24-671 Special Topics: Electromechanical System Design

A.C.I.D.S

(Automated Customizable Ice Dissolving System)

Final Report

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Group 2

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1. Executive Summary

During a snowy winter, the icing on the ground can be a serious safety concern for pedestrians and vehicles, and removing the icing can be difficult and exhausting. To provide a possible solution to the safety concern and inconvenience, we proposed a stationary turret that can autonomously aim at the targeted area and dispense snow-melting solutions to melt ice, requiring only minimum human effort to push the power button and occasionally supply salt solutions in the solution tank. Under the name of A.C.I.D.S, this turret is best to guard the small but complex areas where neither snow plow nor salt spreader truck can reach.

We started from this concept and researched the market for competitors. After concluding the advantages of our concept over the alternatives on the market, we began to determine our stakeholders through brainstorming. Then we conducted surveys among our determined stakeholders to get user expectations and suggestions to further enrich our design requirements. After generating various design concepts, we selected the most promising design mainly based on its functionality, cost efficiency, and feasibility under time and budget constraints. Then we started building prototypes according to the selected design concept and refined it during the process. Each time we tested and received feedback from early prototypes, we discussed and made improvements on previous work. By the end of this semester, we successfully built our final prototype that satisfies most of our expectations.

Our final prototype significantly improved upon our Prototype 1 described in the mid-semester report. Mechanically, we replaced the weak servo motors and stiff garden hoses with two significantly more powerful stepper motors and bendable shower hoses, making the nozzle movement more precise and reliable. The supporting frame was reinforced with a strong metal base and water-proof protective shell to make our system safer, more stable, and more visually appealing. A solar panel was also installed on top of our structure to provide replenishable power to our rechargeable battery during sunny days.

On the electronic side, we built the polynomial regression function between the distance PWM value and vertical angle, providing an accurate control of the area to spray. Additionally, we incorporated the Raspberry Pi and its camera into our system and achieved I2C communication with our Arduino Mega. Once the Pi camera captured a photo, the Raspberry 5 loaded with pre-trained algorithms could determine the 3D coordinates of any given pixel and then generate a list of sparse points representing the user-selected shape. Each point on the photo could be sent to the Arduino Mega with a sophisticated control algorithm to control the voltage of a PWM pump, the angle of one horizontal motor, and the angle of one vertical motor to aim for and spray at the selected region.

However, our final prototype did not satisfy all of our expectations. Firstly, the user-generated shape cannot be directly sent from Raspberry Pi to Arduino due to the transfer limitation of I2C communication, only allowing a single point to be sent each time. Additionally, our 12-volt battery could not provide enough current to all the components simultaneously, resulting in our Raspberry Pi relying on a secondary power source during the final demo to function properly. These flaws were caused mainly by our oversight in material selection, physical analysis, and imperfect scheduling, and each of our group members had to learn to avoid them during future projects.

2. Problem Definition

2.1. Problem Description

The snowfall can facilitate icing on the ground surface during the winter, which can raise significant safety concerns for people [1], and the manual removal of ice from driveways, sidewalks, and stairs can be challenging, particularly for individuals with limited physical capabilities or those leading busy lives. In our conducted survey, 88% of homeowners reported that the physical strain of ice removal has prevented them from adequately clearing their properties[4], indicating that these individuals are unable to ensure completely ice-free environments, increasing the risk of accidents and injuries from slips and falls. These accidents are especially dangerous for the elderly and those with disabilities, as they are more vulnerable to these injuries[5]. Additionally, the time-consuming and exhausting nature of manual ice removal detracts people from other activities, reducing their overall quality of life and contributing to stress and physical fatigue. To provide a solution to this problem, we proposed a device that automatically distributes ice-melting solutions in desired areas even with complex shapes to help users save time, reduce physical strain, and minimize injury risks. If successfully implemented, this innovation would particularly benefit the elderly, those with disabilities, and those busy in life, offering them a way to maintain safe, ice-free environments independently.

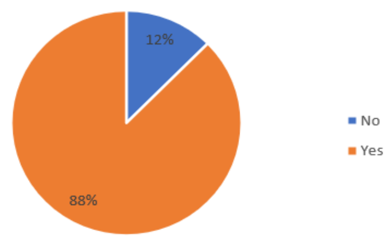


Figure 1: Ice Removal Questionnaire Survey Result, Struggle with Ice Removal

2.2. Markets Addressed

As shown in Figure 2, 75% of respondents believed an automated ice removal device would be highly beneficial for easing their winter maintenance chores[4]. The primary market for A.C.I.D.S will be the elderly and homeowners with physical limitations, as the device's ability to maintain an ice-free outdoor environment can benefit them to a great extent. Secondary markets include busy homeowners who, although capable of manual ice removal, appreciate the time savings and reduced effort.

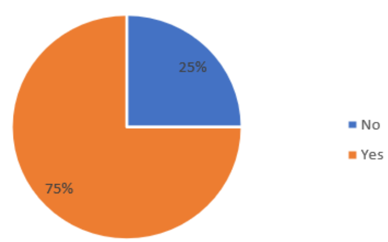


Figure 2: Ice Removal Questionnaire Survey Result, Interest in Automated System

2.3. Current State of Ice Removal Device

In the current market landscape, A.C.I.D.S stands alone with its specialized function; however, several alternative products address the ice removal problem with different approaches. The primary indirect competitor is the under-driveway heating system, which employs embedded snow-melting mats. According to our survey, although this system can melt ice efficiently and work autonomously once installed, it demands significant initial outlay and energy consumption. Specifically, installation alone costs more than $5000, and it operates at a substantial 25kW for a medium-sized area, in stark contrast to our energy-efficient, solar-powered system. Furthermore, its fixed installation lacks adaptability to complex contours and pre-existing structures, limiting its application to flat, pre-planned surfaces[6].

