lighter debris but struggles with wet leaves, twigs, and sediment. May leave residue behind, necessitating occasional extra cleaning efforts.	3 (Good): Effectively clears dry leaves, twigs, and most wet debris. Might have minor difficulties with heavily compacted sediment but generally performs well without needing many repeat passes.	4 (Very Good): Very efficient at removing a wide range of debris including dry leaves, twigs, wet leaves, and most sediment. Rarely leaves residue behind, ensuring clean gutters with minimal effort.	5 (Excellent): Excellently designed for gutter cleaning, effortlessly removing all types of debris, including compacted sediment, in a single pass. Ensures thoroughly clean gutters without the need for re-cleaning or manual intervention.
Energy Usage (Mechanical Adv, Need few eletronics, type pf power system)	0 (Very High Usage): Consumes excessive power for operation, significantly increasing operating costs. Unsustainable for long-term use, potentially due to inefficient motors or mechanisms requiring constant high power.	1 (High Usage): Uses more power than average, making it less efficient and cost-effective. Could be due to lack of energy-saving features or the use of high-power motors without sufficient justification.	2 (Moderate Usage): Energy consumption is reasonable but could be improved. The robot may lack optimized energy management or use slightly outdated technology that does not maximize efficiency.	3 (Low Usage): Efficient in power usage with some energy-saving features implemented. The design is thoughtful in its power consumption, using efficient motors and mechanisms that do not waste energy.	4 (Very Low Usage): Highly energy-efficient with advanced energy-saving technologies. Incorporates features like regenerative braking, optimized power management, and uses the latest efficient motors.	5 (Exceptional Efficiency): Sets the standard for energy efficiency, potentially using innovative energy generation or storage techniques. Operates with minimal power without compromising performance, possibly through ultra-efficient design and cutting-edge technology.
Durability (complcity, point of faluire, water protection, shock etc)	0 (Very High Risk): Multiple evident points of failure; components are highly susceptible to damage even under normal operation. Unlikely to withstand minor stresses, let alone a fall from the roof.	1 (High Risk): Several potential points of failure identified; components may not endure regular usage without significant wear or damage. Durability concerns that could lead to frequent maintenance or part replacement.	2 (Moderate Risk): Some points of failure are apparent, suggesting that while the robot can handle normal operations, certain components may be at risk. There are concerns about its ability to withstand accidental drops or prolonged use.	3 (Resilient Design): Fewer points of failure with a design that appears robust for most operational conditions. Components are selected or designed to endure normal usage and possibly minor accidents without substantial damage.	4 (Highly Durable Components): Very few potential points of failure, with components that seem capable of withstanding significant stress. The design suggests that it could likely survive a fall from the roof with minimal damage.	5 (Exceptional Durability): No apparent points of failure; the design incorporates highly durable components and protective measures, ensuring resilience against falls, operational stress, and extended use. Indicates a thoughtful approach to minimizing wear and damage risks.
User Interaction (potential for automation, few actions, climing onto roof , turn corner, weight)	0 (Highly Complex): Expert knowledge needed; significant manual setup and operation with high risk of error due to complex mechanisms and imprecise control.	1 (Complex): Steep learning curve; requires specific skills for manual operation and handling, with moderate imprecision issues.	2 (Moderately Complex): Some user knowledge required; occasional control and precision issues, with effort needed for setup and removal.	3 (User-Friendly): Straightforward and functional; minimal issues with precision, reasonable effort for manual handling.	4 (Intuitive): Easy and intuitive operation; minimal manual interaction, easy setup and removal, good control precision.	5 (Highly Automated & Intuitive): Minimal user intervention; highly precise and automated, extremely easy to setup, operate, and handle for all users.
Maintenance and Reliability	0 (Very High Maintenance & Low Reliability): Mechanically complex with difficult access for maintenance. Fragile components prone to frequent failure, unsuitable for intended heavy or regular usage.	1 (High Maintenance & Reduced Reliability): Significant mechanical complexity and limited maintenance accessibility. Components relatively fragile, affecting reliability for intended usage.	2 (Moderate Maintenance & Variable Reliability): Moderate mechanical complexity with some accessibility challenges. Some components may be fragile, leading to occasional reliability issues in intended usage.	3 (Low Maintenance & Good Reliability): Reasonably simple mechanics with accessible maintenance points. Durable components suitable for intended usage, ensuring reliable performance.	4 (Minimal Maintenance & High Reliability): Low mechanical complexity with easy access for maintenance. Robust components well-suited to intended usage, offering high reliability.	5 (Negligible Maintenance & Exceptional Reliability): Simplest mechanical design with excellent accessibility for any needed maintenance. Highly durable components, ensuring exceptional reliability for all intended usage scenarios.
Cost-effectiveness	0 (Prohibitive Cost): Extremely high manufacturing, operating, and maintenance costs make it economically unfeasible for most users or scenarios.	1 (High Cost): Significant costs associated with manufacturing, operation, and maintenance, limiting its affordability and practicality.	2 (Moderate Cost): Reasonable manufacturing cost with moderate operating and maintenance expenses. Offers some value but with noticeable cost concerns.	3 (Cost-Effective): Balanced manufacturing cost with low operating and maintenance expenses. Provides good value for the investment.	4 (Highly Cost-Effective): Economical manufacturing with very low operating and maintenance costs. Delivers excellent value and long-term savings.	5 (Exceptional Value): Minimal manufacturing, operating, and maintenance costs. Offers unparalleled cost-effectiveness and return on investment.

Figure 13: Metric used to compare design concepts.

The mentioned design concepts underwent evaluation utilizing the decision matrix criteria illustrated in Figure 13. Six criteria were carefully selected and assessed on a scale ranging from 0 to 5, with 0 representing a low value and 5 indicating a high value. The chosen criteria encompassed cleaning efficiency (the ability to handle various types of debris), energy usage (inclusive of electronics necessity, power system type, and mechanical advantage), durability (considering complexity, points of failure, and protection against water and shock), user interaction (evaluating potential for automation and user actions required for placement and operation), maintenance and reliability, and cost-effectiveness. With the use of the decision matrix the initial eight concept designs were narrowed down to four designs. The order, from highest score to lowest was design 1, design 8, design 2 and design 6.

Stage 1 Design concept review: (After presenting to supervisor Dr. Bill Lin)

During the meeting with Dr. Lin, the four design concepts identified through the decision matrix were presented. The specifics of three distinct design approaches were explored, each design approach was critiqued for its feasibility and innovation potential, summarizing their inherent challenges and mechanical novelties. The design approaches are as follows, deploying a robot inside the gutter, a robot on the roof, and considering a redesign of the gutter for automation, essentially enabling self-cleaning functionality. Each approach presents its unique set of challenges. For instance, with a robot situated inside the gutter, challenges include fitting all components within the confined space, navigating 90-degree turns, and accommodating multi-stage gutters. In the case of a robot on the roof, issues such as instability while climbing or maneuvering on various inclined surfaces and the need to support gutter beams arise. Meanwhile, the redesign of the gutter for automation introduces challenges related to cost, increased complexity, and the infrastructure required for seamless integration, particularly with multi-stage gutters. Each design approach introduces distinct mechanical novelties to address specific challenges. The robot inside of the gutter proposes a unique pole attachment system for precise placement and corner maneuvering, coupled with a specialized debris removal mechanism designed for the semi-solid matter typically found in gutters. The robot on top of the roof focuses on pioneering climbing and maneuvering techniques to ensure stability and mobility on inclined surfaces. Lastly, the redesign of the gutter for automation suggests reconfiguring gutter shapes for improved debris flow and aesthetic appeal. This design also envisions integration with the house's HVAC system and the incorporation of a detection and jet system for routine gutter clearing. Each mechanical innovation contributes to the overall effectiveness and efficiency of its respective design approach.

Near the end of the discussion some alternate solutions were devised. The proposed design pathways included a multimodal robot which could operate within the gutter, climbing onto the roof to get around corners and access multiple levels of the gutter. Additionally, the idea of a dual robot system was introduced, it would employ a collaborative approach, with one robot situated within the gutter and another on the roof, each robot specializing in specific aspects of gutter maintenance.

Moving forward, the concept of a mobile robot (either on the roof/in the gutter/or both) will be pursued and be compared to the final mobile robot design to the self cleaning gutter system concept. Throughout this process various ideas will be tested to gauge their feasibility and will focus more on physical testing rather than simulated testing as for the debris removal system. As an approximation of the nonlinear nature of the plant the base debris are not likely to be transferable in practice. Simulations of the turning mechanisms and maneuverability of the robot on the roof is possible.

Chapter 2 - Prototyping, Benchmarking and Testing

Debris Removal System

1.1 Initial Test - Proof of Concept

After much discussion, it was decided to conduct proof of concept tests on various debris removal systems (components) such as the 45 degree ramp/slide, various augers and rotors, fans and a brush as seen in Figure 14 below. These systems originated from the initial concept designs which can be seen in the design conceptualization section of the report.

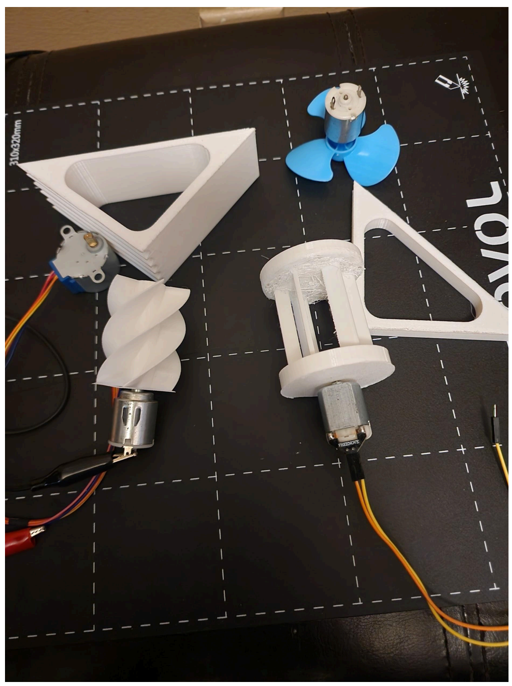


Figure 14: Top row (left to right); wide 45 degree ramp, fan, bottom row; threaded rotor, bladed rotor, narrow 45 degree ramp.

Solidworks was used to design the debris removal systems which were then 3D printed. A 2.5 ft segment of gutter was used for testing to simulate real life operation. In the experiment, debris was collected including leaves, small twigs, and other organic matter, which was then added to the gutter for testing. A small motor was employed (DC 3V-6V 130 Motor 15000 RPM), powered by a 9V battery, to generate rotary motion for specific debris removal systems.

These systems, attached to the motor's axle, were systematically tested within the gutter to evaluate their effectiveness in removing debris. To simulate the anticipated driving mechanism of the robot, a team member manually pushed each debris removal system, whether motorized or not, through the gutter as seen in Figure 15 below. This method allowed assessment of the functionality and efficiency of the various systems in a simulated real-world scenario.

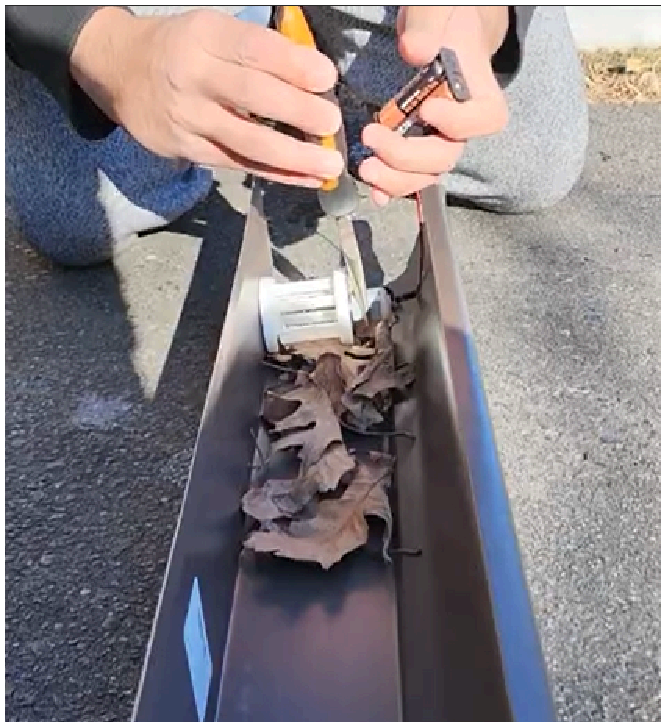


Figure 15: A bladed rotor debris removal system attached to a motor held on by needle nose pliers.

The results of the initial test on Feb 20th are as follows:

Ramps - The efficacy of the ramps in facilitating debris clearance was found to be suboptimal. The intended outcome was for the debris to be propelled upward along the ramp; however, it instead traversed further along the gutter. Additionally, the dimensions of the ramps posed challenges, as they were either excessively elevated or elongated for proper maneuverability within the gutter. Consequently, due to these inherent limitations and operational hurdles, the concept of utilizing ramps for debris clearance was ultimately discontinued.

Threaded rotor - The thread rotor exhibited greater potential compared to the ramp. Leveraging its thread, it managed to dislodge several small debris fragments, but proved inadequate for clearing larger pieces or significant volumes of debris. Moreover, once large and heavier debris was encountered the motor stalled and stopped spinning. Upon assessment, it was concluded that even with a stronger/faster-spinning motor and larger threaded rotor, the debris would not be ejected over the edge in sufficient quantities. Rather, it would persist in rotating within the gutter, possibly fragmenting into smaller pieces.

Fan - The testing involved a compact fan with dimensions (specify diameter or other dimensions) chosen for its intended task of dislodging debris from the gutter. Regrettably, its performance fell short of expectations. The fan's modest size and motor speed proved inadequate for generating the requisite force to clear the debris. Instead of effectively removing it, the fan blades inadvertently sliced through the debris, diminishing its size. Furthermore, during maneuvering within the gutter, the rotating blades collided with the gutter walls. Initial assessments highlighted the need for a larger fan with more substantial blades and a robust motor to achieve the desired force for debris clearance, potentially exceeding the gutter's dimensions. Additionally, concerns arose regarding potential damage to both the fan blades and the gutter caused by the rigid fan blades hitting gutter walls at high speeds. Consequently, this approach was deemed impractical and discontinued.

Bladed rotor - The bladed rotor mimicked an open barrel, featuring slats spaced and angled outward to capture and expel debris as it rotated. However, practical testing revealed shortcomings: upon encountering debris, the spinning rotor either stalled due to insufficient motor torque or failed to effectively engage and displace the debris. It became evident that for the rotor to effectively grip the debris, it would require slats or flaps extending outward, curved to facilitate scooping action. Furthermore, a more robust motor with increased torque would be necessary to overcome the substantial resistance posed by the weight of the debris and ensure adequate rotation of the rotor.

The tests conducted on rotor designs have yielded valuable lessons for future iterations. It is evident that future rotors must be equipped with features such as extended slats or flaps, curved to optimize debris engagement and removal. Additionally, a stronger motor with higher torque capabilities is essential to overcome resistance from heavier debris loads and prevent stalling during operation. Design optimization is crucial to ensure smoother rotor performance and minimize the risk of stalling upon encountering debris. Moreover, careful consideration must be given to balancing rotor size with practical constraints such as gutter dimensions, to avoid potential damage while maximizing debris removal capacity. Integrating these lessons will be paramount in developing more efficient and effective rotor designs for gutter maintenance.

1.2 Second Test - March 3

Prior to the second test three new rotors were designed and 3D printed based on the lessons learned from the initial test. The designs are all variations of curved rotors as follows, Figure 16, is rotor M1, Figure 17 is rotor M2, and Figure 18 is rotor M3. Additionally, a whisk-style rotor was devised to facilitate the scooping of debris, as illustrated in Figure 19 below.

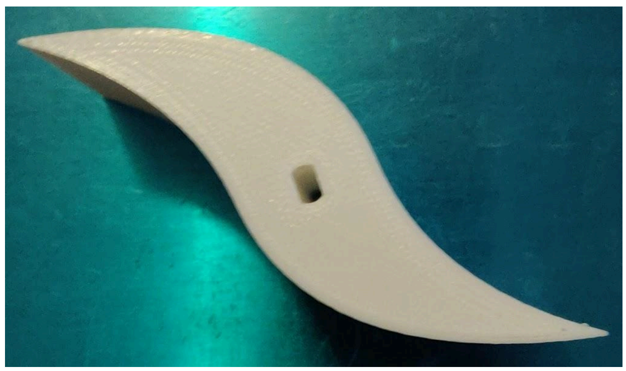


Figure 16: curved rotor M1

Figure 17: curved rotor M2

Figure 18: curved rotor M3

Figure 19: Whisk rotor

Furthermore, alongside the introduction of the new rotor designs, a 28byj-48 stepper motor was employed to rotate the rotors. This stepper motor provided greater torque compared to the previous motor, albeit at a slower pace. Additionally, rubber and foam flaps were affixed to the blade tips of the rotors (M2-M3 and whisk) to enhance their scooping capabilities. Also, for the current testing phase, a jig was devised and utilized to securely position the motor and power source, streamlining the testing process. Lastly for certain rotors, based on their performance on dry debris clearing tests, wet debris tests were conducted.

The results of the initial test on March 3rd are as follows:

Dry Testing

M1 - The M1 was based on the design of a snow blower auger, featuring a curved profile with 2 blades aimed at scooping debris from the gutter, similar to the mechanism used by snow blowers to collect snow. The rotational speed of the rotor was intended to propel the scooped debris off the side of the gutter, effectively clearing it. However, upon initial manufacturing, it was discovered that the M1 rotor was too large to fit within the gutter. Subsequently, a scaled-down model was produced. During dry testing, it was observed that while the M1 rotor could push debris effectively, it struggled to scoop it. Although the stepper motor provided adequate torque to prevent stalling, its slow speed hindered the rotor's ability to eject debris. Given its unsatisfactory performance during dry testing, the M1 rotor was not chosen for wet testing.

M2 - The M2 rotor, also inspired by the design of a snow blower auger, featured a curved profile with four blades, aiming to scoop and eject debris from the gutter, mirroring the purpose of the M1 rotor. However, during dry testing, it became apparent that the M2 rotor faced similar challenges to the M1 in effectively scooping debris. To address this issue, foam flaps were added to two blades of the M2 rotor to aid in debris scooping, as depicted in Figure 20. The rationale behind this modification was to extend the reach of the blades and enable them to scrape debris from the corners and sidewalls of the gutter without causing damage. Despite these adjustments, subsequent tests revealed that while the foam-enhanced rotors could easily move debris, they still struggled to scoop it effectively. This limitation was attributed to the insufficient curvature of the rotor blades, which failed to provide a suitable pocket for trapping debris. Additionally, the slow speed of the stepper motor hindered the ejection of debris from the gutter. Consequently, based on these findings, the M2 rotor was not chosen for wet testing.

Figure 20: M2 rotor with foam flaps

M3 - The M3 rotor, similar to its predecessor M2, featured a curved profile with four blades that tapered and curved more prominently towards the tip. Prior to dry testing, foam flaps were affixed to the M3 rotor, extending from its tip as depicted in Figure 21. Throughout testing, these flaps effectively maneuvered debris and frequently overturned it. However, the slow motor speed hindered the rotor's ability to eject debris over the side of the gutter. It was observed that the compliance (flexibility) of the foam flaps facilitated debris scooping. Furthermore, it was noted that employing more compliant flaps would enhance debris scooping, as they could effectively drag along the gutter profile, ensuring thorough removal of debris from all edges and corners. This discovery regarding the effectiveness of the flaps resulted in subsequent design iterations for the debris removal system, aiming for improvement. Despite these advancements, due to its performance limitations, rotor M3 was not chosen for wet testing.

Figure 21: M3 rotor with foam flaps

Whisk rotor - The whisk rotor, inspired by the design of a snow blower auger blade, featured individual auger blades flaring outwards in an attempt to scoop debris. Building on insights gained from testing the M3 rotor, a foam strip was inserted between the gaps of the blades of the whisk rotor to create a single large flap crossing through the rotor, as illustrated in Figure 22. During dry testing, these flaps effectively overturned debris and occasionally ejected some off the side of the gutter. However, it was noted that despite the compliance of the foam flaps, they exhibited slight stiffness, causing occasional sticking during rotation and bending to the extent that the rotor lifted the testing jig before becoming unstuck and ejecting the debris. Despite this challenge, the whisk rotor with foam flaps was chosen for wet testing.

In addition to the foam flaps, a rubber flap salvaged from a thin rubber mat was fitted onto the whisk rotor, seen in Figure 23. The rationale behind the rubber flap was to provide greater flexibility than the foam flap, allowing for the overturning and ejection of leaves without becoming stuck in the gutter and lifting the jig. However, during dry testing, the rubber flap only managed to overturn a small amount of debris due to the rotor's slow rotation speed. It became apparent that the rubber flap was too flexible and lacked the ability to displace a significant amount of debris. Consequently, it was determined that a flap material with intermediate flexibility between foam and rubber was necessary for effective debris removal. Moreover, a faster motor was necessary to improve debris cleaning efficiency. The whisk rotor with the rubber flap was selected for wet testing.

Figure 22: Whisk with foam flap

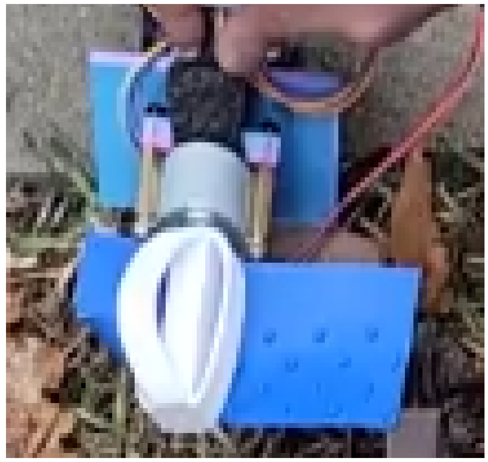


Figure 23: Whisk with rubber flap

Brush - As a proof of concept test the brush rotor was used. A water bottle cleaning brush, as depicted in Figure 24, was affixed to an electric drill for testing purposes. Given that the brush's handle was too large to be coupled directly to a motor's axle, the chuck of the electric drill was utilized to accommodate its size. The concept behind employing the brush mirrored that of the rotors, aiming to overturn and eject debris from the gutter. During dry testing, it was noted that the brush effectively overturned and ejected some debris, primarily due to the high speed of the drill. Consequently, it was chosen to proceed with wet testing.