Winter service vehicles are another potential indirect competitor due to their effectiveness in clearing large spaces, like public roads. These vehicles can distribute de-icing chemicals quickly over extensive areas. Yet, their scale and expense render them impractical for personal use; their operations are not only costly but require manual oversight, falling short of the convenience offered by our system. Regarding precision, these vehicles cannot compete with A.C.I.D.S, which boasts adjustable spray angles and targeted application, making it ideal for small and intricate areas that demand meticulous attention. [7]

Consequently, while these indirect competitors are good at serving their niches, they fail to address the market gap A.C.I.D.S fills — providing a cost-effective, precise, and fully automated de-icing solution for residential and complex surface areas.

Figure 3: Indirect competitors
(a) Under-Driveway Heating System
(b) Winter service vehicle

2.4. Assumptions and Constraints

The constraints shaping the development of A.C.I.D.S are primarily governed by the physical context in which it operates and the user interaction required for its functionality. We recognize the operational limitations imposed by environmental structures — tall obstacles could impede the solution's dispersal, potentially diminishing the device's effective range. Accordingly, we presuppose that our device will be strategically placed in areas free from such obstructions to leverage its maximum coverage capability. Additionally, the assumption is made that the device will be situated in sunlit areas, capitalizing on our solar panel's capacity for sustainable energy capture, thereby ensuring efficient battery recharge during daylight hours.

Operational constraints of our design include the finite scope of the spray radius, which is currently limited to a distance of 5-8 meters owing to the specifications of our chosen pump. The limitations of our hardware, specifically the stepper motors and camera platform, constrain our system's ability to achieve comprehensive coverage across all possible angles. Regarding system maintenance, our design necessitates user vigilance in monitoring the ice-melt solution level, requiring manual replenishment once depleted.

Another notable constraint is the need for manual activation. Our current design does not support autonomous activation, hence relying on the user to activate the power button. This necessity serves to optimize the effectiveness of A.C.I.D.S by allowing operation at the discretion of the user, tailored to the prevailing weather conditions, and to prevent wasting solutions. Despite these limitations, our design endeavors to deliver a practical and user-friendly solution to the challenge of ice removal on complex surfaces.

3. Stakeholders and Customer Needs

3.1. Stakeholder Identification

The stakeholders for the A.C.I.D.S span a broad range of individuals and groups that are likely to try and benefit from our project. The primary stakeholders encompass homeowners with small to moderate-sized properties, particularly those with complex outdoor areas such as courtyards and stairways. Unlike apartment dwellers or renters, these homeowners are usually highly motivated to maintain ice-free spaces for both safety and aesthetics. The A.C.I.D.S automates the de-icing process, ensuring these areas remain safely walking through and visually appealing without the need for laborious manual efforts.

Within this key stakeholder group, specific subgroups are distinguished by unique needs: busy workers and students with tight schedules, elderly individuals, people with disabilities, and those living alone. Notably, there is significant overlap within these subgroups: a busy professional may also live alone, and an elderly individual may have a disability, further amplifying the necessity for an automated de-icing solution that simplifies operation and management. People and groups with one or more of the mentioned features will be our primary stakeholders and other people owning the courtyard or driverways will be our secondary stakeholders.

For the time-constrained workers and students, as well as those living alone, the A.C.I.D.S. represents an invaluable tool. It reduces the burden of manual ice clearance, a frequent winter necessity, freeing up precious time for other essential activities or much-needed leisure.

Elderly individuals and those with disabilities encounter substantial hurdles in manually removing ice, a task that is physically demanding and fraught with injury risks. The A.C.I.D.S addresses this by eliminating the manual effort required, significantly lowering injury risks and bolstering the autonomy of these individuals within their homes.

Moreover, the entities responsible for large outdoor spaces, such as corporate campuses, educational institutions, and residential complexes, alongside the service providers that cater to these areas, are integral stakeholders. They require effective, scalable solutions that minimize manual labor while maximizing safety and accessibility.

Resellers and distributors are also critical stakeholders, as they are key to the widespread availability of the A.C.I.D.S. The system’s design accommodates easy shipping and storage, streamlining logistics and ensuring the product’s appeal in broader markets.

By carefully addressing the unique needs and concerns of these diverse stakeholders, A.C.I.D.S is designed to offer a robust, effective solution that enhances safety and convenience for a broad spectrum of users in snowy regions. Each stakeholder group’s specific requirements and interactions with our system significantly influence our approach to product development, marketing, and customer support, ensuring that our device meets their diverse and critical needs.

3.2. Customer Needs

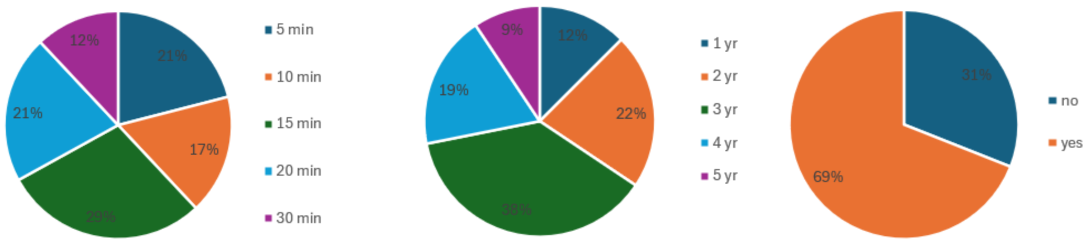


Figure 4: Ice Removal Questionnaire Survey Result
(a) Installation Time
(b) Working Lifespan
(c) Appealing Design

To accurately capture the needs of potential users for our system, our team conducted a comprehensive survey with 32 homeowners in the community through face-to-face meetings. The full list of original survey questions can be found in Appendix A. Key findings from the survey are shown in Figure 4, which underscored the paramount importance of ease of installation, with two-thirds of respondents desiring a system that could be set up in 15 minutes or less, and a robust working lifespan of at least three years[4]. Another crucial aspect of the design is aesthetics, with 69% of respondents expecting the device to visually complement their living spaces[4]. These insights have prompted us to integrate a dual-functionality design, ensuring ice-melting capabilities while enhancing courtyard aesthetics without the need for additional installations. This prioritization of convenience, longevity, and aesthetics guided our classification of customer needs into specific categories including 'Functional Needs,' 'Convenience Needs,' 'Aesthetic and Design Needs,' 'Operational Needs,' and 'Safety Needs' as shown in Table 1. These categories and needs were developed and refined through a collaborative process involving brainstorming sessions and leveraging our technical expertise, ensuring our design meets and exceeds the expectations of our stakeholders.

4. Target Specifications

4.1. Consumer Need

To ensure the de-icer dispenser meets essential user requirements, it is designed to cover at least the average driveway width of 10 feet or approximately 3 meters. However, our goal is to demonstrate that the device can consistently achieve a de-icing range of 5 to 8 meters, accommodating larger driveways and diverse property layouts. We will validate this range through methodical testing, which involves recording the distance that the de-icer is sprayed across a series of trials.

Alongside range, aesthetic appeal is also a priority; a nicer appearance complements a variety of home exteriors. Durability is also another crucial metric, with an expected operational lifespan of at least five years under normal winter conditions, minimizing the need for frequent replacements. Cost-effectiveness is equally essential, ensuring the product remains affordable for our target demographic. Additionally, we aim for ease of installation and maintenance to prevent any additional burden on the consumer post-purchase. Through these metrics, we aspire to fulfill users' functional demands and provide a cost-efficient, durable, and visually pleasing solution for winter conditions.

For detailed customer needs, refer to Table 1.

Category	#	Customer Need	Importance
Functional	1	The device can cover a wide range.	3
	2	The device can rotate freely at a large angle.	3
	3	The device can shoot solutions at a long distance.	4
	4	The device can shoot solutions within a user-defined region without splashing outside.	5
	5	The device can precisely control the angle and distance of the spray.	5
	6	The device allows the user to select the region that needs to be de-iced.	5
Convenience	7	Quick and easy installation process.	1
	8	Convenient shipment and storage process.	4
	9	The device is designed with modular components that can be assembled using screws.	4
	10	The device is lightweight.	2
	11	Simple and mess-free refilling process.	5
	12	The device operates with a long lifespan without maintenance.	5
Aesthetic and Design	13	The device offers a complementary decoration to the outdoor environment.	3

Operational	14	The device offers a user-friendly interface for easy operation.	3
	15	The pump can operate quietly.	2
	16	The device is powered by solar power.	3
	17	The battery can support several rated power operations.	4
Safety	18	The electronics can operate in varying winter conditions.	4
	19	The components are protected against the corrosive ice-melting solution.	5
	20	The solution tank prevents solutions from splashing outside during refilling processes.	2
	21	The device can steadily stand on the ground in all weather conditions.	5
Other	22	The device is low-cost.	1

Table 1: Customer Needs Metrix

4.2. Competitive Analysis

Looking at the competition for our A.C.I.D.S system, we see that while there are no direct competitors with our design, some substitutes are offering different ways to tackle ice removal. These include snow-melting heated driveway and winter service vehicles. The heated driveway is a fast way to melt ice but comes with a high price, both in terms of initial setup and energy costs. They are designed to fit the specific driveway, which means their adaptability to the unique contours of different properties is limited. Moreover, their heavy reliance on electricity can be a significant drawback, especially in areas where energy costs are high.

On the other hand, winter service vehicles have high efficiency in covering large areas quickly and can carry large amounts of ice-melt material. However, their size, cost, and the need for manual operation make them impractical for residential use or for tackling smaller, complex spaces that require precise targeting. Operating these vehicles requires significant human efforts, making them a less attractive option for individuals or businesses looking for a simple solution.

In the competitive landscape another “competitor” would be people choosing to salt their driveways themselves. We stand out with its focus on automation. The alternative relies on manual labor for the processes and caters to people with ample free time. Our company prioritizes ease of use, especially for elderly citizens. Additionally, our offering boasts automatic dispensing capabilities, a feature absent in any industry players' products, signifying a leap forward in convenience and efficiency. Moreover, our extensive utilization of sensors, and convolutional neural networks sets us apart, enabling advanced functionality and enhancing user experience. Despite the absence of direct competitors in this niche market, our innovative solutions position us as pioneers in addressing the unmet needs of our target audience, promising significant market potential and growth opportunities.