Figure 24: Brush

Zip Tie rotor - As part of a proof of concept test, the zip rotor was developed. This rotor utilized zip ties as flaps, with 2-4 zip ties evenly spaced and secured around the curve of the wheel as seen in Figure 25. Powering the rotor was a Dc 5V toy motor, as seen in Figure 26. During dry testing, the rotor demonstrated remarkable efficiency in dislodging and ejecting the majority of debris from the gutter at a high speed. A key factor contributing to the rotor's performance was the motor itself. The toy motor, being notably faster than the stepper motor used in previous tests, possessed sufficient torque to avoid stalling when encountering debris. Additionally, the zip ties exhibited optimal flexibility and durability, enabling them to scrape the gutter sides without causing damage or becoming stuck. This testing revealed that the toy motor boasted an ideal speed-torque ratio for effectively dislodging debris, while the zip ties proved to be highly effective flap materials. As a result of its impressive performance, the zip tie rotor was selected for wet testing.

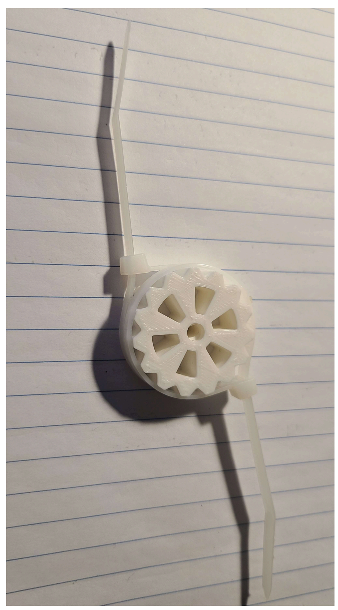


Figure 25: Zip Tie rotor

Figure 26: DC 5V toy motor

Wet Testing

The wet testing replicated the setup of the dry testing, utilizing a 2.5ft length of gutter containing some debris. The primary difference was the addition of water poured onto the collected debris to simulate a wet environment. The presence of water served to increase the weight of the debris, compacting it and facilitating adhesion among the leaves.

Whisk rotor (foam flap) - During wet testing, the whisk rotor equipped with foam flaps exhibited poor performance. It struggled to overturn or eject debris, primarily due to the stiffness of the foam combined with the limitations in speed and torque of the motor. The increased weight of the water and the compact nature of the debris further hindered the rotor's ability to effectively operate.

Whisk rotor (rubber flap) - Similarly, the whisk rotor outfitted with rubber flaps experienced limitations. While it managed to overturn some debris, it failed to eject any. Once again, the motor's inadequate force and speed prevented significant debris clearance, particularly in the wet testing conditions.

Brush - The brush rotor, powered by an electric drill, demonstrated strong performance by effectively overturning and ejecting debris. This success can be attributed to the fast speed and high torque output of the drill, highlighting the necessity for rotor motors to possess sufficient speed and torque for effective debris clearance. However, a notable drawback of the brush was the accumulation of wet leaves in its bristles, potentially rendering it ineffective for debris removal if the buildup persisted.

Zip Tie rotor - The performance of the zip tie rotor was notably impressive, efficiently clearing a substantial amount of debris. Utilizing the same DC 5V toy motor as in dry testing, its success can be credited to the well-balanced speed-torque ratio of the motor and the flexibility of the zip ties.

The March 3rd tests provided valuable insights into the design of the debris removal system and the equipment requirements, particularly concerning the motor. It was determined that a high-speed, high-torque motor, such as a DC 5V toy motor, would be essential for effective operation. This robust motor is necessary to provide the requisite speed and torque for overturning and ejecting debris while preventing rotor stalling or obstruction. Additionally, the flap rotor design showed promise, with the potential for increased effectiveness with a stronger motor. Similarly, the zip tie rotor emerged as the most efficient design for debris clearance, owing largely to the flexibility and durability of the zip ties, combined with the speed and torque of the DC 5V toy motor. Consequently, it was decided to further develop the flap and zip tie rotor designs.

Moreover, it was concluded to forego wet testing due to its potential complications for the design. Observations during wet testing revealed that as the rotors overturned debris, they generated small water droplets that could land on the tester and testing equipment, posing a risk of short-circuiting delicate electronics. Adapting the device for waterproof operation in wet conditions would necessitate significant time and resources, exceeding the project's limited scope. Therefore, the decision to abandon wet testing in favor of focusing on dry conditions was deemed justified, aligning with the intended use case for the device.

1.3 Third Test - March 16th

On March 16th, further testing was conducted with an improved rotor design inspired by the insights gained from previous testing. The flap rotor, depicted in Figure 27 and 28, represents a modular debris removal system characterized by an octagonal prism main body featuring four circular pattern slots. These slots accommodate "L" shaped flaps of varying thickness, ranging from 0.6mm to 1.2mm with 0.2mm increments, which can be easily inserted and removed from the main body, secured via a friction fit. Both the flaps and the main body are manufactured using 3D printing. The modularity of the rotor design was implemented to ensure maintainability, with the recognition that flaps may become damaged over time during device use. By employing a replaceable flap system, the lifespan of the device can be extended. The assortment of flap thicknesses serves to determine the optimal balance between thickness and flexibility required for effective debris clearance.

In addition to the new flap design, another improvement implemented for this testing session was the utilization of two types of motors: a mini DC 6V 200 rpm N20 motor, depicted in Figure 29, and a DC 5V toy motor. The rationale behind incorporating two motors was to investigate the impact of different speeds and torques on the cleaning effectiveness of the flap rotor. This approach aimed to assess how varying motor characteristics influence the device's ability to clear debris.

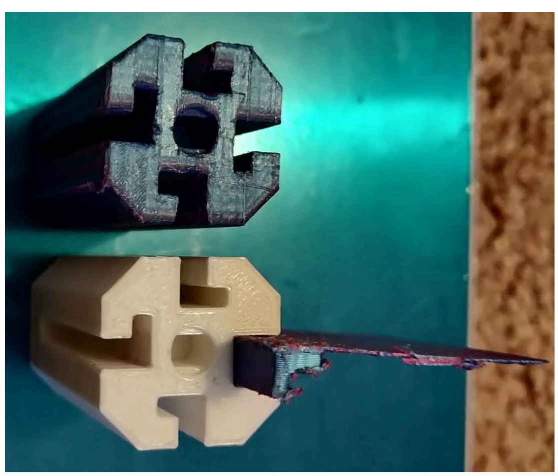


Figure 27: Flap Rotor top view

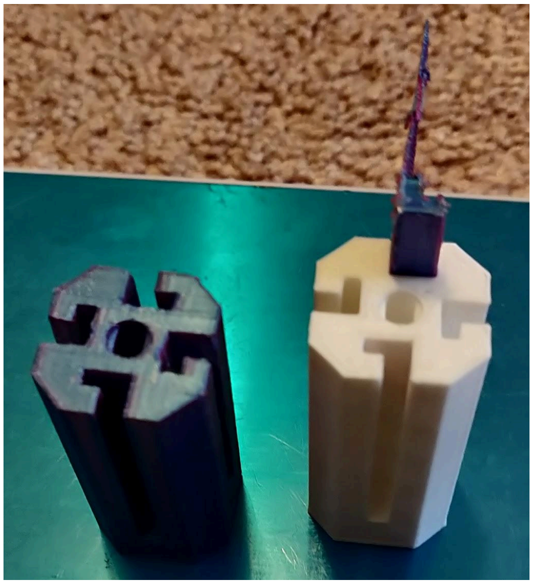


Figure 28: Flap rotor isometric view

Figure 29: Mini DC 6V 200 rpm N20 motor

Initially, the flap rotor was slated for testing with various flap thicknesses. However, upon printing the different flaps and manually bending them, it was observed that flaps ranging from 1.6mm to 0.8mm lacked the necessary flexibility to bend effectively in the gutter. Consequently, the focus of the testing shifted towards evaluating the 0.6mm flap, which exhibited sufficient flexibility. For this testing session, the test layout underwent a slight modification. Prior to commencing the test, debris, mainly leaves and small twigs, was added to a 2.5ft length of gutter and weighed. The test proceeded with the debris removal system completing one pass through the gutter. Subsequently, the gutter and any remaining debris were reweighed. The difference in debris weight before and after the test was calculated as a percentage, representing the cleaning effectiveness. The test results are detailed in Table 8. Notably, both the 0.6mm flap and the

1.6mm flap were evaluated to determine the contrast in performance between different thicknesses.

Table 8. March 16th cleaning effectiveness testing using various flaps and motors on dry leaves.

Cleaning Tool	Motor	Starting Leaves (g)	Residual Leaves (g)	Cleaning Effectiveness
Flaps (0.6mm)	5V Toy Motor	34	16	52.94%
Flaps (0.6mm)	6V mini N20	34	23	32.35%
Flaps (1.6mm)	5V Toy Motor	34	23	32.35%
Flaps (1.6mm)	6V mini N20	36	32	11.11%

The results obtained from the March 16th test provided valuable insights into the subsequent steps regarding both the design and required testing equipment. It was evident that the toy motor outperformed the mini N20 motor in removing debris, particularly with the 0.6mm flaps, compared to the 1.6mm flaps. Despite the 1.6mm flaps achieving a cleaning effectiveness of approximately 32% with the toy motor, which was three times more effective than with the mini N20 motor, the latter motor struggled to replicate these results, particularly with the 1.6mm flap, due to its slower speed and lower flexibility. Ultimately, the findings emphasized the importance of utilizing thinner flaps and faster motors for future enhancements in the design.

1.4 Fourth Test - March 23rd

The fourth test was conducted on March 23rd, the layout of the test was the same as the test on March 16th using a variation of the flap rotor design introduced in test three. The new flap rotor consisted of a multipart cylinder that had slots to house four 0.36mm flaps and four pairs of zip ties covered with a screwed-on lid, as seen in Figure 30 and 31. A 5V toy motor was used to spin the rotor. Due to the weather conditions at the time (recently snowed) collecting debris to place into the gutter was challenging. Instead, ripped up paper was used to simulate dry debris and was placed into the gutter and weighed. The test was conducted and the data was recorded below in Table 9.

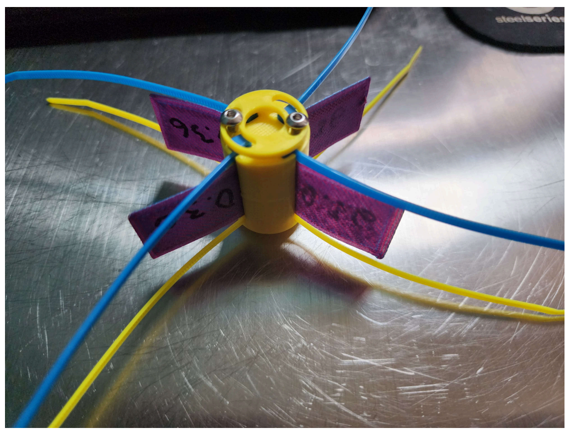


Figure 30: Assembled flap w/zip tie rotor isometric view

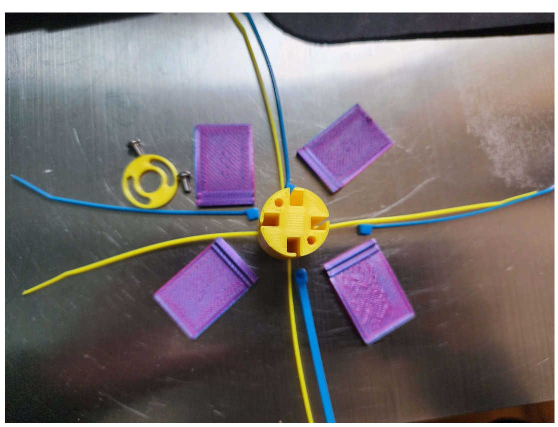


Figure 31: Unassembled flap w/zip tie rotor top view

Table 9. March 23rd cleaning effectiveness testing using a new flap rotor.

Cleaning Tool	Motor	Starting Leaves (g)	Residual Leaves (g)	Cleaning Effectiveness
Flaps (0.36 mm) w/zip ties	5V Toy Motor	29	14	51.72%

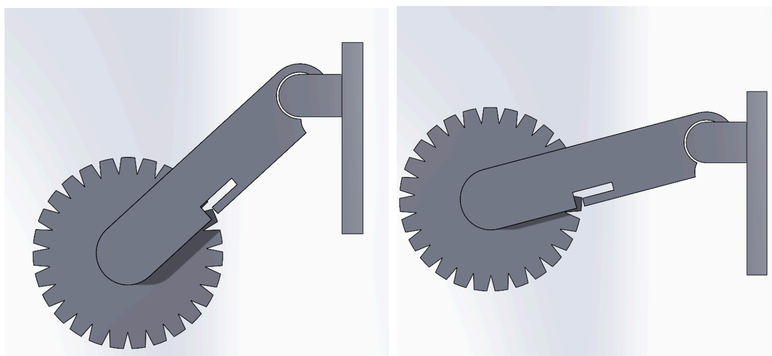
This test showed the efficacy of utilizing a high-speed motor in conjunction with thin flaps for debris removal. However, it was observed that while the 0.36 mm flaps offered flexibility, they lacked durability compared to thicker flaps or zip ties. Notably, the thin flaps tended to crease or deform when manually bent. As a result, for future enhancements, consideration should be given to exploring a zip tie rotor, as zip ties offer comparable flexibility while exhibiting greater durability.

Furthermore, during the test, a 12V DLG 3S RC Lipo battery was employed. At the outset of testing, when connecting the motor wires to the battery, an inadvertent occurrence transpired where one motor pin inadvertently made contact with both the positive and negative terminals of the battery, resulting in a short circuit. This incident generated sparks and briefly ignited a small piece of paper. Fortunately, the spark was short-lived, and the flame quickly extinguished. This experience underscored the importance of following safety protocols when handling batteries and electronics.

Movement/Base System

2.1 Initial Test - Proof of Concept

The main purpose of the movement mechanism is to enable controlled motion of the robot through the gutter as it performs its cleaning operation. It must be powerful enough to move the weight of the robot in addition to the debris in front of it at a desired speed. It must be capable of moving such that it is slow enough to be thorough in its cleaning, yet fast enough to complete it within a reasonable time. In the design of the movement/base system, a major constraint is the size of the robot. Since the robot was decided to be placed inside the gutter, it must physically fit within the constraints/bounds of the gutter profile, including the gutter hanger. This available cross-sectional area is very small and so space efficiency is the main concern in the design. The wheels should also establish contact with the gutter interior at all times to maintain traction throughout the entire operation.



Figures 32.1 & 32.2: Initial suspension design

A prototype suspension system was contrived to satisfy the requirement of ensuring wheels made contact with the ground at all times and prevent the robot from getting stuck when elevated. A single control arm with a tension spring attached applied a constant spring force on the wheel against the ground. As the wheels were depressed, the force enacted on the wheel increased approximately linearly with the amount of displacement. In the event that a wheel was elevated above the ground, the spring would drag it down to re-establish contact and re-enable controlled movement. Unfortunately, the system proved to be too space-intensive and was not utilized in the final design.

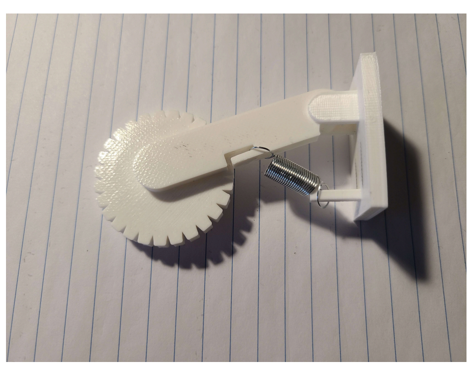


Figure 33: 3D printed suspension prototype

To select the appropriate components comprising the system, an initial configuration was devised and components were tested independently. The initial design consisted of slots for dual stepper motors and slots for the motor housing. The wheels were circular with transverse treads to grip the gutter floor as it moves and divert debris underneath. The turning mechanism used both wheels to turn in opposing directions to achieve the minimum turning radius to navigate the gutter corner. A third non-driven wheel was used to ensure the robot stayed upright while not obstructing movement.

2.2 Second Test - March 3

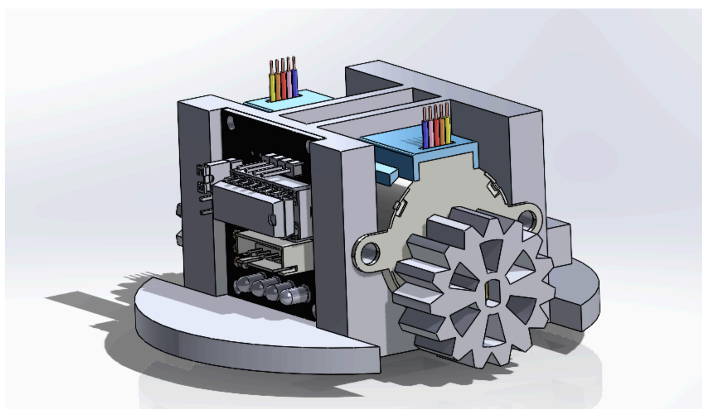


Figure 34: Stepper motor based movement system

From the testing for the debris removal mechanism, it was revealed that the stepper motor used was lacking in both speed and torque. It stalled at the first sign of any resistance and took a significant amount of space. Additionally, the drivers required to power it were separate boards and took up even more space. This left little room for any of the other components. Two motors were required to power both wheels. On the other hand, the DC motor tested had more than enough torque, higher speed, and did not require drivers. It was much more space efficient when compared to the stepper motor. It also had a bidirectional shaft, allowing use of one motor to drive both wheels. The downside with that was that both wheels had to move in tandem like a locked differential. From this round of testing, it was clear that DC motors were superior for this application and procurement for even smaller motors began.

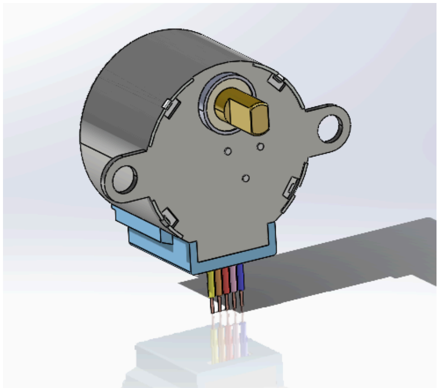
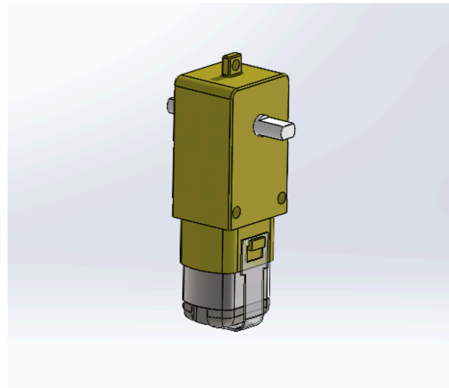
 

Figure 35.1 & 35.2: Stepper motor and yellow gearbox motor (respectively)

With the knowledge that a relatively heavy debris removal mechanism would be required, the center of gravity was considered. A similarly heavy battery will be located at the center or rear of the robot and a front non-driven wheel will provide support for the front-heavy robot. A ball caster wheel was selected due to its ability to roll in any direction without resistance yet provided vertical support when loaded.

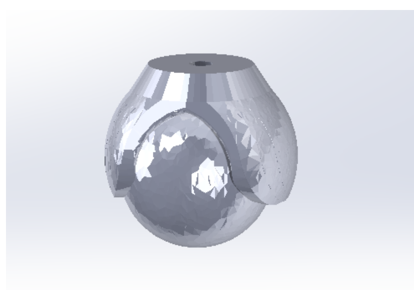


Figure 36: Swivel ball caster roller

For wheel selection, a primitive 3D-printed design resembling a spur gear was used as a placeholder. The intention for the final design was to add a rubber coating or another intermediate material on the outside to further enhance traction. The center of the wheel was adapted for the motor shafts of both motor types for testing, and additional holes were placed into the design to save on material and printing time.

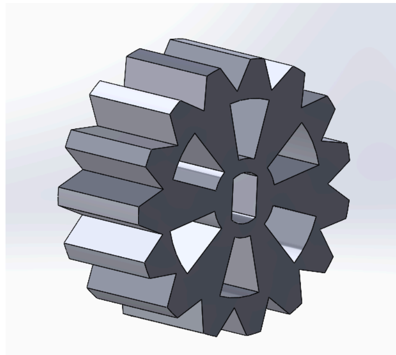
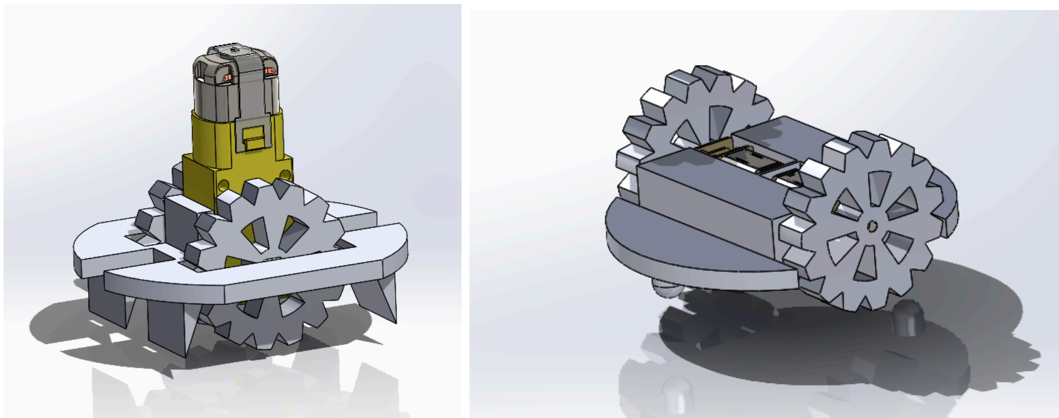


Figure 37: Wheel CAD

The testing conducted on the base on March 3 concluded with the following results. Testing could not be performed on the toy DC motor, since the printed wheels had insufficient clearance for the motor shaft. The wheel design was too large, obstructing the mechanical fasteners used to secure the stepper motors. This issue was resolved by both reducing the wheel size and using a different motor. Although the ball caster wheel was functional, the ball ran the risk of slipping out. It was also discovered that the friction of PLA against the aluminum gutter was very low, so simpler static mechanisms could be implemented to remove the risk of the ball slipping while retaining the same performance qualities and saving valuable space. Stabilizers are added to the front and the back to serve as support in the case of leaning too far forward and too far back, instead of just having one in the front. At the time of the test, there was insufficient space in the design to allow for all the required electronics or an area to mount the debris removal mechanism. The general space-efficiency of the space design was quite low compared to what it could have been. The electronics also provided subpar performance relative to the space they consumed. Smaller, more powerful electronics should be used.