Figure 5: Competitive

Our A.C.I.D.S system stands out by offering a unique solution that addresses these issues. It is designed to be user-friendly, requiring only a one-time setup. Once the setup is completed, it will operate mostly autonomously, only requiring manual activation and periodic solution supply. The system's precision in targeting specific areas ensures that ice melt solutions are used efficiently, avoiding waste and minimizing environmental harm. Additionally, its capability to reach tight and complex spaces makes it more versatile than traditional heated driveway or service vehicles. This precision, combined with the system's autonomous nature, means that A.C.I.D.S is not only a practical solution for ice removal but also a smart investment in safety and convenience. By eliminating the need for manual spreading of ice melt solutions and reducing the risk of slips and falls, A.C.I.D.S offers convenience for homeowners, especially those with limited physical ability or time. This thorough comparison highlights the innovation of A.C.I.D.S, showcasing its potential to meet the needs of a market seeking efficient, cost-effective, and user-friendly ice removal solutions.

4.3. Target Specifications

Matrix Number	Need Number	Matrix	Unit	Marginal	Ideal
1	1,2,3	The device sprays over a large sector area with a large radius and wide angle	Meters & Degree	5±0.2 meters & 90°±5°	8±0.5 meters & 120°±10°
2	4,5,6	The device can shoot solutions within a user-defined region with small or no error	Centimeter	5±1	1±0.5
3	7,8,9,10,11	Quick and easy installation process.	Minutes	60±20	20±5
4	8,9,10	Convenient shipment and storage process.	N/A	N/A	N/A
5	10	Simple and mess-free refilling process.	N/A	N/A	N/A
6	12,18,19,20,21	The device operates with a long lifespan without maintenance.	Year	2±0.5	5±1

7	13,15	The device offers a complementary decoration to the outdoor environment.	N/A	N/A	N/A
8	7,10,14	The device offers a user-friendly interface for easy operation.	N/A	N/A	N/A
9	19,20,21	The electronics can operate in all winter conditions.	N/A	Under -20±5 ℃	Under -30±5 ℃
10	22	The device is cost-competitive	USD	750±200	400±50

Table 2: Target Specification

In Table 2, we define the target specifications that embody the performance and operational expectations for the A.C.I.D.S system. These specifications are instrumental in guiding the design process, ensuring that the device meets the practical needs and desires of our stakeholders.

The first specification highlights the operational reach of the device, targeting a substantial spray coverage with specified radius and angle dimensions. Ideally, the device should cover an 8-meter radius with a 120-degree angle, providing extensive coverage suitable for diverse property layouts and ensuring that no area prone to icing is left untreated.

The precision with which the device can target and treat specified areas is critical, as outlined in the second specification. The aim is for a minimal margin of error, ideally within a mere 1 centimeter, to ensure that the de-icing solution is applied exactly where needed, reducing waste and increasing efficiency.

Installation ease and speed are the focus of the third specification, recognizing the importance of user-friendly design. The goal is to make the setup process as swift as 20 minutes, allowing users to quickly deploy the system as soon as it is needed, which is especially valuable during sudden weather changes.

The specifications also prioritize the system's longevity and minimal maintenance requirements, emphasizing the device's capability to operate effectively for up to five years without significant upkeep. This durability is essential for providing users with a reliable solution throughout multiple winter seasons, thereby enhancing user satisfaction and trust in the product.

Lastly, the cost-competitiveness of the device is addressed in the tenth specification. An ideal price point is targeted at approximately $400, making the A.C.I.D.S system an affordable option for a broad range of consumers. This pricing strategy is intended to make the innovative technology accessible to more households, increasing the product's market penetration and impact.

Each specification in Table 2 has been crafted with the utmost consideration for the functional, aesthetic, and economic aspects of the device, ensuring that it not only functions effectively as a de-icing tool but also integrates seamlessly into the user's environment and lifestyle.

5. Concept Generation

5.1. Concept Generation

Initially, we proposed two possible directions: a static spraying turret or an autonomous moving robot. Users would like to use the device on various terrains, making the stationary design a preferred choice, as an autonomous robot traversing through complex terrain and spraying solution will be difficult to design with the time and resource limitations. Once this decision was made, our focus shifted to a static device that only is responsible for cleaning its surrounding area. With the focus in mind, we separated our system into 4 subsystems: the Power subsystem, the Mechanical Subsystem, the Sensing Subsystem, and the Control subsystem.

Power system:

The power system serves as the backbone of the entire setup, supplying the necessary energy to all components of the de-icer dispenser. Since different electrical components may have different rated voltages, we need a high-voltage power source and several linear regulators to provide optimal voltage for each component.

Thus, we soon discuss with each other the selection of our power supply. By brainstorming and research, we found that the technique for solar panels is very developed nowadays. The solar panels are enough to support 12V voltage to the system, which can be sufficient for the pump and motors. We also chose a wall plug, as we believe that a wall plug would provide a much more stable voltage to the system than other choices. Lastly, we chose a battery, which is indeed a middle choice between solar panels and wall plugs.

Figure 6: Selections of Power System

Mechanical system:

The mechanical system provides the fundamental functionality of the dispenser, including nozzle angle adjustment and pumping power. It should be engineered to precisely and efficiently dispense the ice-melting solution onto user-predefined surfaces after receiving the control signal from the control subsystem. After short research on the motors and pumps, we decided to use a PWM pump, two stepper motors, and one nozzle to achieve the dispense tasks.

Sensing system:

The sensing system should collect critical environmental data, such as distance to selected areas and obstacles, to accurately dispense ice-melting solutions to the area while avoiding dispensing on humans, animals, and vehicles. These data should be constantly monitored and analyzed to determine when and where the dispense action is required.

We talked about our ideas with the professor and then researched the technique now people use for vision. We concluded that the computer vision technology is very developed, and it will be sufficient to finish the task. However, it is possible that the hardware device we are using can not provide enough computing power. We thus include sonar and lidar. While sonar is cheap, it cannot provide accurate data. Lidar on the other hand will be too expensive compared to other choices.

Figure 7: Selections of Sensing System

Control system:

The control subsystem receives and processes input from the sensing subsystem to make decisions for the mechanical subsystem. This subsystem should utilize algorithms and analyze collected data to generate control signals that dictate the operation of the mechanical components, ensuring timely and efficient de-icing. We decided to use Arduino Mega in our design as we realized that the Arduino Uno didn’t have enough pins to support our control algorithm.

5.1.1. External Search

In detail for our research for the components, we utilized online resources to search for suitable sensors to ensure functionality across various subsystems. In the mechanical subsystem, we explored diverse design options to ensure optimal functionality and user acceptance. Factors such as stability, portability, and aesthetic appeal guided our search for an appropriate mechanical design. Furthermore, in the sensing subsystem, our exploration extended to a variety of sensor combinations that would give us the various feedback required for our work. We evaluated options based on factors such as cost-effectiveness, reliability, and versatility to enable efficient obstacle detection and control capabilities. Finally, in the control subsystem, our research delved into microcontroller options capable of executing precise movements and the computational tasks involved in using computer vision. We assessed criteria such as processing power, peripheral compatibility, and potential for future enhancements to inform our selection process. In future prototyping, we will begin researching the various CV algorithms that can be used to effectively map out a region, and give us the information required to accurately cover the required regions of a user's property.

5.1.2. Internal Search

Within our group, we created multiple basic drawings that depicted various ways to integrate the sensory and mechanical needs of our device. We began by conducting brainstorming sessions to generate a wide range of conceptual ideas so we have a large variety of unique insights. Subsequently, we translated these ideas into tangible sketches and diagrams to visualize our ideas. Each team member independently crafted around 1-2 distinct drawings that we then took the best attributes from each which resulted in the chosen design concept. The biggest criterion that we used to select the design included both effectiveness and manufacturability. These initial ideations were crucial in integrating initially neglected factors to consider when creating our designs for prototype 1.

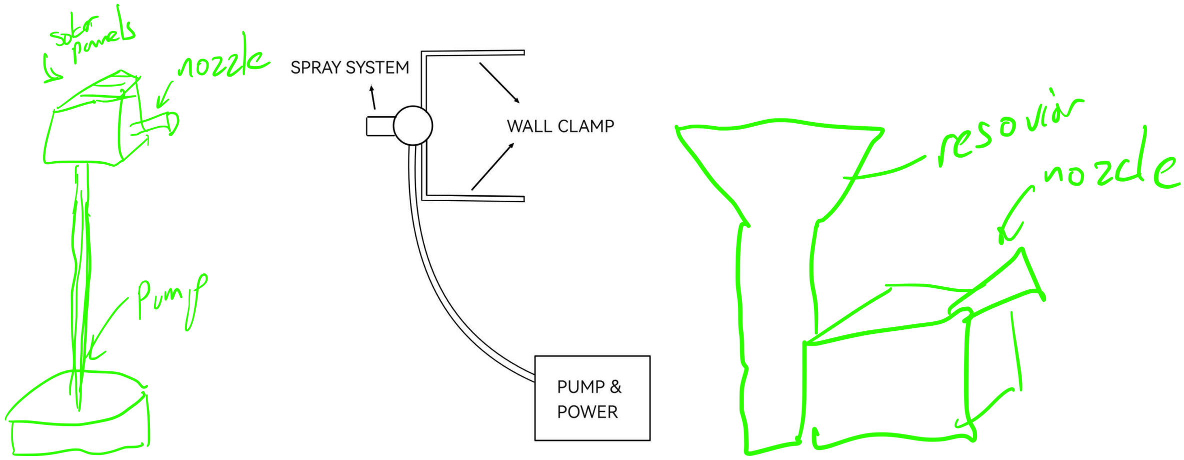


Figure 8: design concept drawings

5.2. Classifications and Combinations

Power Subsystem Classification

- ***Solar-Powered:*** Utilizes solar panels to charge during daylight and switches to battery power under low light conditions. This ensures continuous operation and minimizes energy costs.
- ***Grid Power:*** Primarily powered by a direct electrical connection.
- ***Battery-Only:*** A purely battery-operated system.

Sensing Subsystem Classification

- ***Depth-Sensing Cameras:*** Utilize depth-sensing cameras to map the area and detect obstacles.
- ***Lidar:*** Employ Lidar for obstacle detection and basic area mapping, offering a precise solution.
- ***Sonar:*** Use ultrasonic sensors for distance measurements and obstacle detection, providing a balance between cost and functionality.

Weather detection Classification

- ***Internet:*** Using wifi to get weather data directly from the internet, offers a cheap solution.
- ***Snow Rain Sensor:*** Offers precise results of local weather conditions.
- ***Raspberry Pi CV:*** Employ Computer vision to detect weather conditions, offering a balance between cost and functionality.