2.3 Third Test - March 16



Figures 38.1 & 38.2: Yellow gearbox DC motor and N20 DC motor based movement systems (respectively)

With the above test results in mind, two new parallel iterations were generated. The first parallel iteration used the toy DC motor and static triangular stabilizers on all quadrants. The track width was reduced due to the nature of the wheels, which provided slightly more space for other components. On the other hand, the motor was quite sizable in the vertical direction, negating the gained space. The second parallel iteration was realized after deciding that DC motors were more practical for the application, and so much smaller DC micro motors were procured and used in the design. The profile of the robot was significantly smaller than all other previous designs, leaving plenty of room for the remaining components while not compromising on performance. This design experimented with a round tip on the front and back in the place of the ball caster. Both designs had improvements in size, handling of dynamic center of gravity, and complexity. Neither of the motors required separate drivers, as they were integrated within the motor itself, which led to significant improvements in space.

Figure 39.1 & 39.2: Third iteration testing within gutters

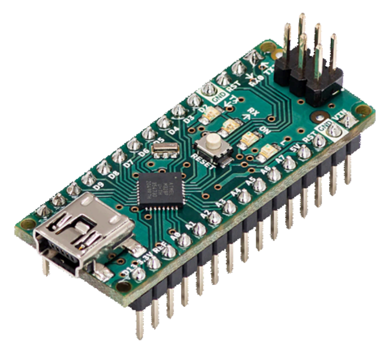
Testing was subsequently performed on both robot bases, and the performance of the new components was determined. On March 16, the tests conducted resulted in the following conclusions. The base design itself has more or less reached a point of saturation. It performs its functions well but could still be improved slightly by optimizing its profile through lowering its center of gravity. As the electronics were finalized, the focus shifted toward creating a housing for the electronic components and beginning to integrate with the debris removal system. The micro motors required some level of additional tuning via pulse-width modulation (PWM) or gearing modifications to further reduce its speed, since it was found to be far too fast for normal operation. They also required a mechanical retainer rather than the use of hot glue or other adhesive fasteners to ensure they remain in place. Further reduction in wheel size will help in space savings in addition to reducing the speed of the motors. Options to add grip to the wheel should be explored to increase traction and avoid slipping. Integration with electronics and debris removal systems should commence.

Controller Management System

Due to the nature of testing, these changes could not be addressed to individual testing dates and were made at seemingly random points over the span of 3 months. Hence, the change in format.

3.1 Arduino

Arduino boards are widely embraced for prototyping due to their intuitive design, facilitating swift hardware exploration, and boasting an extensive array of compatible components. Bolstered by robust community backing and an open-source ethos, they foster a culture of innovation. However, these boards do have limitations; their processing power can be restricted, necessitating supplemental modules for advanced connectivity. Additionally, while they offer real-time capabilities, the finite number of I/O pins might present constraints for certain projects. Nevertheless, for the intervention prototyping use case, Arduino boards prove exceptionally adept and satisfy all anticipated requirements seamlessly.



Figures 40.1 & 40.2: Arduino UNO R3 [27] and arduino nano [28](respectively)

Choosing the most appropriate Arduino board for the specified use case initially led to the Arduino Uno, prized for its versatility and ample array of I/O pins, which allow for extensive connectivity. However, it was swiftly realized that the Uno's larger footprint—approximately 7 cm x 5.5 cm—would encroach upon the designated wiring space. This became especially problematic as additional components were required such as H-bridges and stepper motor controllers. Hence, thequest led to smaller alternatives, leading to the discovery of the Arduino Nano. Despite its diminutive size, the Nano boasted identical functionality to the Uno. While initially concerned about the Nano's reduced I/O pin count, rigorous testing revealed it to be more than sufficient for the robot’s needs. Ultimately, the Nano emerged as the perfect fit, seamlessly integrating into the form factor while delivering exceptional performance.

3.2 Motor Controller Selection

The journey of selecting motor controllers began with the initial tests utilizing pre owned components like the 28BYJ-48 5V stepper motor, earmarked for both motion and cleaning functions. To regulate these motors, the ULN2003 motor controller was selected, which showcased excellent stepper motor control and seamless integration with Arduino. However, a stumbling block emerged as each motor necessitated its own controller, rendering the setup cumbersome with a collective dimension of 3.5 cm x 3 cm for three separate controllers. Moreover, despite the effort to render it functional, it became apparent that these motors lacked the requisite force to handle debris removal effectively. Consequently, the design pivoted towards smaller DC motors boasting greater torque.

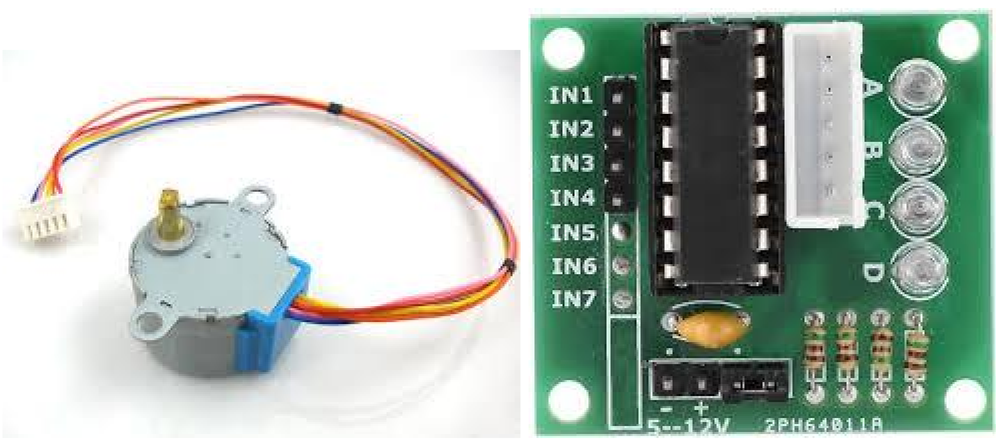
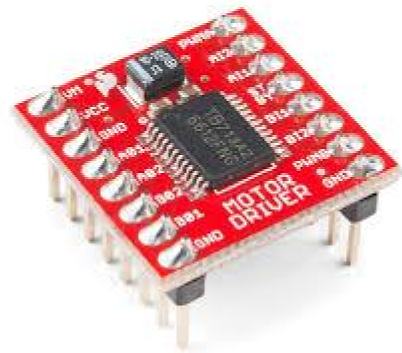


Figure 41.1 & 41.2: Stepper motor [29]and motor controller [30] (respectively)

Enter the H-bridge, where the L298N emerged as a frontrunner due to its ability to control two motors independently, enabling individual control over the motion-associated motors, thereby facilitating nuanced maneuvers like cornering. While this solution appeared ideal on paper, its physical dimensions proved incompatible with the form factor, rendering it unsuitable despite meeting all other criteria.



Figures 42.1 & 42.2: H-bridge [31]and motor driver [32](respectively)

The final solution was the TB6612FNG, seamlessly incorporating all functionalities of the L298N while fitting snugly into its form factor. While its total current output ratings may pose a limitation in other contexts, it poses no hurdle for the specific use cases, cementing its status as the best solution to the motor control related issues. Besides this, it also cost significantly more, when compared to the L298N but that was a price that was still justifiable for the functionality it provided.

3.3 Battery and Voltage Regulator Selection

To power all the components effectively, 9V lithium-ion batteries were initially considered for each element, aiming to ensure stable power distribution across the system. However, setbacks were encountered as these batteries failed to meet longevity expectations, prompting an effort to seek a more reliable power source. The search led to RC power supplies, fitting neatly within the designated dimensions and boasting superior longevity, especially suited for components with higher power demands such as motors.

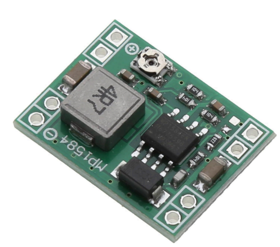
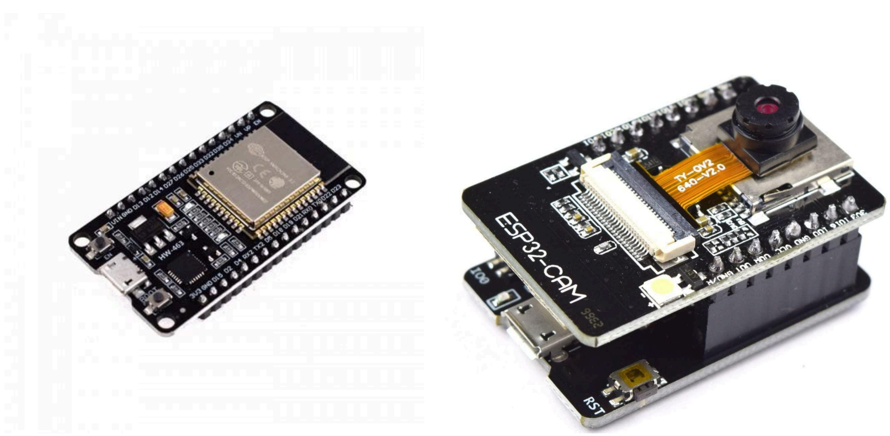


Figure 43.1 & 43.2: battery [33] and step down convertor [34] (respectively)

While contemplating direct connection to a 12V battery, past experiences were considered and a more cautious approach was chosen. A voltage regulation module was used to step down the incoming high voltages from the power source, ensuring a constant and consistent 5V supply to the motors. This decision prompted the selection of a buck DC to DC step-down converter as the optimal choice. This converter would seamlessly reduce the 12V power supply to a stable 5V output, offering reliable power distribution across all components. Among the various options, the MP1584EN emerged as the ideal candidate, fulfilling the requirements while maintaining a compact form factor conducive to integration onto the circuit board. Centralizing all power distribution through the buck converter ensured efficient and uniform power delivery throughout the system, enhancing overall performance and reliability.

3.4 Connectivity Module Selection

To ensure remote operability, establishing a connection between the user and the device became imperative. While various options like wired, Wi-Fi, Bluetooth, and IR presented themselves, each had its own set of considerations. Initially, IR emerged as a frontrunner, but its requirement for a direct line of sight proved limiting. Wired connections were quickly dismissed due to their impracticality and varying length requirements. Bluetooth appeared promising, but the flexibility offered by Wi-Fi connectivity ultimately tipped the scales in its favor.

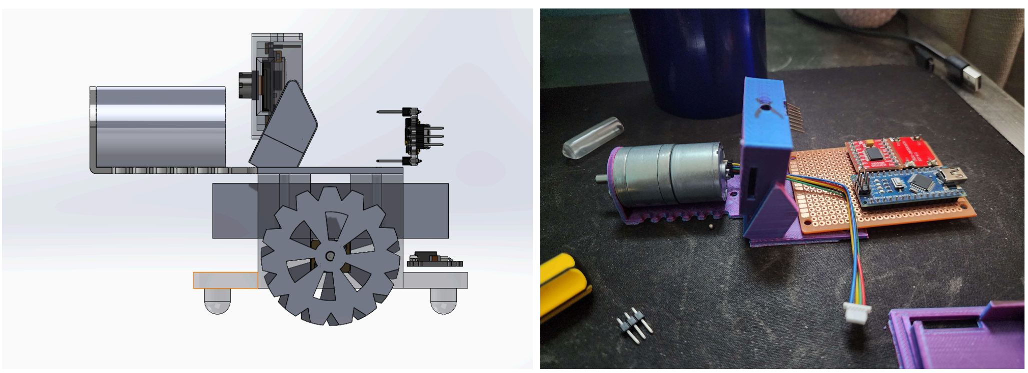


Figures 44.1 & 44.2: ESP32-VROOM [35] and an ESP32-CAM [36](respectively)

For achieving this connectivity, the ESP boards emerged as the solution of choice. Initially contemplating the ESP32-VROOM for system control, the realization dawned that opting for the ESP32-CAM model not only provided the desired functionality but also offered direct vision capabilities, enhancing system management and intervention control. While concerns regarding the ESP32's limited GPIO pins and camera integration complexity lingered, a thorough evaluation concluded that the available GPIO pins sufficed for the needs. With these considerations in mind, the ESP32 emerged as the optimal choice for realizing the connectivity requirements.

Integrated System

4.1 First Integrated Test - March 23



Figures 45.1 & 45.2: First CAD iteration of the integrated system and initial setup.

The first iteration of an integrated system was created by simply combining the latest iteration of all systems. From the debris removal system, the Pololu 25D DC motor in conjunction with a ziptie-based paddle was selected. The battery was mounted in the middle to keep the center of gravity low, while the remaining electronics (motor, controller, camera, etc.) were all mounted on top. The front profile was well within the geometric constraints provided by the gutter.

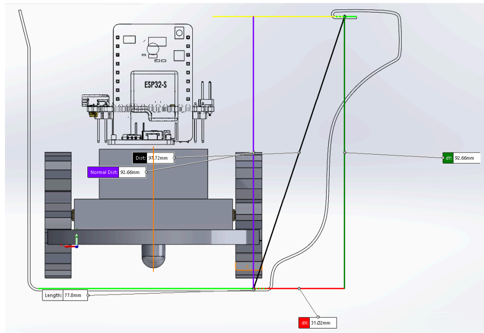
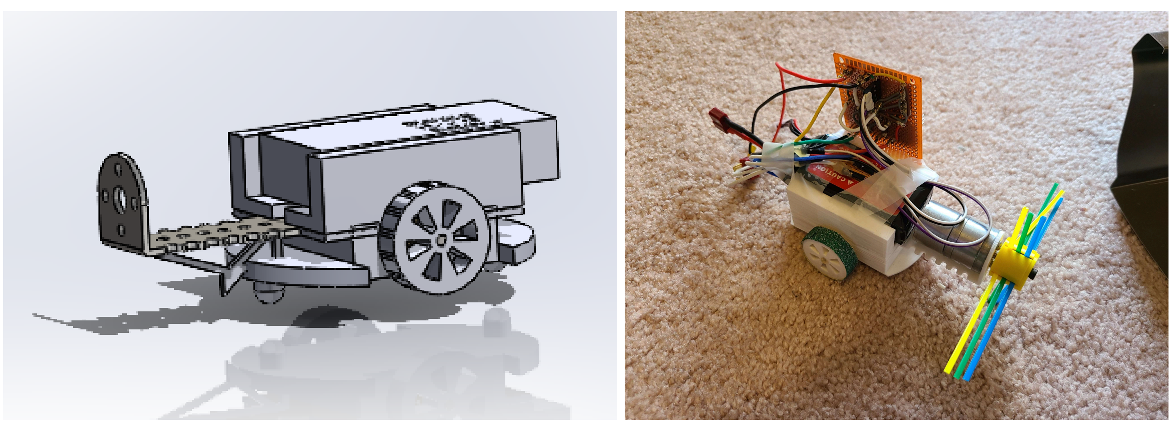


Figure 46: Comparison of intervention to gutter dimensions

From this test, it was concluded that a new method of securing the wiring was required, since existing electrical connections were poorly secured. As wires were poorly stripped, signals were lost and power was not transferred. Crimping tools were ordered to secure the most vulnerable connections, as there was insufficient lead time to manufacture a PCB.

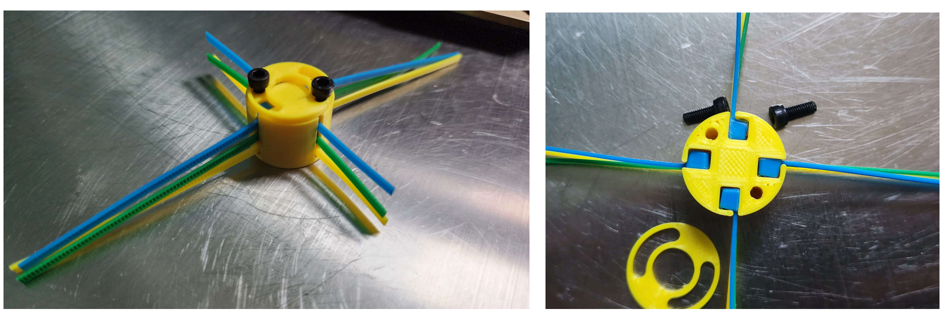
4.2 Second Integrated Test - March 31



Figures 47.1 & 47.2: CAD model (left) and assembled prototype (right) used for form factor testing in the second integrated test.

The next iteration utilized findings from the March 23 testing to further improve the design. The motor placement was lowered such that it was aligned with the battery to lower the center of gravity yet again, and a supporting piece was placed below the motor. The heaviest components being the debris removal motor and battery, they were placed such that they are balanced over the axle to improve stability and weight distribution. This modification came at a cost of having a longer length, which affected the minimum possible turning radius. Additionally, the toothed wheels were replaced with a circular profile to accommodate a range of frictional surfaces to improve traction. Wheels with a surface consisting of rubber bands, textured rubber, and sandpaper were compared. The lowest grit sandpaper available (60 grit) was procured to maximize traction, and it proved to be the superior wheel surface through this round of testing. The scope in this round of testing included gaining quantifiable performance data with regards to cleaning efficiency, energy consumption, durability, and connectivity.

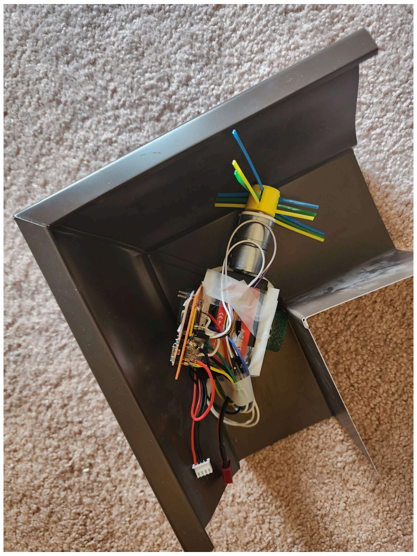
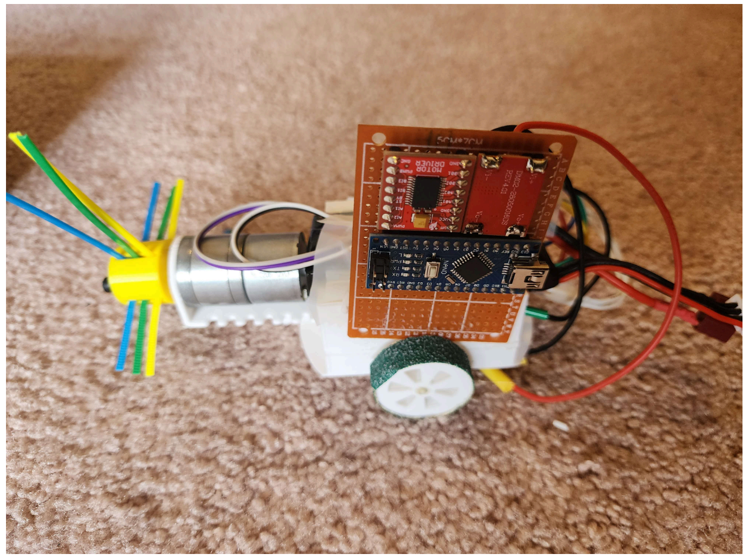
In addition to the enhanced base design, a new zip tie rotor has been developed, showcased in Figure 48.1 & 48.2. This rotor follows a modular design similar to the zip tie with flap rotor, featuring a short cylinder with four slots capable of accommodating three zip ties each. To secure the zip ties in their respective housings, a screw-on cover has been integrated. The primary distinctions between the new zip tie rotor and the zip tie with flap rotor lie in the absence of flaps and its shorter profile. This alteration was made to reduce the overall dimensions of the device, thereby enhancing its maneuverability, particularly around corners.



Figures 48.1 & 48.2: 3D printed new zip tie rotor design

Figure 49: Intended testing environment for the second integrated test, consisting of a forest abundant with dried leaves

Unfortunately, the robot's motors were unable to operate reliably and very little was revealed in a prolonged effort of troubleshooting. It was later discovered that there had been an electrical short which resulted in damage to the motor driver, rendering it inoperable. Thus, the cleaning efficiency, energy consumption, and durability tests were unable to be performed. With the deadline fast approaching, a replacement motor driver was rapidly acquired for testing the following day. Instead of proceeding with the normal tests, the robot was placed into a gutter corner piece to see if it was geometrically possible to perform a turn. The robot was found to be too long to turn corners with ease.