Combinations:

- Solar-powered system with Cameras and Raspberry Pi CV (Balance option)
- Grid-powered system with Lidar and Snow Rain Sensor (Powerful and precise option)
- The battery-only system with Sonar and Internet (cost-efficient option)

6. Concept Selection

6.1. Concept Selection Process

The concept selection process involved finding the most effective way to incorporate and integrate the various sensing and motion needs into our system. With clear functionality assigned for each subsystem during the concept generation process, various criteria need to be addressed and our group utilized Pugh charts that compared the most common ways of solving these problems.

6.1.1. Methods

During the concept generation process, we proposed a multitude of different designs and narrowed them down to 3-4 designs that we then compared against each other using 3 different Pugh charts for each of the subsystems.

Description		Sonar	Lidar	Camera
Sketch-				
Criteria	Weight			
Cost	4	0	-	+
Effectiveness	2	0	+	-
Reliability	1	0	+	+
Power Needed	3	0	-	+
Feasibility	3	0	0	0
Size	1	0	-	+
+		0	3	10
0		0	0	0
-		0	8	2
Net score		0	-5	8

Chart 1: Sensing Subsystem

The above chart is our selection of the sensing subsystem, which consists of Sonar, Lidar, and Camera. Based on the Pugh charts selection process, the sonar gets a grade of zero, which means it was a fair choice. The Camera has a score of 8, which is obviously higher than the score of sonar and lidar. Thus, in our design, we decided to use Camera as our sensing subsystem.

Description		Plug in Wall	Solar Power	Battery
Sketch				
Criteria	Weight			
Cost	2	0	+	+
Power Output	2	0	+	++
Ease to fix	1	0	-	0
Outlet Needed	3	0	+	-
Feasibility	3	++	+	++
Enviro	1	0	++	--
+		6	12	12
0		0	0	2
-		0	1	5
Net score		6	11	7

Chart 2: Power system

The above chart is our selection of the power system, which consists of a wallplug, solar power, and battery. We noticed that the score of solar power is significantly higher than the other two, and we thus decided to use solar power as our power source. However, we soon realized that solar power still needs a battery to operate. The score of the battery is also higher than the wall plug, and thus we decided to use both solar power and battery as our power source.

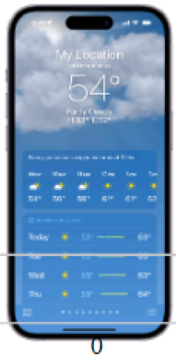
Description		Internet Weather Data	Snow/Rain Sensor	Raspberry Pi CV
Sketch				
Criteria	**Weight**			
Cost	**4**	0	- -	+
Effectiveness	**2**	0	+	+
Reliability	**1**	+	+	+
Power Needed	**3**	0	-	0
Size	**1**	+	-	-
Feasibiliy	**3**	0	3	0
+		0	12	5
0		0	0	1
-		0	12	1
Net score		2	0	4

Chart 3: Vision Subsystem

The above chart is our selection of the vision subsystem, which consists of internet weather data, the snow sensor, and the Raspberry Pi CV. To detect the snow accurately, we researched the snow sensor and soon noticed that the snow sensor was not accurate in distinguishing between snow and rain. Meanwhile, the snow sensor is expensive, which drives away from our initial goals. The Raspberry Pi CV has a higher score than internet weather data, as we noticed that it would be harder to implement the internet function into our program.

6.2. Top Concepts Assessment and Justification

Power Subsystem: Lithium iron phosphate battery with solar panel and grid power.

The lithium battery we eventually chose was a 12V, 7A lithium iron phosphate rechargeable battery, which will provide enough voltage and power for all of the electrical components we decided to use. According to the system setup, the pump consumes most of the power, 45W, and two servos consume 12W in total while the microcontroller has negligible power consumption. This data indicates the capacity of this battery is sufficient for the entire system to run continuously with maximum power for approximately 2 hours once fully charged. As our device will only need to be activated during snowy days in winter, the two-hour battery lifespan will be more than sufficient for one mission. After each activation, the solar panel can recharge the battery through solar power without human intervention, and the user typically will not need to activate this device a second time any time soon. According to our test, under the sunlight of Pittsburgh, our solar panel takes approximately 10 hours to fully recharge the battery from empty. Although the time of recharge can vary depending on the weather and location, the battery is most likely to be fully charged between two activations, as ice-melting solutions like rock salts are expected to have a long-lasting effect on keeping the surface free from ice. Additionally, we tested that the battery can be charged and provide power to the system at the same time, so the effective lifespan of the battery will be longer. Therefore, the user would not need to be concerned about the power supply in most scenarios. In the worst case when the solar panel cannot provide power for the battery due to extreme weather or damage, the user needs to charge the battery with conventional methods, but extreme situations like this are not likely to happen during its functional lifespan.

Mechanical Subsystem: Lamp-style device.

The lamp-style shape is the best visual design of all current concepts: it provides not only high aesthetic value but also acceptable portability, and according to our survey, most respondents accept this visual design. The only possible disadvantage is that the lamp-style device may be more susceptible to external force than other designs, making its stability. However, we believe we can minimize this problem by putting the solution storage tank above the base of the lamp to reinforce the lamp, making it heavier and less likely to shake during extreme weather. On the other hand, the wall attachment design is discarded after discussion, as walls and porch pillars vary in shape and height, so the clamp is required to be highly versatile, which is difficult to design and implement. and it will also limit the possible installation position of our device. The buried sprinkler design was most often used for watering grass, and it is more convenient to be half buried in dirt. However, this design is inconvenient to install, and it also cannot be installed on concrete surfaces. Moreover, since the de-icer is a salt solution, it is not friendly for any plants in the courtyard, so burying it under dirt is not a plausible decision. Therefore, the lamp-style design is adopted due to its visual design, portability, and versatility.