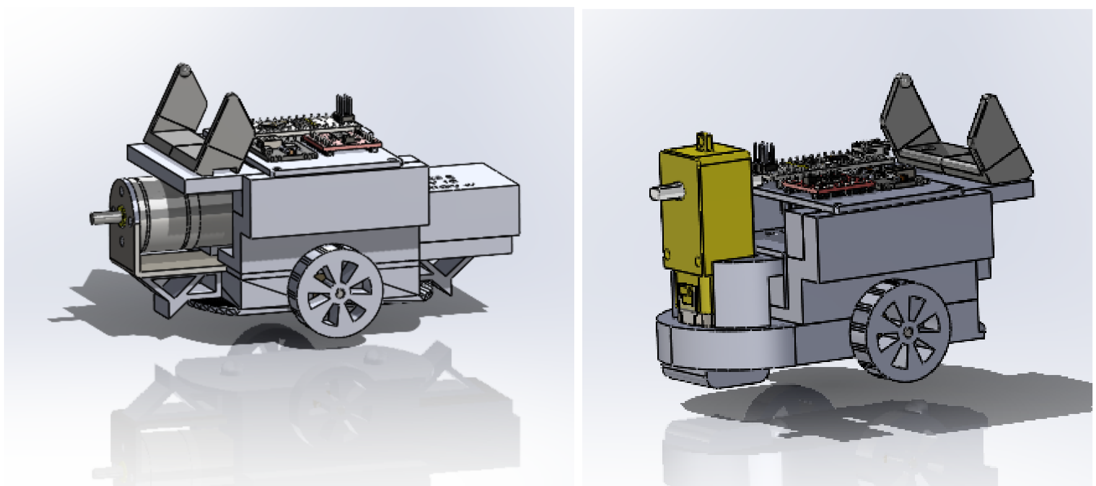
Figures 50.1 & 50.2: Turn radius testing

As for the connectivity test, the ESP32 camera module and antenna was brought outdoors. GPS was used to measure the distance between the transmitter and receiver before the connection was unacceptable. The requirement outlined in the performance benchmark was for an operational distance of at least 15 meters unobstructed, which it surpassed by being capable of communicating at a range of 50 meters. Despite the lack of a signal extension device, the signal was broadcast to a satisfactory distance and strength.

Figure 51: Approximate ESP32 max control range

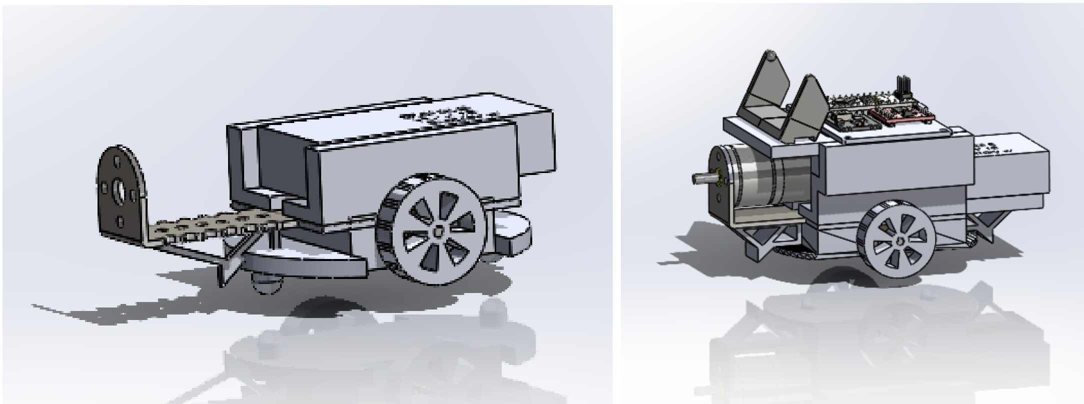
From the second integrated test, the following was learned that troubleshooting of electronics had to be a priority in the coming days since it was the bottleneck in the project. The length was too long for turning corners, so a new base must be designed to accommodate it. Proper mounting points for the electronics needed to be integrated, with additional room for wiring and pins. A parallel design with the toy motor for debris removal should also be created for redundancy and to potentially compare the two motor designs.

4.3 Third Integrated Test - April 1



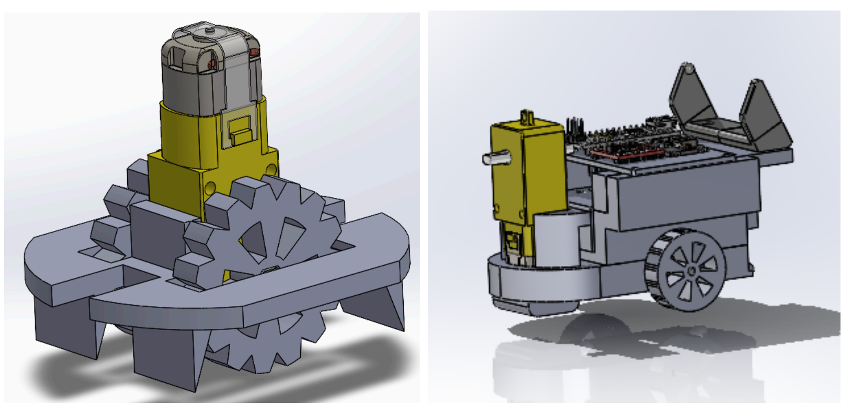
Figures 52.1 & 52.2: Prospective final models with the 25D and yellow gearbox motors (respectively)

The third integrated test saw 2 new iterations of the prototype, one intended for the large DC motor and the other for the toy motor. Both designs included proper mounting points for all electronic components and sufficient room for routing of wires. They were also made to be more stable in all axes by optimizing the position of non-driving stabilizers and again lowering the center of gravity. In addition, friction fits were used throughout in addition to the existing M3 screws used as mechanical fasteners to increase structural rigidity where applicable. This included areas such as the motor retainers, camera mount, battery holder, and motor shafts. More open space was also provided to encourage ventilation/cooling and alternative wiring routes during troubleshooting.



Figures 53.1 & 53.2: Previous iteration (left) compared with the latest iteration (right) for the large motor base design.

The first design using the large debris removal motor had its motor-battery positions reconfigured longitudinally to allow easier navigation of corners. Its overall wheelbase was not reduced in size but since the front and back lengths relative to the turning center were now more similar, it was now able to turn. An additional supporting truss was placed in the rear to support the additional overhang of the battery and further restrict the allowable angle of pitch.



Figures 54.1 & 54.2: Previous iteration (left) compared with the latest iteration (right) for the toy motor base design.

The second design using the toy motor as debris removal saw a significant upgrade in the base. Space-efficiency was significantly improved by using the toy motor as the debris removal motor instead of the driving motor. The motor featured a shaft which extends in both directions, so sufficient clearance from the electronics and wiring was important. Despite this, the length was significantly reduced and thus the space-efficiency was the best when compared to all previous designs, allowing it to turn with ease while being compact. This was in part due to the vertical orientation of the motor, which resulted in a shorter but taller design.

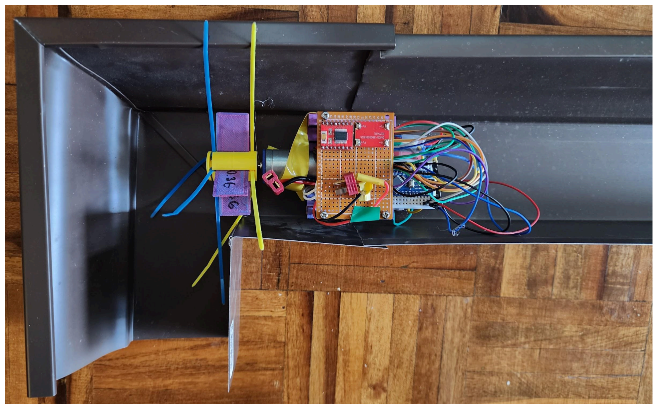


Figure 55: Rotor with flaps and Zipties

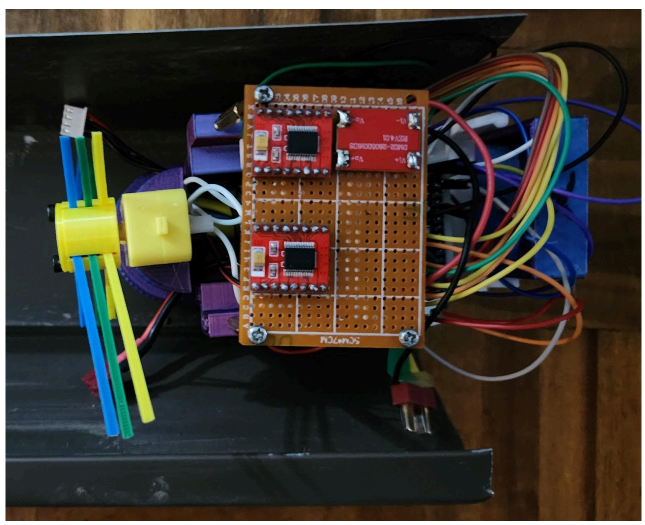


Figure 56: Rotor with only zip ties

The tests for cleaning efficiency, energy usage, and durability were performed simultaneously. All involved running the robot through the gutter. The cleaning efficiency measured the percentage of leaves removed from the gutter in a single pass, and the benchmark was 30%. The energy usage/consumption was measured by running the robot along the gutter length for 60 linear meters, and it passed if it succeeded without running out of power. The durability was measured by observing for any worn components or required maintenance after one cleaning cycle or 60 linear meters. For the purpose of the test, it was assumed that 30% of the gutter was clogged with leaves in a realistic scenario.

Thus, to gauge all 3 metrics, the robot was to run through a gutter full of simulated leaves for 18 meters, then subsequently run through 42 meters without leaves. During the test, 3 pieces of gutter at 2.5 ft each were placed in a line for each run. Using a motor speed of 100rpm for the wheels, the robot was run through the 3 pieces of gutter filled with leaves for 8 repetitions to achieve a length of 18 meters. After each run, it was measured with the residual leaves and reset. The table below shows the results of the test and the respective cleaning effectiveness. With an average of 81.67% gutter cleaning effectiveness in the first configuration as per Table 10, it massively surpassed the benchmark. It was also quite fast in its cleaning speed, completing the 7.5 feet of gutter length within 1.5 minutes per each run. The remainder of the testing was performed without further electrical or mechanical problems. The battery had plenty of charge remaining by the end and no maintenance was required. Before the test the measured voltage was 11.44V and at the end of testing it was 11.28 V. Therefore, the robot met the criteria laid out for it in terms of durability and battery life.

Table 10. Cleaning effectiveness of the large DC motor debris removal system using dry paper.

Test Run Number	Gutter Weight after cleaning (g)	Gutter Weight (g)	Total Weight of Leaves (g)	Residual Weight of Leaves (g)	Cleaning Effectiveness (%)	Cleaning Rate (ft/min)
1*	317	304	90	13	85.56	4.73
2	398	371	90	27	70%	6
3	382	370	90	12	86.67%	4.78
4	383	370	90	13	85.56%	5.35
5	389	373	90	16	82.22%	5.11
6	385	371	90	14	84.44%	5.625
7	390	370	90	20	77.77%	5.48
8	386	369	90	17	81.11%	6.42

In tables 11 and 12, the same motor was used to perform cleaning of wet debris within a gutter weighing 361 grams. The result was a reduction in both cleaning rate and cleaning effectiveness when compared with the dry cleaning. When comparing two different cleaning tools, it was revealed that the one consisting purely of zip ties performed significantly better than that of the flaps. Although the design was not optimized for removal of wet leaves, it still performed to a satisfactory level and showed significant improvement when compared to early tests with wet debris.

Table 11. Wet debris removal testing of new zip tie rotor, gutter weight 361g

Test Run Number	Gutter Weight w/debris (g)	Cleaned Gutter Weight (g)	Total Weight of Leaves (g)	Residual Leaves (g)	Cleaning Effectiveness	Cleaning Rate (ft/min)
1	908	777	186	55	70.43%	3.33
2	912	802	190	80	57.89%	2.5

Table 12. Wet debris removal testing of zip tie & flaps rotor, gutter weight 361g

Test Run Number	Gutter Weight w/debris (g)	Cleaned Gutter Weight (g)	Total Weight of Leaves (g)	Residual Leaves (g)	Cleaning Effectiveness	Cleaning Rate (ft/min)
1	820	789	98	67	31.63%	1.25
2	908	777	186	55	70.43%	1.67

Next, testing was performed using the toy motor as the debris removal driver. The same two cleaning tools were used, one consisting entirely of zip ties and another using a combination of zip ties and 3D-printed flaps. Unfortunately, though this design was expected to outperform the Pololu motor, it was found to be underwhelming in comparison. The cleaning speed was reduced significantly and the entire robot kept getting stuck. This was likely due to the elevated center of gravity and shorter length, compromising its stability. A reduction of cleaning speed of 3 to 5 times while yielding similar levels of cleaning efficiency clearly indicates that in its current indication, it was inferior.

Table 13. Dry debris removal testing of toy motor with zip tie using paper.

Test Run Number	Gutter Weight after cleaning (g)	Gutter Weight (g)	Total Weight of Leaves (g)	Residual Weight of Leaves (g)	Cleaning Effectiveness (%)	Cleaning Rate (ft/min)

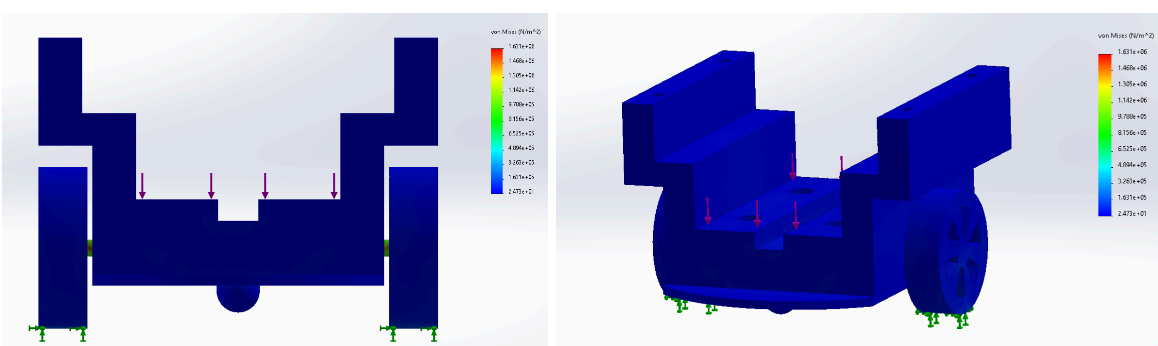
1	377	362	90	15	83.33%	1.5

Table 14. Dry testing of toy motor with zip tie & flaps using paper.

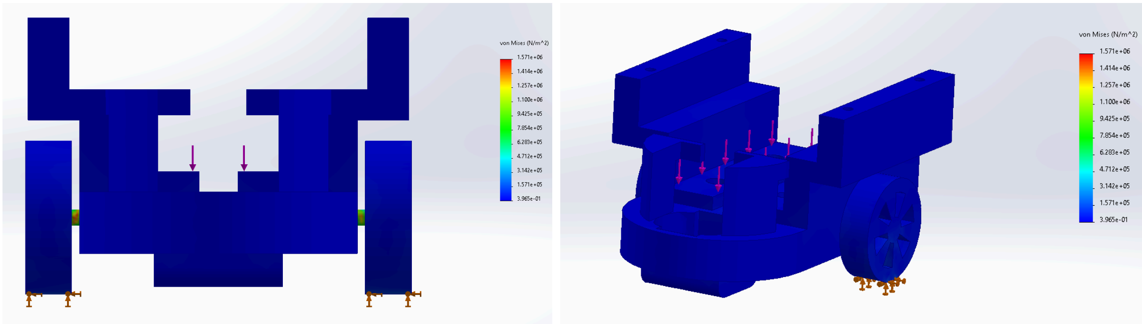
Test Run Number	Gutter Weight after cleaning (g)	Gutter Weight (g)	Total Weight of Leaves (g)	Residual Weight of Leaves (g)	Cleaning Effectiveness (%)	Cleaning Rate (ft/min)
1	372	362	90	20	77.77%	1.07

Maintenance and Reliability

In addition to the physical testing of the prototypes, static loading stress analysis simulations were produced using SOLIDWORKS Simulation software to predict the most likely mechanical failure modes. Simplified CAD models of both designs were made and subjected to 10N of downward loading while the wheels were fixed in place. A force of 10N was selected as a conservative estimate of approximately 1 kg of load. This accounted for the true approximate weight of the robot at an acceleration of 2G. The results indicated that there were stress concentrations on the interface between the driving motor shafts and wheels, though the remainder of the structure was unaffected. Luckily, the motor shafts were not made of the same PLA plastic used in the 3D-printed structure, so it was already reinforced.



Figures 56.1 & 56.2. Static loading simulation at 10N load performed on the large DC motor base.



Figures 57.1 & 57.2. Static loading simulation at 10N load performed on the toy motor base.

In the robot using the large DC motor, the plate holding the motor and the battery may be a potential point of failure. The length of the plate supports two of the heaviest components distributed across its large area. It has a relatively thin profile but is reinforced with supporting trusses below it which bear some of the load and share it with the base.

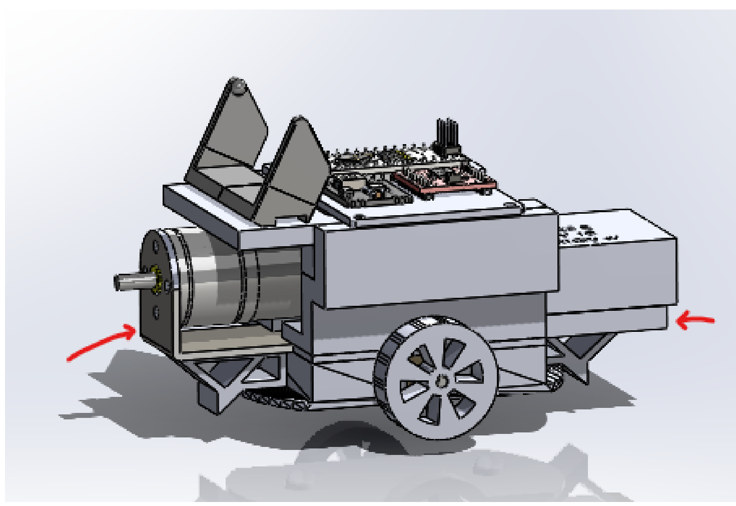


Figure 58. Annotated large DC motor CAD, highlighting the motor plate.

In addition to the above components, the components enduring frequent contact with the gutter and debris should be considered consumables. These components include the zip tie paddles used in the debris removal system and the coarse sandpaper surface on the wheels. It could be reasonably expected that some amount of material wears off with each use and that it would require replacement in its useful life.

Table 15. FMEA for mechanical failure modes.

Step	Mode	Potential Effect	SEV	Potential Causes	OCC	Controls	DET	RPN
Construction	Base Breakage	Component Damage, Task Failure	5	Improper assembly, careless use	1	Strong enough base material, safe and careful building conditions	1	5
Operation	Wire gets stuck in motor	Wires get unplugged	3	Improper sheathing	3	Printing internal circuit boards/ encasing the wires	3	27
Operation	Worn Wheels	Causes slippage, loss of driving control	5	Wear through use on gutter surface	6	Use more durable material for wheel tracks, replace wheel tracks often	2	60
Operation	Worn Flaps	Poor performance, device gets stuck in debris	4	Wear through use on hard debris and gutter walls	6	Use more durable material for flaps, replace flaps often	3	72

Operation	Tipping Over	Damage to device and parts	1	Loss of balance, rotor stuck on debris	4	Ensure more weight at the base	7	28
Operation	Getting Stuck	Damage to device and parts	5	Trapped in debris	5	Use a reversing system	6	150

Table 16. FMEA for electrical failure modes.

Step	**Mode**	**Potential Effect**	**SEV**	**Potential Causes**	**OCC**	**Controls**	**DET**	**RPN**
Construction	Reverse Power Terminals	Nothing happens but nothing works	1	Negligence	1	Pay attention to wiring and check wire ends before wiring	7	7
Construction	Short Circuit Power	Start a Fire	10	Loose wires and/or improper coverage of wires	6	Using electric taping or heat shrink on any visible bits of wire along with the power cabales	6	360
Construction	Short Circuit General IO	Could potentially fry / Mess with signals	6	Improper connections and live wires not being sheathed well enough	4	Tape or heat shrink all live wire ends	6	144
Operation	Motor	Voltage	6	Lack of	2	Sending all	5	60

	EMF	spike damages microcontroller		voltage and current regulation module		power through the voltage regulation module		
Operations	Thermal runaway	High temperature causes damage to the microcontroller	6	Lack of heat dissipation techniques or voltage regulation	3	Adding a heat sink to vulnerable components	3	54

Chapter 3 - Product to Market

Budget Analysis

Table 17. Total testing cost in CAD including tax

No.	Part name	Part type	Total number	Cost per part	Total cost
1	28byj-48	Stepper motor	3	9.03	27.09
2	ULN2003	Motor controller	3	2.65	7.95
3	N20 DC motor	DC motor	2	11.08	22.16
4	L298N	Motor driver	1	8.47	16.94
5	Prototype boards	PCB	1	1.13	1.13
6	Arduino UNO	Microcontroller	1	27.10	27.10

7	TB6612FNG	Motor controller	2	10.24	20.48
8	Arduino Nano	Microcontroller	1	36.14	36.14
9	MP1584EN	DC step down and voltage regulator	1	1.92	1.92
10	DLG 3S	3 cell lipo battery	1	20.22	20.22
11	Energizer 9V	Lithium ion batteries	3	4.50	13.5
12	Pololu 25D motor	DC motor	1	18.07	18.07
13	Yellow gearbox (toy) motor	DC motor	1	1.70	1.70
14	Jumper wires	Wiring	1 box of 120 wires	7.89	7.89
15	10 ft. x 5-inch Aluminum Gutter	Aluminum Gutter	1	28.53	28.53
16	5-inch Aluminum Outside Corner Gutter	Gutter Corner	1	29.19	29.19
17	Overall Cost				279.99

Table 18. Final prototype component cost in CAD including tax

No.	Part name	Part type	Total number	Cost per part	Total cost
1	Arduino nano	Microcontroller	1	36.14	36.14
2	TB6612FNG	Motor controller	1	10.24	10.24

3	N20 DC motor	DC motor	2	11.08	22.16
4	MP1584EN	DC step down and voltage regulator	1	1.92	1.92
5	DLG 3S	3 cell lipo battery	1	20.22	20.22
6	Prototype boards	PCB	1	1.13	1.13
7	Jumper wires	Wiring	20	N/A	N/A
8	3D printed parts	Main body	N/A	N/A	5
9	Pololu 25D motor	DC motor	1	18.07	18.07
	Overall Cost				114.88

The table presented above outlines the total expenses incurred for testing, amounting to $279.99, with the prototype costing $114.88. Major testing expenditures encompassed electronics, including microcontrollers (Arduinos), motor controllers, DLG 3S battery, and the Pololu motor. Notably, the 10 ft gutter and gutter corner constituted the most substantial expenses among physical testing equipment. Similarly, within the prototype, electronics represented the most significant cost component. Manufacturing costs primarily associated with 3D printing were minimal, given its cost-effective nature. Estimating the expense of 3D printing prototype parts would approximate $5. Scaling up prototype production would likely yield reduced electronics costs. Scaling up manufacturing would result in a high initial cost to accommodate the production of the molds, however the subsequent part/piece costs would be significantly lower than if they were 3D printed. Moreover, large scale manufacturing would result in a stronger, more durable and more reliable device.

Final Implementation

Control components

Transitioning to mass manufacturing necessitates a shift away from the current practice of utilizing disparate components like motor drivers, voltage regulators, Arduinos, and ESPs. The present setup, while functional, poses challenges in terms of space constraints and wiring complexities. The abundance of jumper wires navigating through tight spaces presents a significant hurdle.

To optimize for mass production, consolidating all circuitry and components onto a single PCB emerges as the most prudent approach. This integration streamlines assembly and reduces the footprint of the system, leading to notable cost savings. By minimizing the number of individual integrated circuits and instead leveraging microcontrollers, overall component costs are significantly reduced without compromising functionality.

Furthermore, adopting a single PCB design diminishes the likelihood of failure modes associated with loose or snagged wires, thereby enhancing reliability. With only the motors and power source requiring wiring, assembly becomes more efficient, reducing both production time and potential points of failure. This streamlined approach not only enhances manufacturability but also ensures a more robust and reliable end product.

Main body

In the material selection process for the body, options were meticulously weighed including wood, metal, and plastic. Wood, although a natural choice in some respects, posed a risk of rot and required costly preservation methods to mitigate. Metal, while renowned for its durability, carried the burdens of weight and susceptibility to rust, not to mention the inherent expense associated with its use.

Consequently, plastic emerged as the most pragmatic choice, offering a compelling balance of affordability and durability. Its versatility and cost-effectiveness made it an ideal candidate for the project. Moreover, the decision to employ plastic for prototyping purposes via 3D printing not only expedited the development phase but also allowed for swift iterations and testing, aligning seamlessly with the project's objectives.

3D printing serves as an invaluable tool for rapid prototyping, offering the ability to swiftly iterate on designs and test functional components. This approach grants the advantage of quickly evaluating design changes with tangible, working parts. However, it's essential to acknowledge the limitations inherent to this method, particularly when employing Fused Deposition Modeling (FDM). FDM 3D printing builds objects layer by layer, resulting in parts that may lack the robustness required for rigorous testing. The layered structure renders them susceptible to damage from lateral forces, undermining reliability.

Moreover, while 3D printing accelerates the prototyping phase, its inefficiency in terms of time per part renders it unsuitable for large-scale production. Injection molding and compression molding emerge as superior alternatives for mass manufacturing due to their remarkable efficiency once the production setup is established. These methods, while less suited to prototyping, boast rapid production rates that far exceed those achievable through 3D printing, making them the pragmatic choice for large-scale manufacturing endeavors.

Motors

While the motors proved largely functional, the endeavor encountered notable challenges. Chief among these was the difficulty in sourcing motors that offered the precise balance of torque and RPM necessary for the application. Initially, the motors procured either fell short in revolutions per minute, hampering the efficacy of leaf removal from gutters, or exhibited excessive torque, posing potential operational issues.

Ultimately, the N20 motors were chosen with dedicated gearboxes and yellow plastic motors boasting an internal 1:48 gear ratio gearbox. However, the latter's form factor posed a significant constraint. Looking ahead to large-scale production, it became evident that a more optimal solution would involve custom gearboxes tailored to standard motors, thus ensuring a better fit for the system requirements. This strategic adaptation would not only enhance performance but also streamline manufacturing processes for future iterations of the project.

Discussion and Conclusion

Throughout the project, the prototyping phase posed numerous challenges, particularly in wiring the electronics on the robot. One significant issue arose during wire crimping, where the exposed ends failed to adequately make contact with the crimping surface, leading to unreliable current flow along certain sections of the wire. This resulted in intermittent power disruptions within the electronic assembly, causing periods where the robot would fail to power on. Additionally, initial wiring attempts on a printed circuit board (PCB) proved problematic due to the substantial number of wires needed, resulting in overcrowding and subsequent short circuits as exposed wire ends made unintended contact. In one instance, a short circuit led to the loss of a motor controller. In the final integrated design, a breadboard was employed as the foundation for wiring, effectively preventing power loss and short circuits. However, to further enhance the design's reliability and ease of assembly, future iterations should consider developing a custom PCB, enabling easier electronics connection, reduced dimensions, and improved operational reliability.

One of the foremost challenges encountered in this project revolved around integrating the device into the confined space of the gutter, underscoring the critical role of the device's form factor in its design. A significant obstacle encountered was the motor gearbox configuration. While motors such as the toy motor exhibited strong performance attributable to their gear ratio during testing and development, their size proved too bulky for practical implementation. Subsequent exploration of the N20 motor revealed its inadequacy in providing the requisite power to operate the rotor effectively. Ultimately, the Pololu 25D motor was selected for the prototype, demonstrating satisfactory performance; however, its substantial size remained a concern. To address this challenge and minimize the form factor, the imperative arises for the development and manufacture of a custom motor and gearbox.

On a similar note, the power source also played a large role in managing spatial efficiency and the center of gravity as well. During the second iteration of the integrated design, the large heavy battery was found to be an issue during turning. The extended length of the battery relative to the turning center prevented it from performing the turn successfully. Alternative designs were considered to reduce the overall length but the final solution which was decided upon was to move the motor-battery assembly back so that the length extending forward and back were equal. The battery’s heavy nature also lowered the center of gravity, enhancing stability and traction by increasing the normal force.

Table 19. Performance Metric Evaluation

Performance Metric	Evaluation	Completed/Not Completed	Desirable
Cleaning Efficiency	$P_1 = \frac{81.67\%}{30\%} = 2.72 > 1$	Completed	Yes
Energy Usage	$P_2 = \frac{60m}{60m} = 1$	Completed	Yes
Durability	$P_3 = \frac{18m}{18m} = 1$	Completed	Yes
Survivability*	$P_4 = \frac{N/A}{1\ fall\ at\ 3m} = 0$	Not Completed	-
Connectivity	$P_5 = \frac{50m\ range}{15m\ range} = 3.33 > 1$	Completed	Yes
Maintenance and Reliability	$P_6 = \frac{MTBF}{50\ operating\ hours} = 0$	Not Completed (time constraints)	-
Cost-effectiveness	$P_7 = \frac{\$500}{\$114.88} = 4.35 > 1$	Completed	Yes
Navigation Capability	$P_{s1} = Autonomous = 0$	Completed	No
User Interaction	$P_{s2} = \frac{5\ actions\ to\ operate}{1\ action\ to\ operate} \times 100$	Completed	Yes
Innovation	$P_{s3} = Mech\ Novelty = 0$	Completed	No

The prototype meets five of the seven critical performance metrics, showcasing strong capabilities in cleaning efficiency, energy usage, durability, connectivity, and cost-effectiveness. However, it fails to meet the benchmarks for survivability and navigation capability. Achieving all seven metrics is essential for the design to be competitive in the market. To address these gaps, further design iterations are recommended.

For survivability, the prototype requires optimization of the casing and the PCB/soldering wire to enhance its robustness for passing drop tests. Regarding navigation, the integration of an Inertial Measurement Unit (IMU) is proposed to enable environmental responsiveness, allowing the design to operate autonomously. Alternatively, utilizing the ESP32-CAM to develop a camera detection and motion algorithm could improve decision-making on when to turn.

To facilitate these enhancements, a redesign of the form factor is necessary to create adequate space for turning mechanisms. This may involve repositioning or possibly switching to a smaller battery, which is viable given that the current design significantly exceeds the energy efficiency requirements. Implementing these changes will improve the prototype's survivability and autonomous navigation, making it a stronger contender in its market segment.

In conclusion, the solution’s form factor is compact and aligns with the predefined constraints. Trade-offs between size, power, and functionality were carefully managed, guided by performance metrics that steered the solution. While the prototype achieves respectable results in several key areas, it is evident that additional iterations are necessary to fully realize a market-ready product. Nevertheless, a solid foundation has been established for a competitive product, and the insights gained provide a clear direction for future development. The core motivation behind this project is to mitigate the risks associated with traditional gutter cleaning methods, which pose significant safety hazards and health risks. The prototype is able to mitigate dangers of high-altitude falls, house protection and the health issues stemming from stagnant water in clogged gutters. Future iterations will focus on enhancing the prototype's durability and autonomous navigation to ensure it can safely and effectively perform its tasks.

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Appendix A - Testing Videos

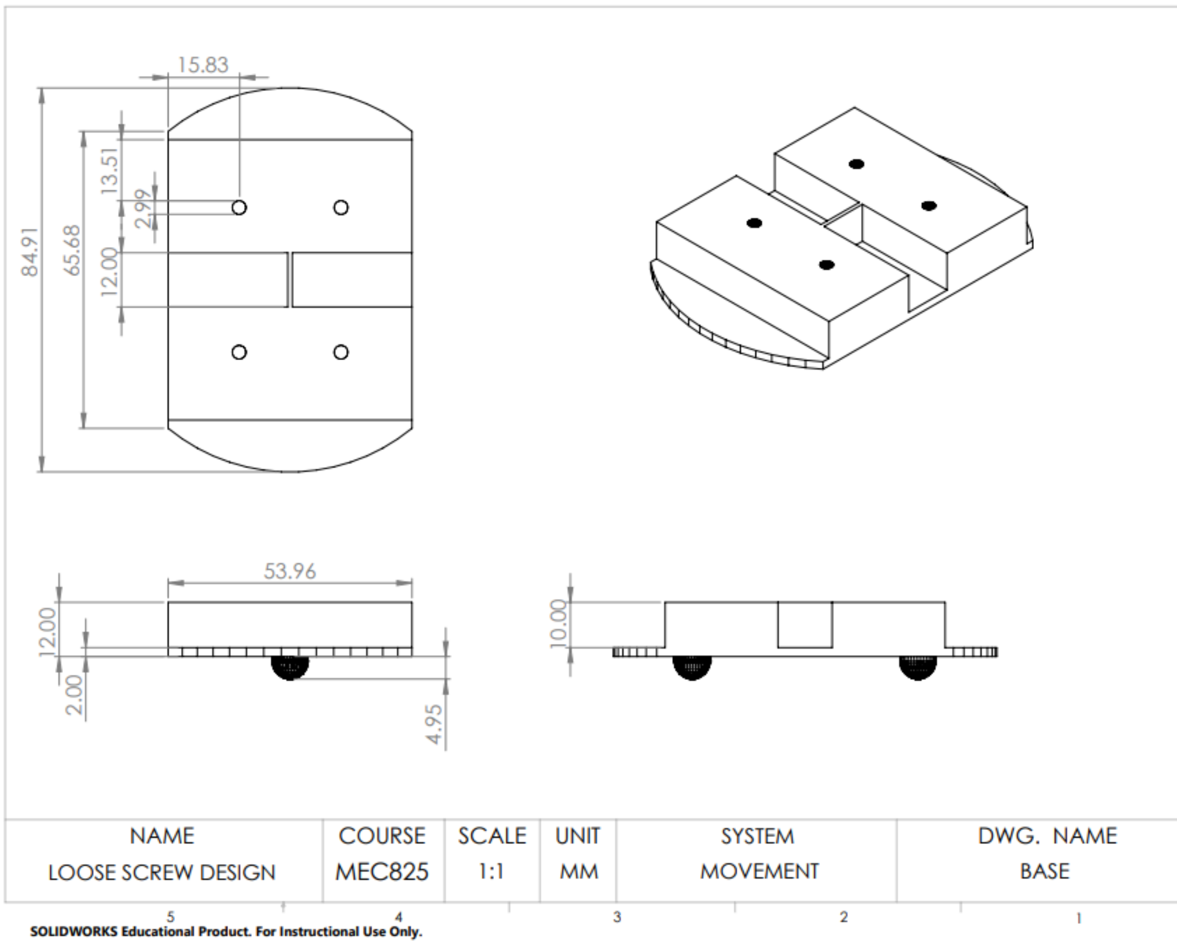
A folder with testing videos can be found here:

https://drive.google.com/drive/folders/1TO58iOMjs1CJISsOagaBUZzIY-Kse5rT?usp=sharing