Sensing Subsystem: Camera and ultrasonic sensor combination.

The camera and sonar combination is adopted due to its low cost and imagery capability. Although LiDAR has great performance in identifying locations to dispense, high-precision LiDAR has proved to be too expensive to set our final product at a reasonable price. On the other hand, the image captured by the auto-focus camera can be processed by computer vision algorithms to determine the distance of each pixel on the photo, the disadvantage of this method is that it requires more work to implement the computer vision algorithm. The sonar is utilized to detect moving obstacles like pedestrians, vehicles, or animals. If the sonar detects an obstacle in range, it will send a signal to the control subsystem, and the control subsystem will consequently send a signal to the mechanical system to stop spraying.

Control Subsystem: Raspberry Pi as the microcontroller.
We concluded that to achieve the desired automated behavior of the turret, our control subsystem should have the capability of precise movement control and depth analysis, which requires computer vision and high computation power. As a result, the computation power of Arduino does not meet our standard, but it can be utilized as a capable platform for testing PWM pumps and servo motors in Prototype 1. Eventually, our control subsystem will switch from Arduino board to Raspberry Pi, as it has enough processing power and control GPIOs and thus is more common in computer vision applications. After the discussion, we temporarily discarded the concept of wifi-connected local forecast activation due to its difficulty and our lack of experience in wireless system design. Therefore, our design will require manual activation, and the wifi activation could be implemented as an improvement in the future if conditions allow.

6.3. Detailed Model

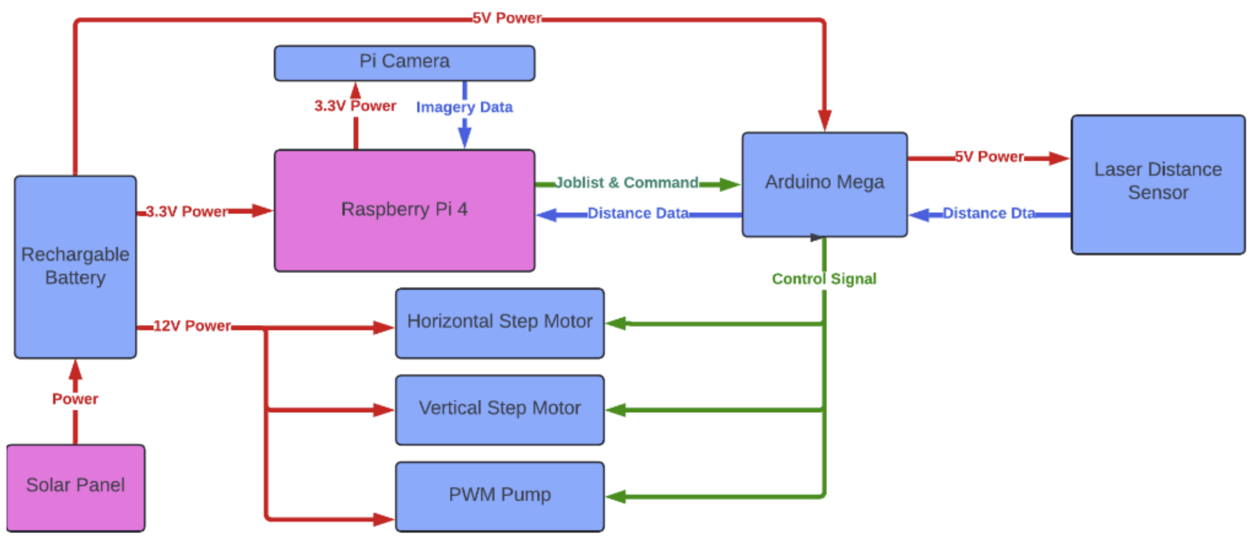


Figure 9: Block Diagram

The block diagram represents the architecture of an automated system, carefully designed to outline the distribution of power and data among its components. This system integrates various hardware elements including a Raspberry Pi 4, an Arduino Mega, a Pi Camera, stepper motors, a PWM pump, and a laser distance sensor, each playing a critical role in the device's operation.
The power supply chain begins with a solar panel that charges a 12V rechargeable battery, ensuring a sustainable energy source. The battery directly powers the horizontal step motor and also steps down to 3.3V to supply the Raspberry Pi 4 and indirectly the Pi Camera. Additionally, it steps down to 5V to energize the Arduino Mega and the laser distance sensor. The Raspberry Pi 4 acts as the central processing unit, receiving imagery data from the Pi Camera and distance data from the Arduino

Mega, which communicates with the laser distance sensor. The Pi sends commands to the Arduino Mega, which in turn controls the vertical step motor and the PWM pump, adjusting their operation based on received commands.

This structured layout ensures efficient power management and precise control flow within the system. Before diving into concept generation, the team meticulously analyzed how each component would interact within the system, identifying separate functions such as imagery analysis and distance measurement managed by the Raspberry Pi 4 and the Arduino Mega respectively. This functional decomposition highlighted the distinct roles of user interaction handled by the Pi and motion control managed by the Arduino, thereby defining clear subsystems that operate independently yet are interconnected. As such, these subsystems were developed separately to ensure each functioned optimally without compromising the integrity of the other, mirroring the approach used in the design of complex, multi-component systems.