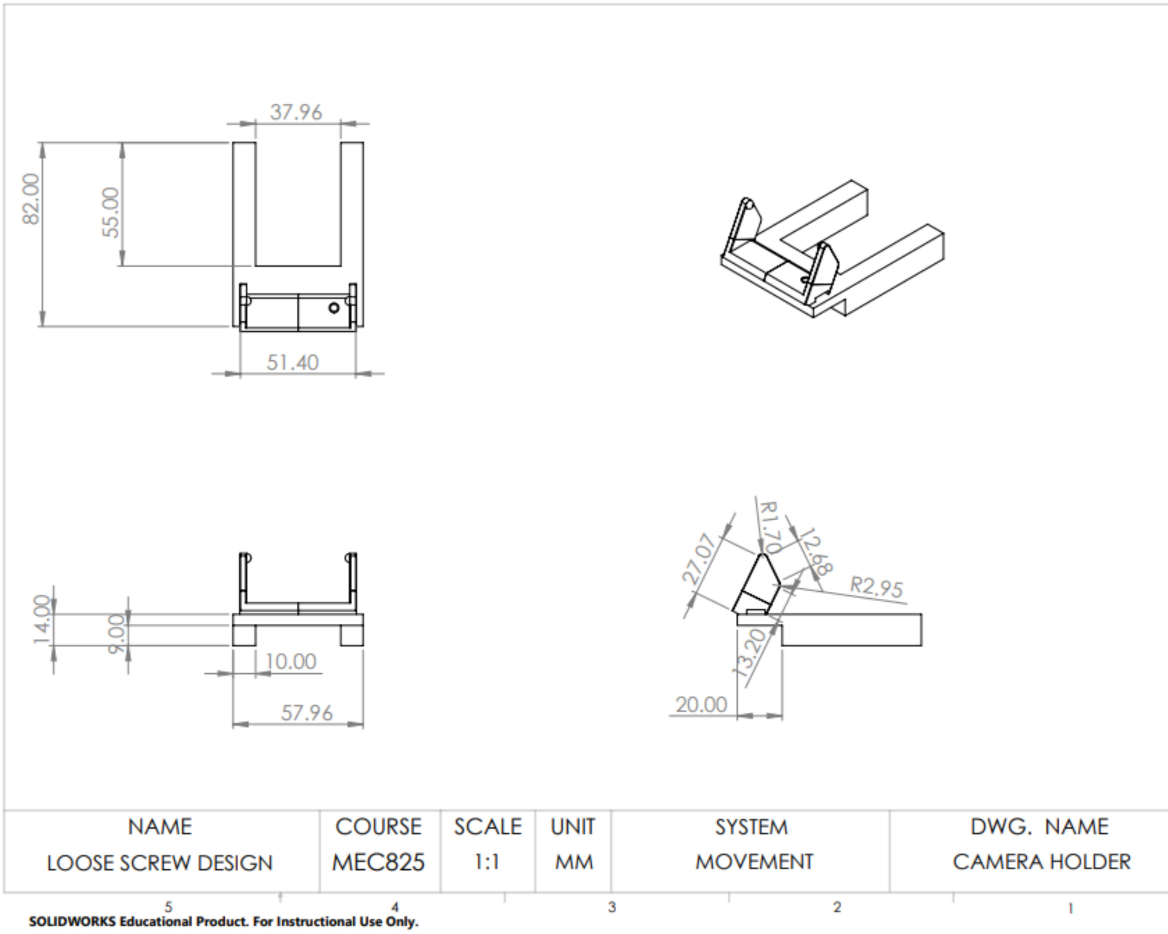
Appendix B - CAD Drawings

Pololu Motor Design

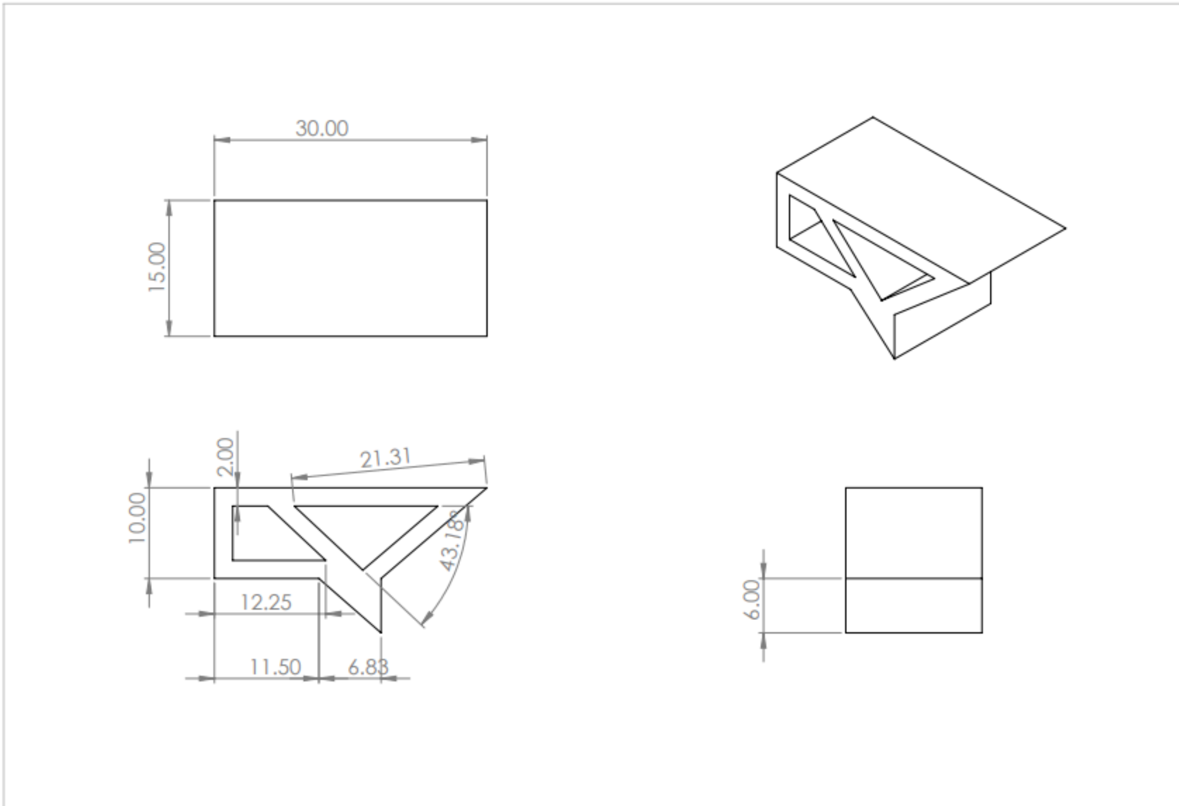
Base



Camera Holder

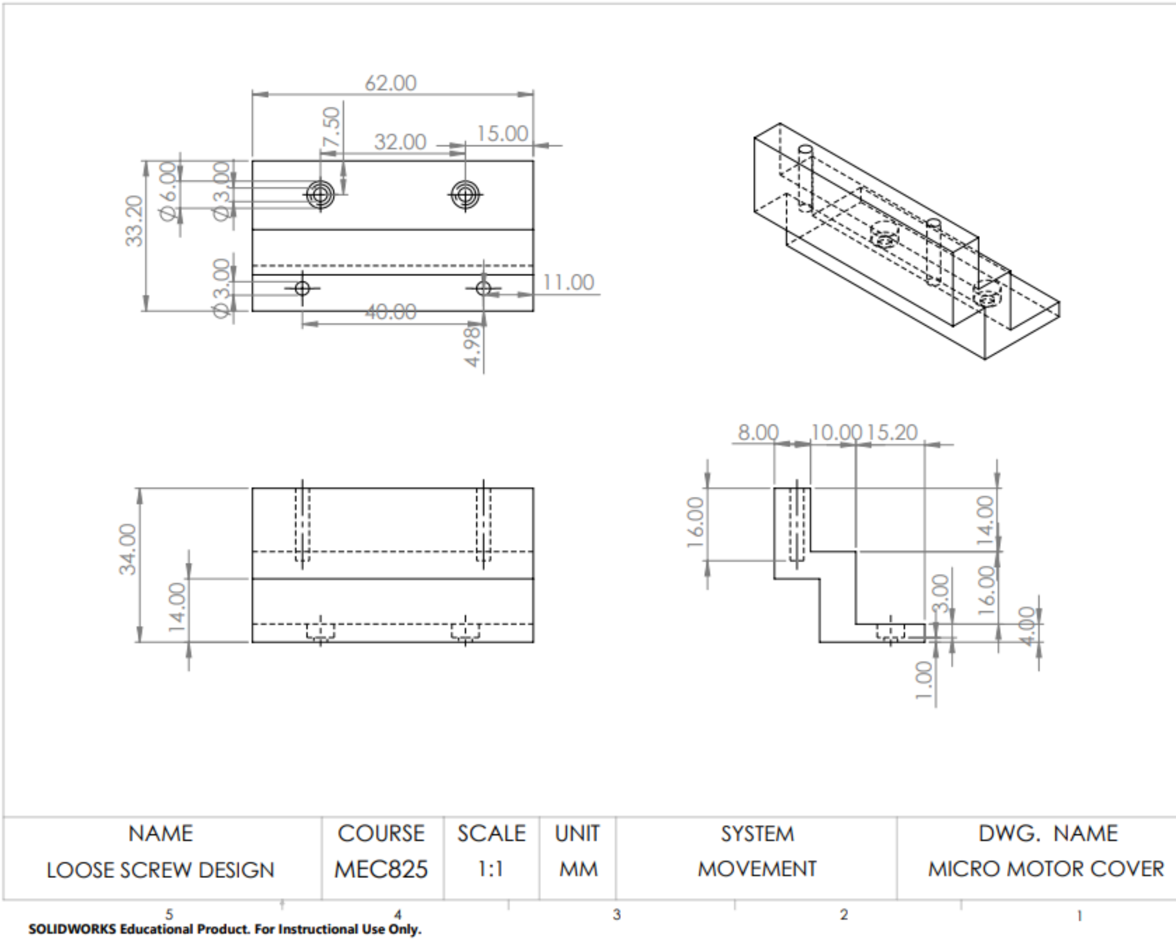


Cleaner Support

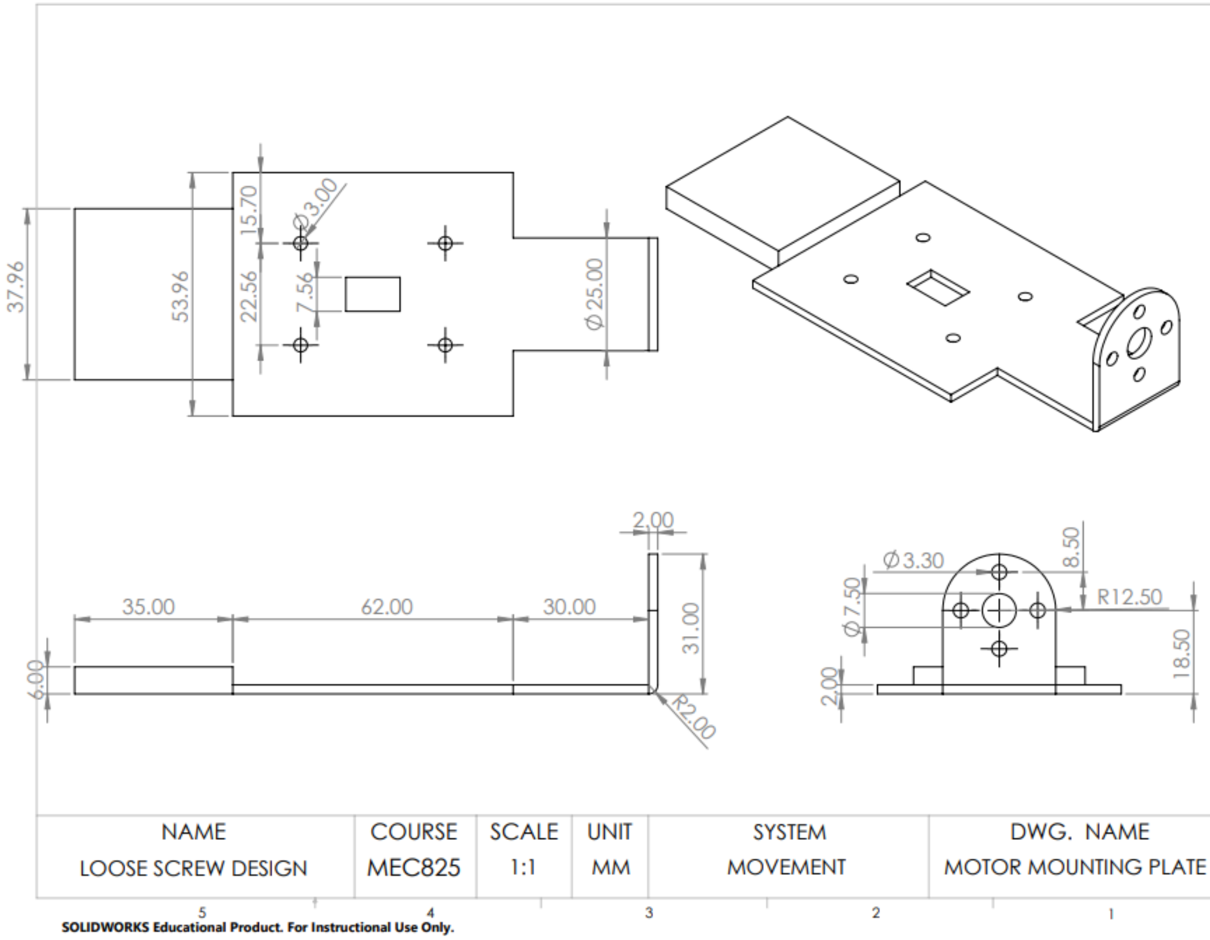


NAME	COURSE	SCALE	UNIT	SYSTEM	DWG. NAME
LOOSE SCREW DESIGN	MEC825	1:1	MM	MOVEMENT	CLEANER SUPPORT

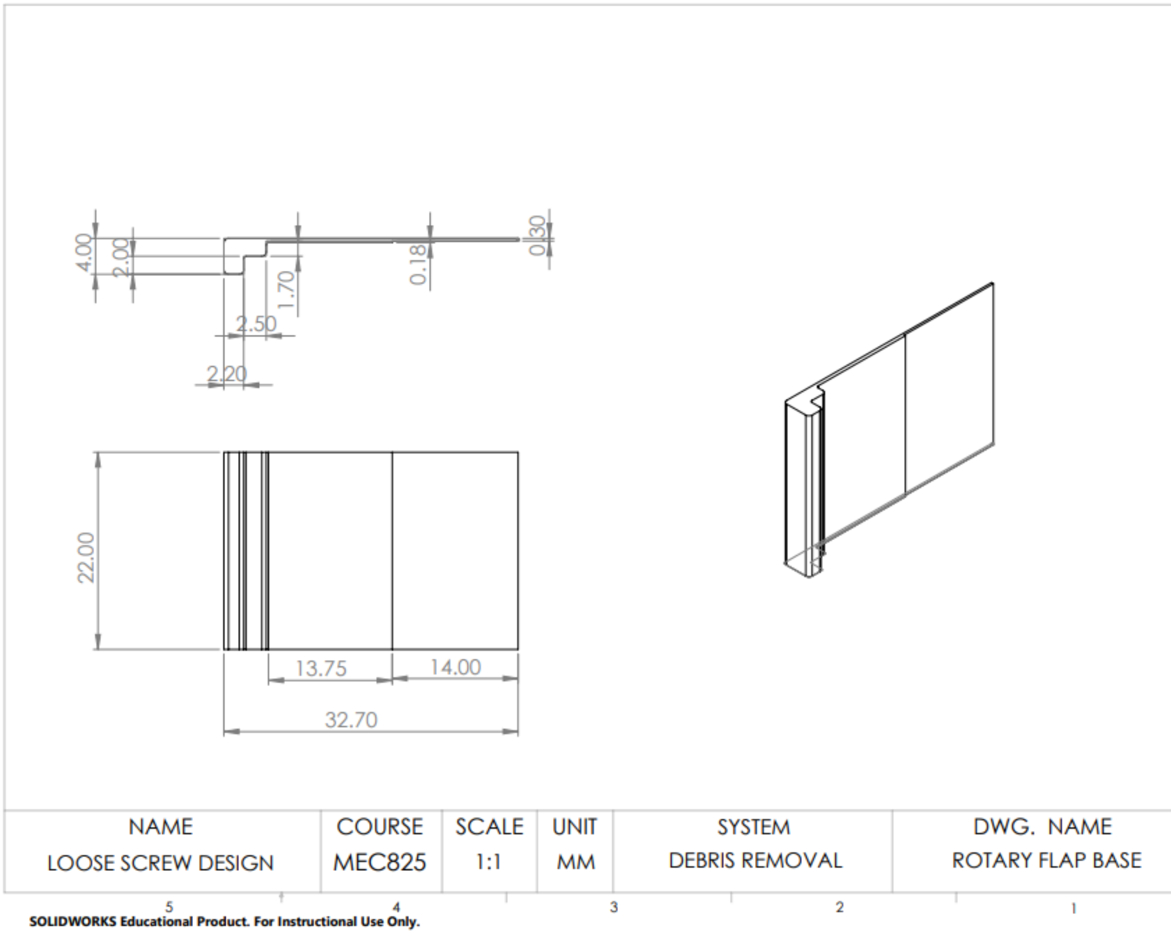
Micro Motor Cover



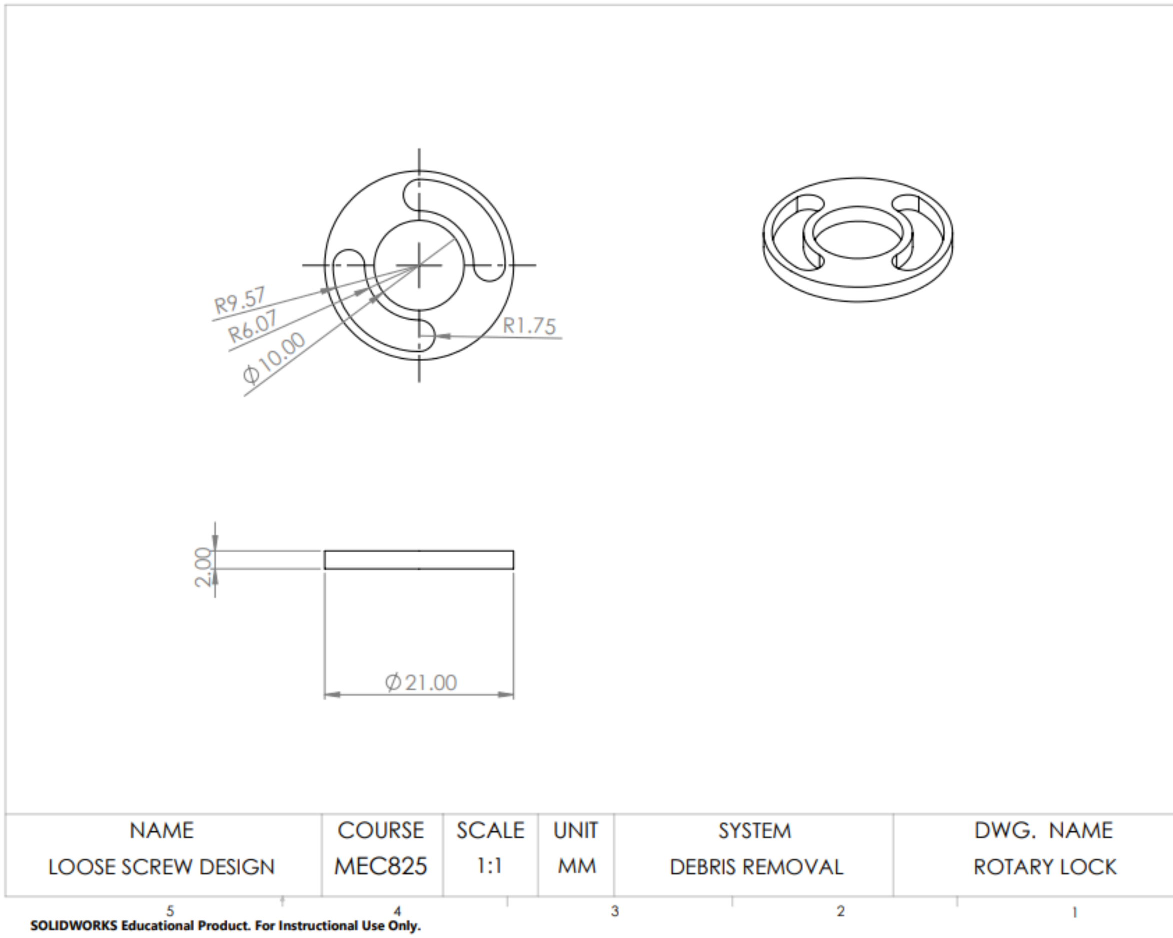
Motor Mounting Plate



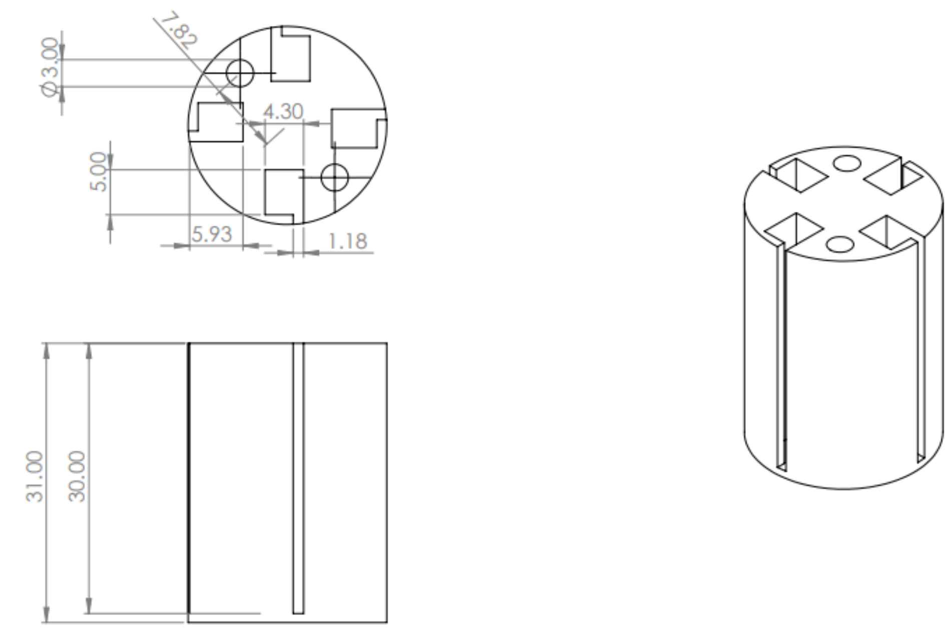
Rotary Flap Base



Rotary Lock


R9.57
R6.07
Ø10.00
R1.75
2.00
Ø21.00
NAME
LOOSE SCREW DESIGN
COURSE
MEC825
SCALE
1:1
UNIT
MM
SYSTEM
DEBRIS REMOVAL
DWG. NAME
ROTARY LOCK
5
4
3
2
1
SOLIDWORKS Educational Product. For Instructional Use Only.

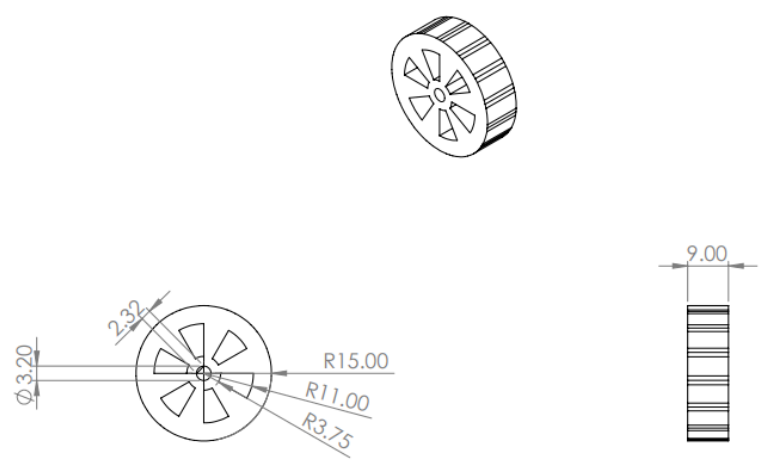
Rotary Piece



NAME	COURSE	SCALE	UNIT	SYSTEM	DWG. NAME
LOOSE SCREW DESIGN	MEC825	1:1	MM	DEBRIS REMOVAL	ROTARY PIECE

5 4 3 2 1

Wheel

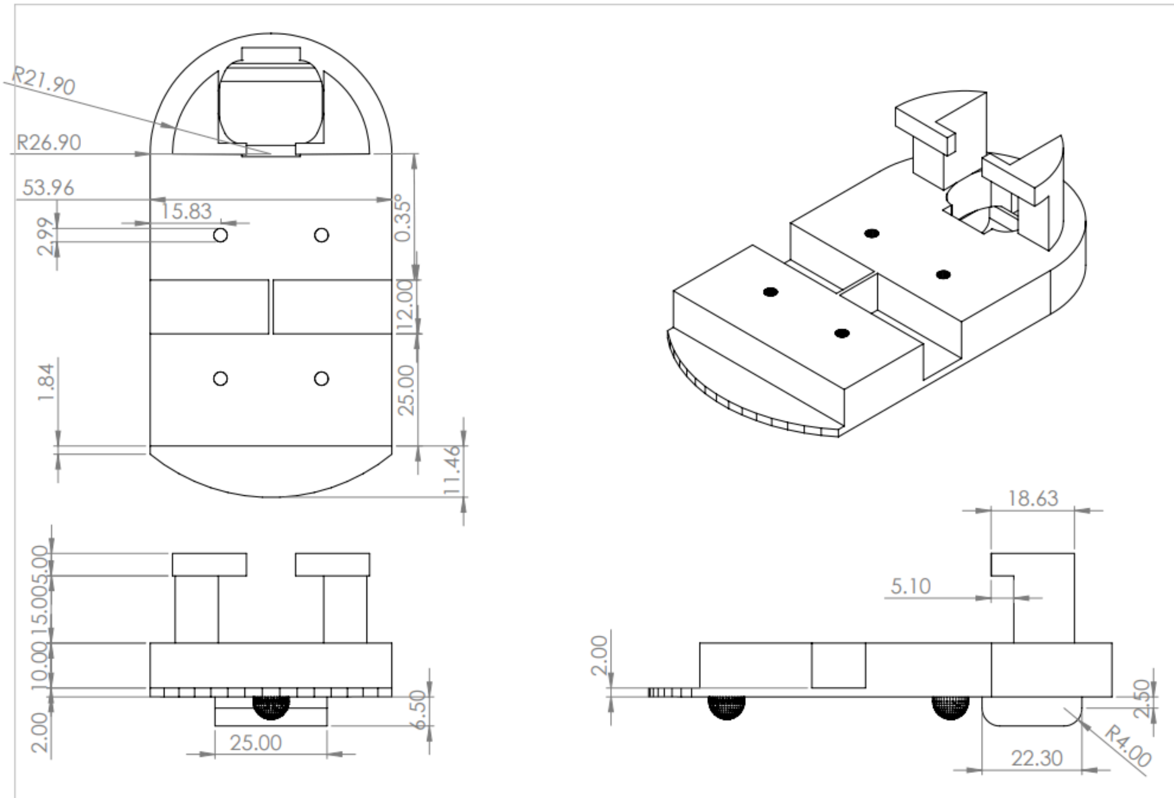


NAME	COURSE	SCALE	UNIT	SYSTEM	DWG. NAME
LOOSE SCREW DESIGN	MEC825	1:1	MM	MOVEMENT	WHEEL

5 4 3 2 1

Toy Motor Design

Base



NAME	COURSE	SCALE	UNIT	SYSTEM	DWG. NAME
LOOSE SCREW DESIGN	MEC825	1:1	MM	MOVEMENT	BASE

5 4 3 2 1

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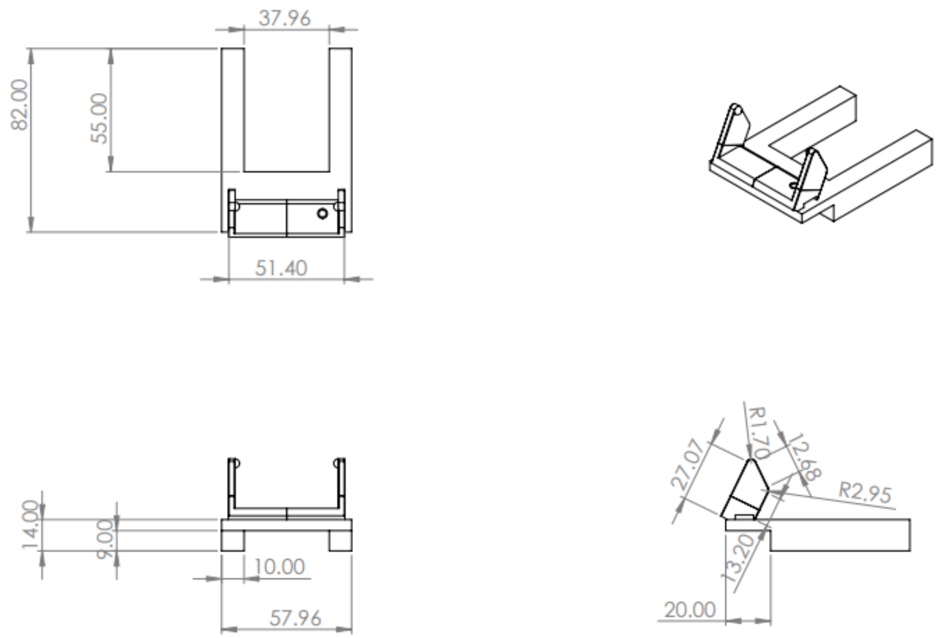
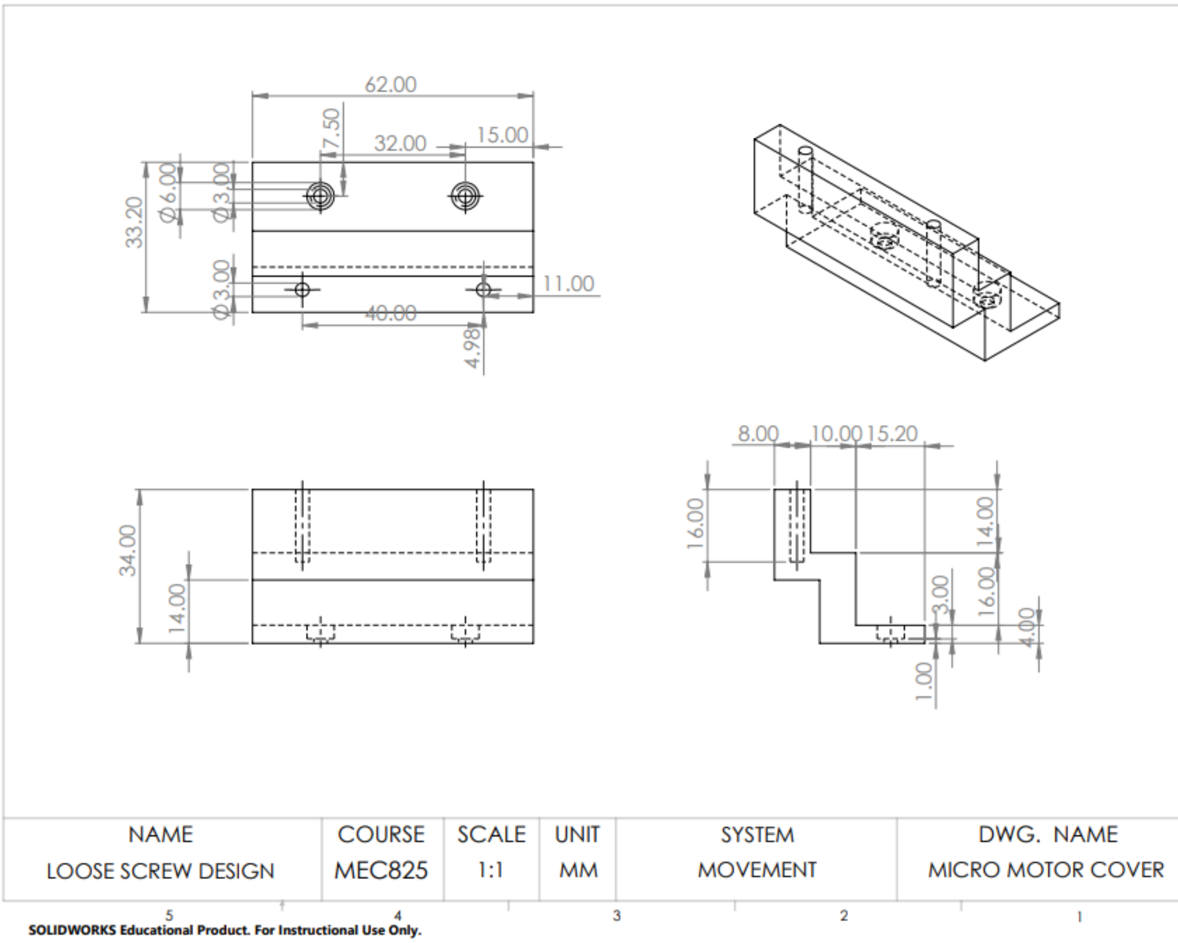
Camera Holder



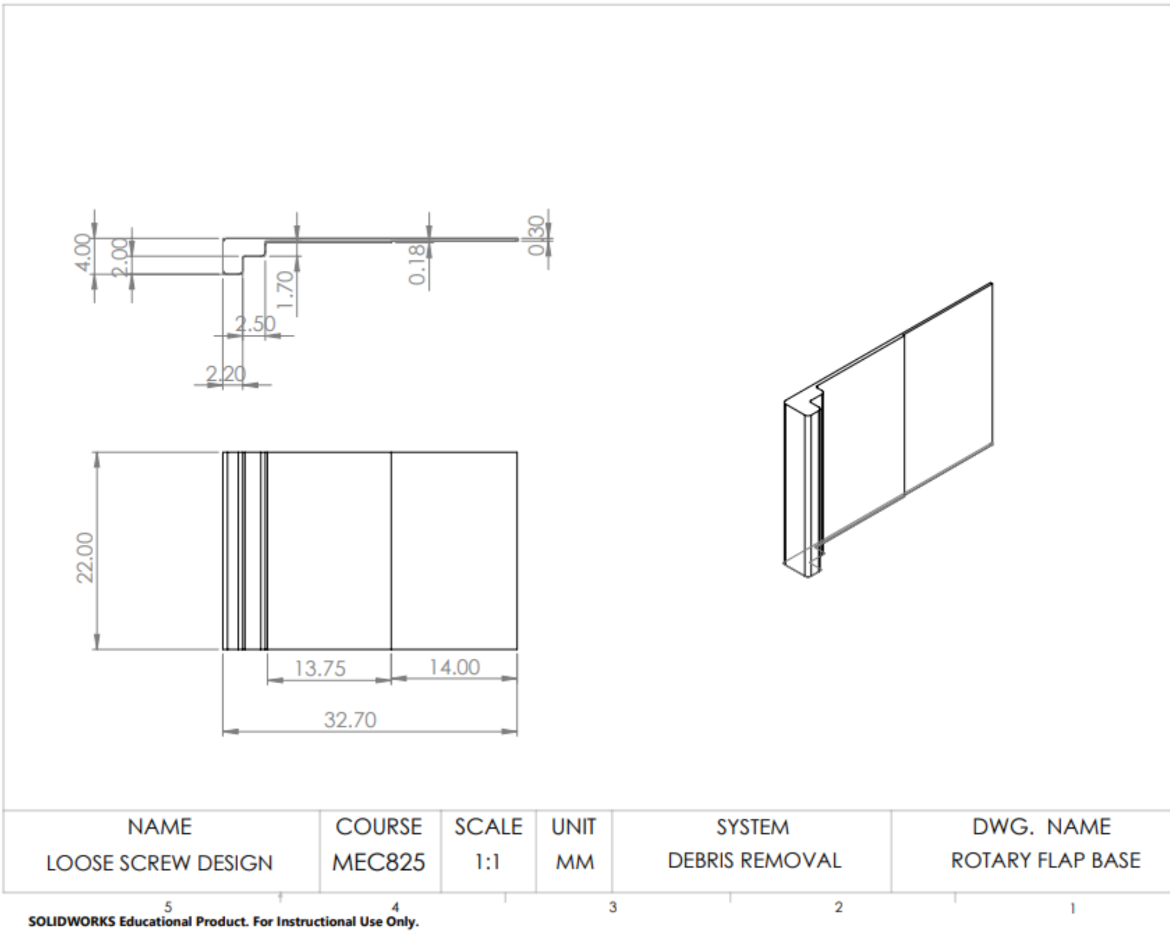
NAME	COURSE	SCALE	UNIT	SYSTEM	DWG. NAME
LOOSE SCREW DESIGN	MEC825	1:1	MM	MOVEMENT	CAMERA HOLDER

5 4 3 2 1

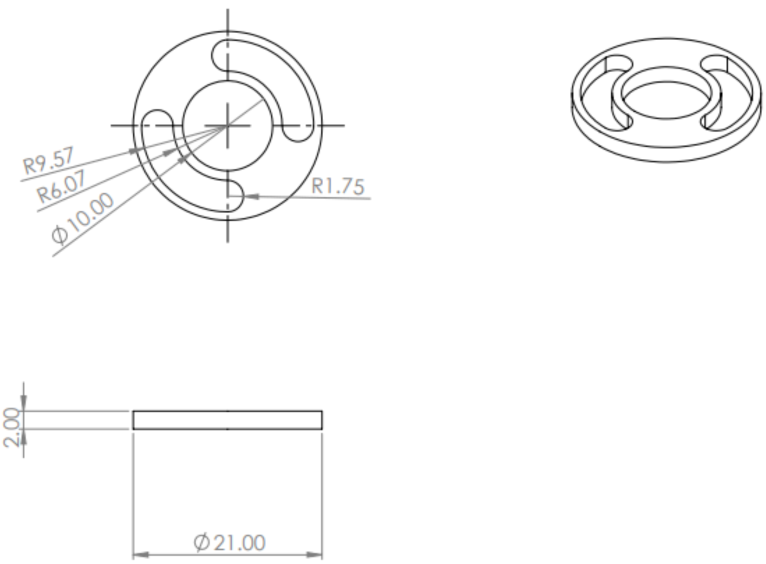
Micro Motor Cover



Rotary Flap Base

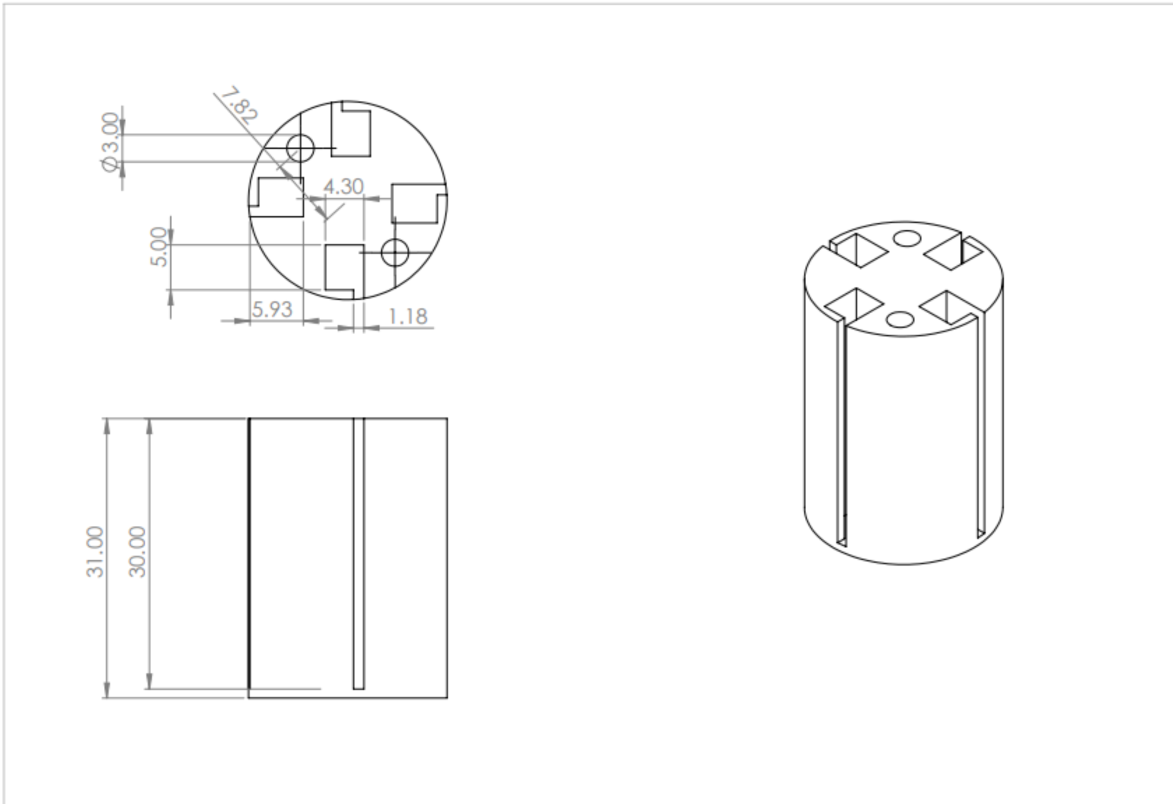


Rotary Lock



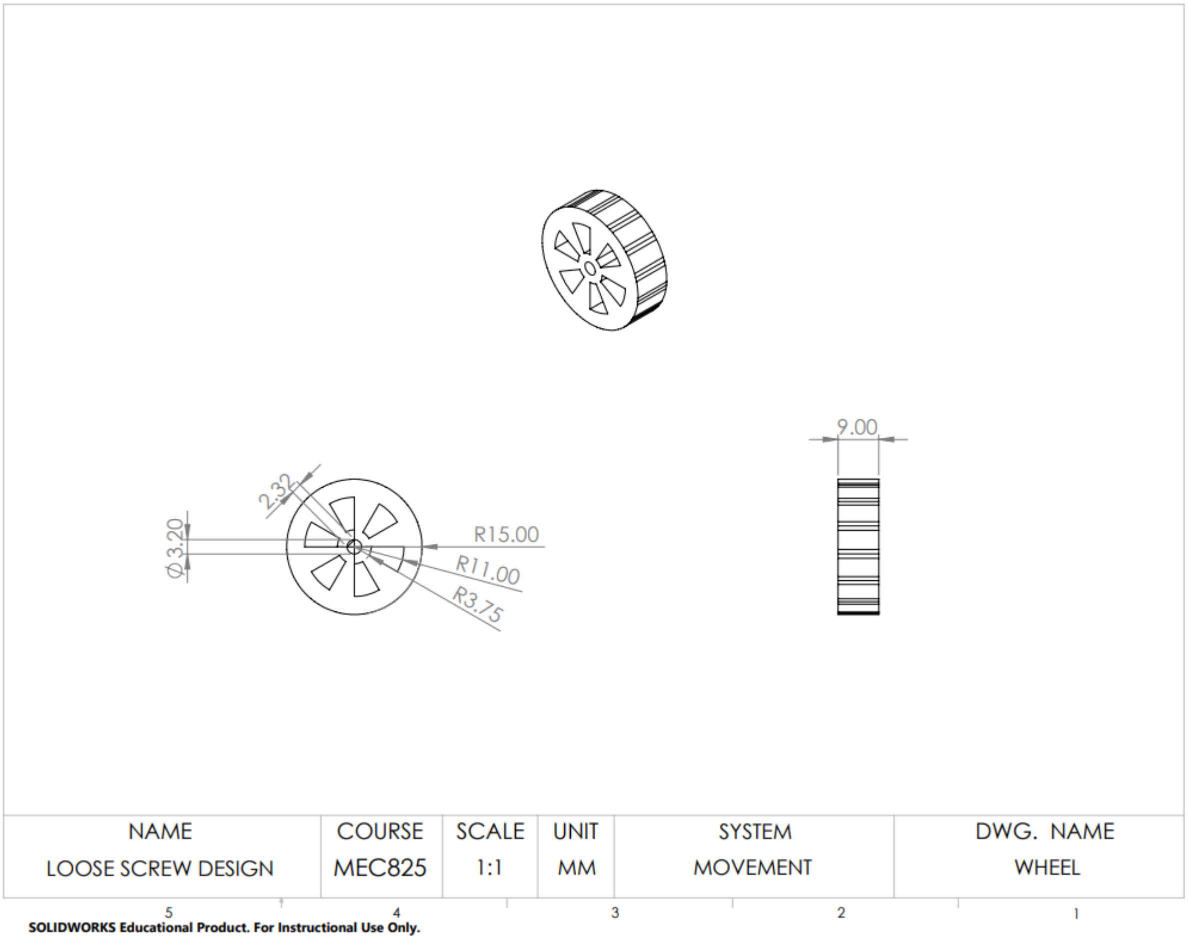
NAME	COURSE	SCALE	UNIT	SYSTEM	DWG. NAME
LOOSE SCREW DESIGN	MEC825	1:1	MM	DEBRIS REMOVAL	ROTARY LOCK

Rotary Piece



NAME	COURSE	SCALE	UNIT	SYSTEM	DWG. NAME
LOOSE SCREW DESIGN	MEC825	1:1	MM	DEBRIS REMOVAL	ROTARY PIECE

Wheel


9.00
2.32
Ø3.20
R15.00
R11.00
R3.75
NAME
LOOSE SCREW DESIGN
COURSE
MEC825
SCALE
1:1
UNIT
MM
SYSTEM
MOVEMENT
DWG. NAME
WHEEL
5
4
3
2
1
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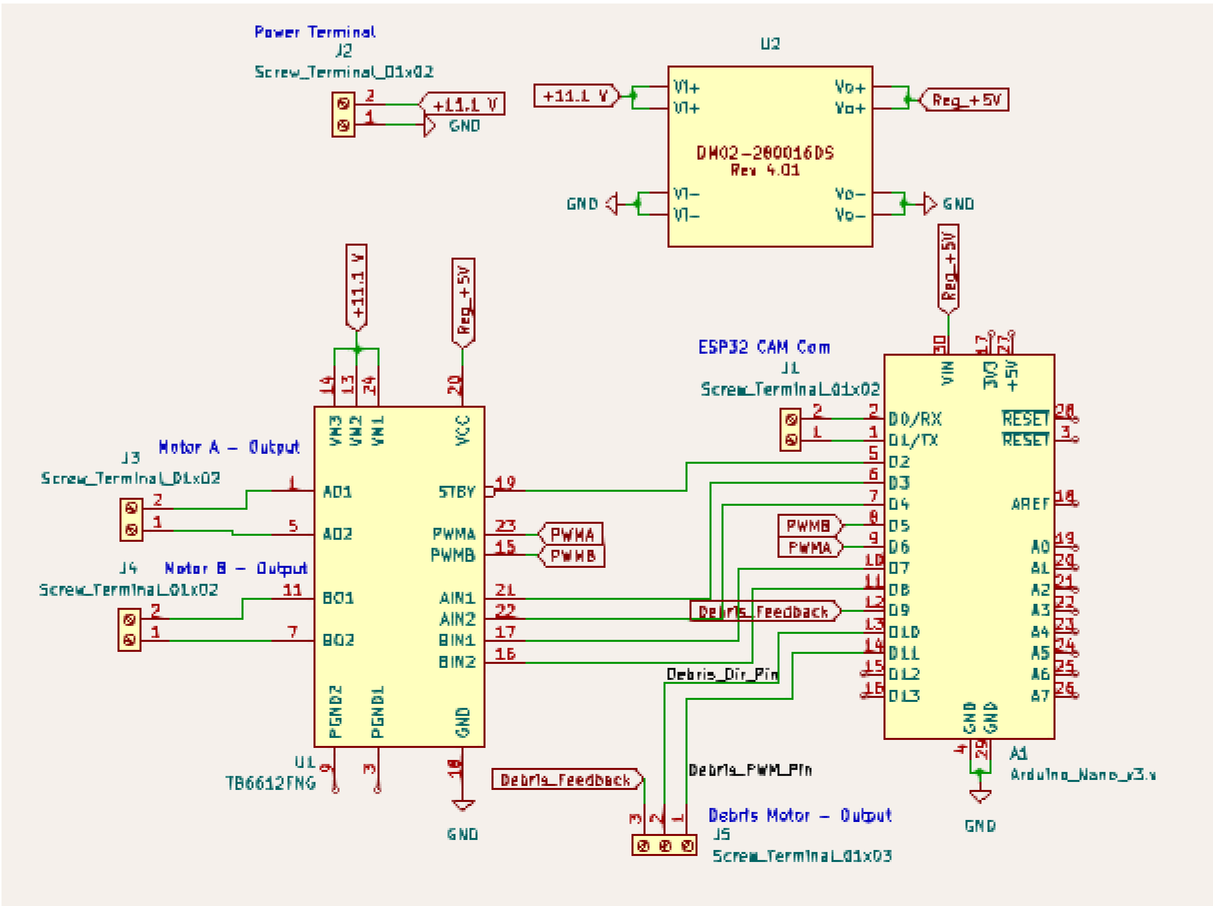
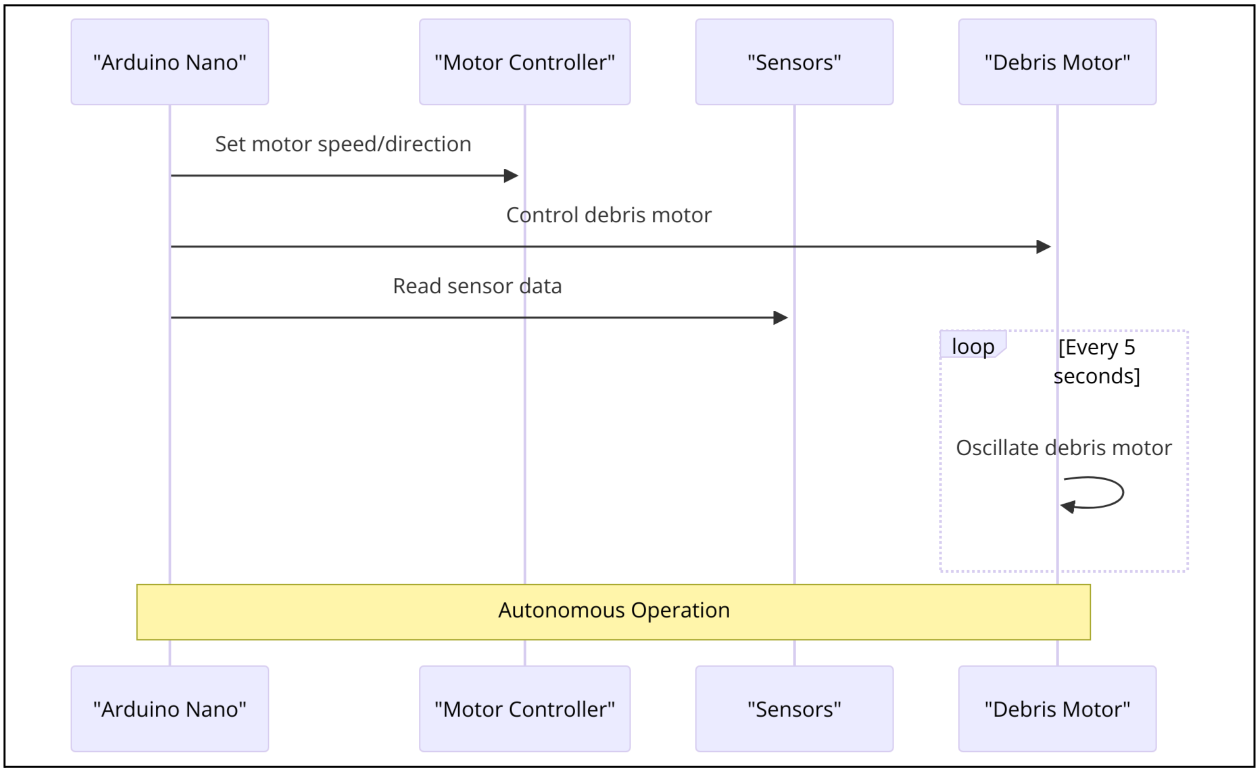
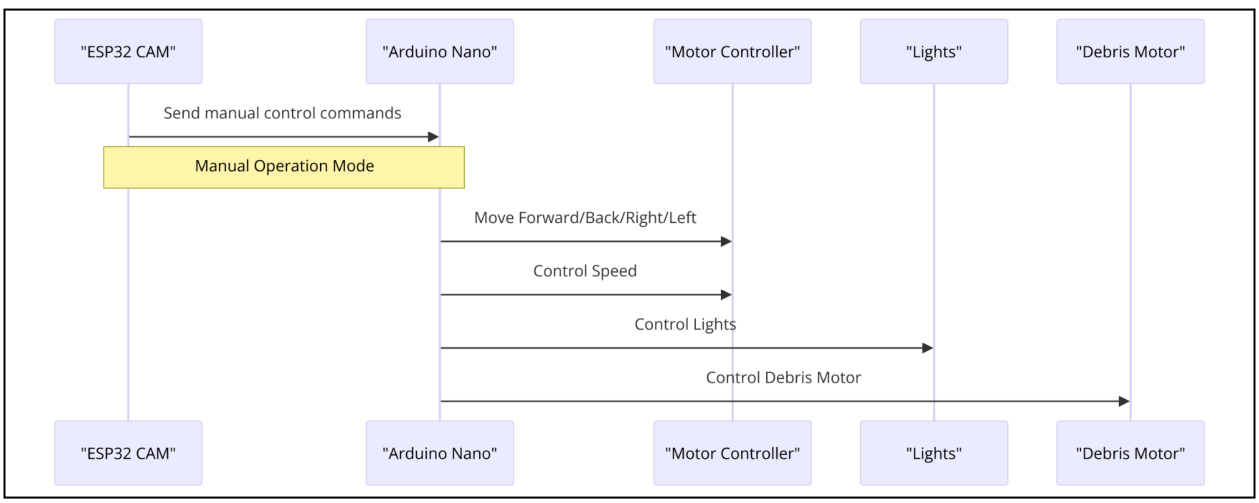
Appendix C - Electrical Drawing and Code

Electrical Diagram







Operation Code:

Arduino Nano:

```
#include <SparkFun_TB6612.h>

class FIT0441_Motor {
 private:
  int directionPin;
  int pwmPin;
  int signalPin;
  unsigned long lastDirectionToggleTime;
  unsigned long oscillationPeriodMillis; // Stores the oscillation period in milliseconds
```

```
  bool directionFlag;

 public:
  FIT0441_Motor(int dirPin, int pwm, int sigPin) : directionPin(dirPin), pwmPin(pwm), signalPin(sigPin), lastDirectionToggleTime(0),
oscillationPeriodMillis(5000), directionFlag(HIGH) {}

  void setup() {
    Serial.begin(115200);
    pinMode(directionPin, OUTPUT);
    pinMode(pwmPin, OUTPUT);
    pinMode(signalPin, INPUT_PULLUP);
    stop();
  }

 void setSpeed(int inputSpeed) {
    // Use map() to invert the speed logic: map from (0, 255) to (255, 0)
    int speed = map(inputSpeed, 0, 255, 255, 0);
    analogWrite(pwmPin, speed);
  }

  void rotateCW() {
    digitalWrite(directionPin, HIGH); // Set direction to clockwise
  }
  void rotateCCW() {
    digitalWrite(directionPin, LOW); // Set direction to counter-clockwise
  }

  void changeDirection() {
    directionFlag = !directionFlag;
    digitalWrite(directionPin, directionFlag);
  }

  void oscillate_mode(int seconds = 5) {
    oscillationPeriodMillis = seconds * 1000UL; // Convert seconds to milliseconds
    if (millis() - lastDirectionToggleTime > oscillationPeriodMillis) {
      changeDirection();
      lastDirectionToggleTime = millis();
    }
  }

  int readSpeed() {
    int i = 0;
    for(int j = 0; j < 8; j++) {
      i += pulseIn(signalPin, HIGH, 500000); // Read the signal pin
    }
    i = i >> 3; // Average the 8 readings. Bit shift of 3 is eqaual divide 2*2*2 = 8

    if(i == 0) {
      return 0; // Avoid division by zero and return 0 if no pulses are read
    }

    int speed = 111111 / i; // Calculate speed in r/min
    Serial.print(speed);
    Serial.println(" r/min");
    return speed;
  }
  void stop() {
    analogWrite(pwmPin,255); // Motor is stopped at PWM 255
  }
};
```

```
// Pins for all inputs, keep in mind the PWM defines must be on PWM pins
// the default pins listed are the ones used on the Redbot (ROB-12097) with
// the exception of STBY which the Redbot controls with a physical switch
#define AIN1 2
#define BIN1 7
#define AIN2 4
#define BIN2 8
#define PWMA 5
#define PWMB 6
#define STBY 9

// DF Robot Motor
#define DEBRIS_MOTOR_PWM 11 // Motor Pin 1 - on our cable its black
#define DEBRIS_MOTOR_DIR 10 // Motor Pin 3 - on our cable its green
#define DEBRIS_MOTOR_FEEDBACK 3  //Motor Pin 4 - on our cable its blue
// these constants are used to allow you to make your motor configuration

// line up with function names like forward.  Value can be 1 or -1
const int offsetA = 1;
const int offsetB = -1;

// Initializing motors.  The library will allow you to initialize as many
// motors as you have memory for.  If you are using functions like forward
// that take 2 motors as arguements you can either write new functions or
// call the function more than once.
Motor drive_motor_1 = Motor(AIN1, AIN2, PWMA, offsetA, STBY);
Motor drive_motor_2 = Motor(BIN1, BIN2, PWMB, offsetB, STBY);

FIT0441_Motor debris_motor = FIT0441_Motor(DEBRIS_MOTOR_DIR, DEBRIS_MOTOR_PWM, DEBRIS_MOTOR_FEEDBACK);

// Define states for the state machine
enum RobotState { MOVING_FORWARD, ROLLING_BACK };
RobotState currentState = MOVING_FORWARD; // Start with moving forward

// Time tracking variables
unsigned long stateChangeTime = 0; // Keeps track of the last time we changed states
const unsigned long movingForwardDuration = 10000; // 10 seconds in milliseconds
const unsigned long rollingBackDuration = 2000;    // 2 seconds in milliseconds

//Declreation
void moveForward();
void rollBack();
void updateState();


void setup()
{
  stateChangeTime = millis(); // Initialize the state change time to the current time
}


void loop()
{
  // forward(drive_motor_1,drive_motor_2, 100); // Move forward at speed 100/255
  // debris_motor.setSpeed(255);

   switch (currentState) {
    case MOVING_FORWARD:
      moveForward();
      break;
```

```
  case ROLLING_BACK:
   rollBack();
   break;
 }
 updateState(); // Check and update the state if necessary

}

void moveForward() {
 forward(drive_motor_1, drive_motor_2, 100); // Move forward at speed 100/255
 debris_motor.setSpeed(255); // Set the speed of the debris motor
}

void rollBack() {
 back(drive_motor_1, drive_motor_2, 100); // Move backward at speed 100/255
 debris_motor.oscillate_mode(0.5); // Oscillate the debris motor
 debris_motor.setSpeed(255); // Set the speed of the debris motor
}

void updateState() {
 unsigned long currentTime = millis(); // Get the current time
 switch (currentState) {
  case MOVING_FORWARD:
   if (currentTime - stateChangeTime >= movingForwardDuration) { // Check if it's time to change state
    currentState = ROLLING_BACK;
    stateChangeTime = currentTime; // Update the time we changed states
   }
   break;

  case ROLLING_BACK:
   if (currentTime - stateChangeTime >= rollingBackDuration) { // Check if it's time to change state
    currentState = MOVING_FORWARD;
    stateChangeTime = currentTime; // Update the time we changed states
   }
   break;
 }
}
```

EPS32 CAM:

```
#include "esp_camera.h"
#include <Arduino.h>
#include <WiFi.h>
#include <AsyncTCP.h>
#include <ESPAsyncWebServer.h>
#include <iostream>
#include <sstream>
#include "SD_MMC.h"

#define LIGHT_PIN 4

#define UP 1
#define DOWN 2
#define LEFT 3
#define RIGHT 4
#define STOP 0

const int PWMFreq = 1000; /* 1 KHz */
const int PWMResolution = 8;
const int PWMSpeedChannel = 2;
```

```
const int PWMLightChannel = 3;

//Camera related constants
#define PWDN_GPIO_NUM     32
#define RESET_GPIO_NUM    -1
#define XCLK_GPIO_NUM      0
#define SIOD_GPIO_NUM     26
#define SIOC_GPIO_NUM     27
#define Y9_GPIO_NUM       35
#define Y8_GPIO_NUM       34
#define Y7_GPIO_NUM       39
#define Y6_GPIO_NUM       36
#define Y5_GPIO_NUM       21
#define Y4_GPIO_NUM       19
#define Y3_GPIO_NUM       18
#define Y2_GPIO_NUM        5
#define VSYNC_GPIO_NUM    25
#define HREF_GPIO_NUM     23
#define PCLK_GPIO_NUM     22

const char* ssid     = "MyWiFiCar";
const char* password = "12345678";

AsyncWebServer server(80);
AsyncWebSocket wsCamera("/Camera");
AsyncWebSocket wsCarInput("/CarInput");
uint32_t cameraClientId = 0;


void setUpPinModes()
{
  //Set up PWM
  ledcSetup(PWMSpeedChannel, PWMFreq, PWMResolution);
  ledcSetup(PWMLightChannel, PWMFreq, PWMResolution);

  pinMode(LIGHT_PIN, OUTPUT);
  ledcAttachPin(LIGHT_PIN, PWMLightChannel);
}



void moveCar(int inputValue) {
  Serial.printf("Got value as %d\n", inputValue);
  switch(inputValue) {
    case UP:
      Serial.println("Forward");  // Sending command through Serial
      break;

    case DOWN:
      Serial.println("Backward");
      break;

    case LEFT:
      Serial.println("Left");
      break;

    case RIGHT:
      Serial.println("Right");
      break;

    case STOP:
```

```
      Serial.println("Stop");
      break;

    default:
      Serial.println("Stop All");
      break;
  }
}


void handleNotFound(AsyncWebServerRequest *request)
{
    request->send(404, "text/plain", "File Not Found");
}

void onCarInputWebSocketEvent(AsyncWebSocket *server,
                      AsyncWebSocketClient *client,
                      AwsEventType type,
                      void *arg,
                      uint8_t *data,
                      size_t len)
{
  switch (type)
  {
    case WS_EVT_CONNECT:
      Serial.printf("WebSocket client #%u connected from %s\n", client->id(), client->remoteIP().toString().c_str());
      break;
    case WS_EVT_DISCONNECT:
      Serial.printf("WebSocket client #%u disconnected\n", client->id());
      moveCar(0);
      ledcWrite(PWMLightChannel, 0);
      break;
    case WS_EVT_DATA:
      AwsFrameInfo *info;
      info = (AwsFrameInfo*)arg;
      if (info->final && info->index == 0 && info->len == len && info->opcode == WS_TEXT)
      {
        std::string myData = "";
        myData.assign((char *)data, len);
        std::istringstream ss(myData);
        std::string key, value;
        std::getline(ss, key, ',');
        std::getline(ss, value, ',');
        Serial.printf("Key [%s] Value[%s]\n", key.c_str(), value.c_str());
        int valueInt = atoi(value.c_str());
        if (key == "MoveCar")
        {
          moveCar(valueInt);
        }
        else if (key == "Speed")
        {
          ledcWrite(PWMSpeedChannel, valueInt);
        }
        else if (key == "Light")
        {
          ledcWrite(PWMLightChannel, valueInt);
        }
      }
      break;
    case WS_EVT_PONG:
    case WS_EVT_ERROR:
```

```
    break;
  default:
    break;
 }
}

void onCameraWebSocketEvent(AsyncWebSocket *server,
                   AsyncWebSocketClient *client,
                   AwsEventType type,
                   void *arg,
                   uint8_t *data,
                   size_t len)
{
 switch (type)
 {
  case WS_EVT_CONNECT:
    Serial.printf("WebSocket client #%u connected from %s\n", client->id(), client->remoteIP().toString().c_str());
    cameraClientId = client->id();
    break;
  case WS_EVT_DISCONNECT:
    Serial.printf("WebSocket client #%u disconnected\n", client->id());
    cameraClientId = 0;
    break;
  case WS_EVT_DATA:
    break;
  case WS_EVT_PONG:
  case WS_EVT_ERROR:
    break;
  default:
    break;
 }
}

void setupCamera()
{
 camera_config_t config;
 config.ledc_channel = LEDC_CHANNEL_0;
 config.ledc_timer = LEDC_TIMER_0;
 config.pin_d0 = Y2_GPIO_NUM;
 config.pin_d1 = Y3_GPIO_NUM;
 config.pin_d2 = Y4_GPIO_NUM;
 config.pin_d3 = Y5_GPIO_NUM;
 config.pin_d4 = Y6_GPIO_NUM;
 config.pin_d5 = Y7_GPIO_NUM;
 config.pin_d6 = Y8_GPIO_NUM;
 config.pin_d7 = Y9_GPIO_NUM;
 config.pin_xclk = XCLK_GPIO_NUM;
 config.pin_pclk = PCLK_GPIO_NUM;
 config.pin_vsync = VSYNC_GPIO_NUM;
 config.pin_href = HREF_GPIO_NUM;
 config.pin_sscb_sda = SIOD_GPIO_NUM;
 config.pin_sscb_scl = SIOC_GPIO_NUM;
 config.pin_pwdn = PWDN_GPIO_NUM;
 config.pin_reset = RESET_GPIO_NUM;
 config.xclk_freq_hz = 20000000;
 config.pixel_format = PIXFORMAT_JPEG;

 config.frame_size = FRAMESIZE_VGA;
 config.jpeg_quality = 10;
 config.fb_count = 1;
```

```
 // camera init
 esp_err_t err = esp_camera_init(&config);
 if (err != ESP_OK)
 {
  Serial.printf("Camera init failed with error 0x%x", err);
  return;
 }

 if (psramFound())
 {
  heap_caps_malloc_extmem_enable(20000);
  Serial.printf("PSRAM initialized. malloc to take memory from psram above this size");
 }
}

void sendCameraPicture()
{
 if (cameraClientId == 0)
 {
  return;
 }
 unsigned long  startTime1 = millis();
 //capture a frame
 camera_fb_t * fb = esp_camera_fb_get();
 if (!fb)
 {
   Serial.println("Frame buffer could not be acquired");
   return;
 }

 unsigned long  startTime2 = millis();
 wsCamera.binary(cameraClientId, fb->buf, fb->len);
 esp_camera_fb_return(fb);

 //Wait for message to be delivered
 while (true)
 {
  AsyncWebSocketClient * clientPointer = wsCamera.client(cameraClientId);
  if (!clientPointer || !(clientPointer->queueIsFull()))
  {
   break;
  }
  delay(1);
 }

 unsigned long  startTime3 = millis();
 Serial.printf("Time taken Total: %d|%d|%d\n",startTime3 - startTime1, startTime2 - startTime1, startTime3-startTime2 );
}



void setup(void)
{
 setUpPinModes();
 Serial.begin(115200);

 WiFi.softAP(ssid, password);
 IPAddress IP = WiFi.softAPIP();
 Serial.print("AP IP address: ");
 Serial.println(IP);
```

```
  if (!SD_MMC.begin()) {
   Serial.println("SD Card Mount Failed");
   return;
  }

   server.on("/", HTTP_GET, [](AsyncWebServerRequest *request) {
   request->send(SD_MMC, "/index.html", "text/html");
  });

  server.on("/style.css", HTTP_GET, [](AsyncWebServerRequest *request) {
   request->send(SD_MMC, "/style.css", "text/css");
  });

  server.on("/script.js", HTTP_GET, [](AsyncWebServerRequest *request) {
   request->send(SD_MMC, "/script.js", "text/javascript");
  });


  // Initialize other server routes and WebSocket handlers

  wsCamera.onEvent(onCameraWebSocketEvent);
  server.addHandler(&wsCamera);

  wsCarInput.onEvent(onCarInputWebSocketEvent);
  server.addHandler(&wsCarInput);

  server.begin();
  Serial.println("HTTP server started");

  setupCamera();
}

void loop()
{
  wsCamera.cleanupClients();
  wsCarInput.cleanupClients();
  sendCameraPicture();
  Serial.printf("SPIRam Total heap %d, SPIRam Free Heap %d\n", ESP.getPsramSize(), ESP.getFreePsram());
}
```

Website Saved on the SD CARD

Index.html:

```
<!DOCTYPE html>
<html>
<head>
  <meta name="viewport" content="width=device-width, initial-scale=1, maximum-scale=1, user-scalable=no">
  <link rel="stylesheet" type="text/css" href="style.css">
</head>
<body class="noselect" align="center" style="background-color:white">
  <!-- Content -->
  <table id="mainTable" style="width:400px;margin:auto;table-layout:fixed" CELLSPACING=10>
    <tr>
      <img id="cameraImage" src="" style="width:400px;height:250px"></td>
    </tr>
    <!-- Control buttons -->
 <tr>
       <td></td>
```

```
        <td class="button" ontouchstart='sendButtonInput("MoveCar","1")' ontouchend='sendButtonInput("MoveCar","0")'><span class="arrows"
>&#8679;</span></td>
        <td></td>
      </tr>
      <tr>
        <td class="button" ontouchstart='sendButtonInput("MoveCar","3")' ontouchend='sendButtonInput("MoveCar","0")'><span class="arrows"
>&#8678;</span></td>
        <td class="button"></td>
        <td class="button" ontouchstart='sendButtonInput("MoveCar","4")' ontouchend='sendButtonInput("MoveCar","0")'><span class="arrows"
>&#8680;</span></td>
      </tr>
      <tr>
        <td></td>
        <td class="button" ontouchstart='sendButtonInput("MoveCar","2")' ontouchend='sendButtonInput("MoveCar","0")'><span class="arrows"
>&#8681;</span></td>
        <td></td>
      </tr>
      <tr/><tr/>
      <tr>
        <td style="text-align:left"><b>Speed:</b></td>
        <td colspan=2>
         <div class="slidecontainer">
            <input type="range" min="0" max="255" value="150" class="slider" id="Speed" oninput='sendButtonInput("Speed",value)'>
          </div>
        </td>
      </tr>
      <tr>
        <td style="text-align:left"><b>Light:</b></td>
        <td colspan=2>
          <div class="slidecontainer">
            <input type="range" min="0" max="255" value="0" class="slider" id="Light" oninput='sendButtonInput("Light",value)'>
          </div>
        </td>
      </tr>
  </table>
  <script src="script.js"></script>
</body>
</html>
```

Script.js:

```
var webSocketCameraUrl = "ws://" + window.location.hostname + "/Camera";
var webSocketCarInputUrl = "ws://" + window.location.hostname + "/CarInput";
var websocketCamera;
var websocketCarInput;

function initCameraWebSocket() {
  websocketCamera = new WebSocket(webSocketCameraUrl);
  websocketCamera.binaryType = "blob"; // Set the WebSocket to receive binary data
  websocketCamera.onopen = function (event) {
    console.log("Camera WebSocket Opened");
  };
  websocketCamera.onclose = function (event) {
    console.log("Camera WebSocket Closed");
    setTimeout(initCameraWebSocket, 2000); // Try to reconnect every 2 seconds
  };
  websocketCamera.onmessage = function (event) {
    var imageElement = document.getElementById("cameraImage");
    var imageUrl = URL.createObjectURL(event.data);
    imageElement.src = imageUrl;
  };
```

```
  websocketCamera.onerror = function (event) {
    console.error("Camera WebSocket Error", event);
  };
}


function initCarInputWebSocket() {
  websocketCarInput = new WebSocket(webSocketCarInputUrl);
  websocketCarInput.onopen = function (event) {
    console.log("Car Input WebSocket Opened");
    // Optionally, send an initial state or synchronize state with ESP32-CAM here
      var speedButton = document.getElementById("Speed");
      sendButtonInput("Speed", speedButton.value);
      var lightButton = document.getElementById("Light");
      sendButtonInput("Light", lightButton.value);
  };
  websocketCarInput.onclose = function (event) {
    console.log("Car Input WebSocket Closed");
    setTimeout(initCarInputWebSocket, 2000); // Try to reconnect every 2 seconds
  };
  websocketCarInput.onerror = function (event) {
    console.error("Car Input WebSocket Error", event);
  };
}

function initWebSocket() {
  initCameraWebSocket ();
  initCarInputWebSocket();
}

function sendButtonInput(key, value) {
  if (websocketCarInput && websocketCarInput.readyState === WebSocket.OPEN) {
    var data = key + "," + value; // Format the command as 'key,value'
    websocketCarInput.send(data);
  } else {
    console.log("Car Input WebSocket is not open. Command not sent.");
  }
}


window.onload = initWebSocket;
document.getElementById("mainTable").addEventListener("touchend", function(event){
  event.preventDefault()
});
```

Style.css:

```
.arrows {
  font-size:40px;
  color:red;
}
.button {
  background-color:black;
  border-radius:25%;
  box-shadow: 5px 5px #888888;
}
.button:active {
  transform: translate(5px,5px);
  box-shadow: none;
}
.noselect {
```

```
 -webkit-touch-callout: none; /* iOS Safari */
   -webkit-user-select: none; /* Safari */
    -khtml-user-select: none; /* Konqueror HTML */
      -moz-user-select: none; /* Firefox */
       -ms-user-select: none; /* Internet Explorer/Edge */
           user-select: none; /* Non-prefixed version, currently
                                 supported by Chrome and Opera */
}

.slidecontainer {
 width: 100%;
}

.slider {
 -webkit-appearance: none;
 width: 100%;
 height: 15px;
 border-radius: 5px;
 background: #d3d3d3;
 outline: none;
 opacity: 0.7;
 -webkit-transition: .2s;
 transition: opacity .2s;
}

.slider:hover {
 opacity: 1;
}

.slider::-webkit-slider-thumb {
 -webkit-appearance: none;
 appearance: none;
 width: 25px;
 height: 25px;
 border-radius: 50%;
 background: red;
 cursor: pointer;
}

.slider::-moz-range-thumb {
 width: 25px;
 height: 25px;
 border-radius: 50%;
 background: red;
 cursor: pointer;
}
```