7. Detailed Design and Engineering Analysis

7.1. Analysis

The most important engineering problem that our device needed to address was stress-related failures, as well as to balance the applied reaction forces that would be placed on our device. The first goal would be to ensure that the device can withstand expected stresses and loads related to balance without failure. These loads are mostly based on the height requirements of our device. The second goal would be additional tolerancing based on wind, as well as 3rd law pairs of the forces generated by our pump described as outlet momentum. Finally, we can perform a buckling analysis using SolidWorks simulations to determine if the device would fail under the failure mode of buckling.

<u>Analysis 1</u>

In our first static analysis, we used assumptions to the free body diagram to simplify our analysis for the most important aspects of failure from tipping over due to weight.

Assumptions:

- The top plate can be represented as a point mass
- The motors attached to it as a singular beam with a point mass representing the weight density distribution
- Represent the weight of the steel beam as a single force at the center of the beam
- We assumed that the resulting moment would act at the bottom of the beam

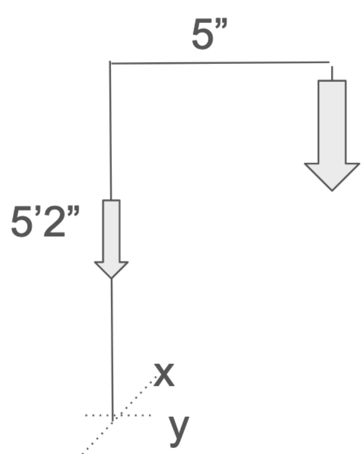


Figure 10

The two forces from this are represented by the weight of the beam, and the weight of the top plate, and its components. After solving the static model we get a reaction moment around the x-axis to be 2.494N·m (about the x-axis in the xy-plane). When compared to the weight of the device this is a relatively negligible moment which leads us to believe that balance due to the top plate will not necessarily be an issue. After validating our static analysis and design decisions we are confident in the structural integrity and stability based on the device's weight of the final prototype concept. Furthermore, the insights gained from this analysis will inform future iterations and improvements, ensuring continued optimization and reliability in subsequent designs.

Analysis 2

In our second static analysis, we used assumptions to the free body diagram to simplify our analysis for the most important aspects related to potential forces such as wind, and the 3rd law pair of the pump.

Assumptions:

- The top plate can be represented as a point mass
- The motors attached to it as a singular beam with a point mass representing the weight density distribution
- Represent the weight of the steel beam as a single force at the center of the beam
- We assumed that the resulting moment would act at the bottom of the beam
- Assuming forced applied from wind act as described in Sussex Universities analysis

Mathematical Model For Outlet Momentum: $\rho * 7.68 * 10\text{-}7\ m^3/s : \sim 7.68 * 10^{-2}$ kgm/s

$\rho = 1020\text{-}1030\ kg/m^3$

The resultant force from this is negligible compared to the weight of the device but can come into play if the pump or nozzle is changed. It is not crucial to include in the current calculations however will be important for future iterations of this device if you use a stronger pump combination

The most important force that we needed to consider was the force from any wind. Using this model we could calculate the reaction Moment (about the y-axis in the xy-plane): Areatop * Pwind * 1.5856 meters

For two common wind speeds

- 20 mph Wind = Pressure of $76.548 N/m^2$
- 10 mph Wind = Pressure of $16.548 N/m^2$

We utilized the chart below, and the force body diagram for our analysis

Wind Speed and Resulting Force on a Flat Vertical Surface					
			Pressure	Pressure	
	Beau-	Km	Pounds	Pounds	
	fort	per	per Square	per Square	
MPH	Scale	Hour	Foot	Metre	Kg/m2
1	1	1.6	0.004	0.04	0.02
2	"	3.2	0.016	0.17	0.08
3	"	4.8	0.036	0.39	0.18
4	2	6.4	0.064	0.69	0.31
5	"	8.1	0.1	1.08	0.49
6	"	9.7	0.144	1.55	0.70
7	"	11.3	0.196	2.11	0.96
8	3	12.9	0.256	2.75	1.25
9	"	14.5	0.324	3.49	1.58
10	"	16.1	0.4	4.30	1.96
11	"	17.7	0.484	5.21	2.37
12	4	19.3	0.576	6.20	2.82
13	"	20.9	0.676	7.27	3.31
14	"	22.5	0.784	8.44	3.83
15	"	24.2	0.9	9.68	4.40
16	"	25.8	1.024	11.02	5.01
17	"	27.4	1.156	12.44	5.65
18	"	29.0	1.296	13.94	6.34
19	5	30.6	1.444	15.54	7.06
20	"	32.2	1.6	17.22	7.83
25	6	40.3	2.5	26.90	12.23
30	"	48.3	3.6	38.74	17.61
32	7	51.5	4.096	44.07	20.03
35	"	56.4	4.9	52.72	23.97
39	8	62.8	6.084	65.46	29.76
40	"	64.4	6.4	68.86	31.30
45	"	72.5	8.1	87.16	39.62
47	9	75.7	8.836	95.08	43.22
50	"	80.5	10	107.60	48.91
55	10	88.6	12.1	130.20	59.18
60	"	96.6	14.4	154.94	70.43
64	11	103.0	16.384	176.29	80.13
65	"	104.7	16.9	181.84	82.66
70	"	112.7	19.6	210.90	95.86
75	12	120.8	22.5	242.10	110.05
80	"	128.8	25.6	275.46	125.21
85	"	136.9	28.9	310.96	141.35
90	"	144.9	32.4	348.62	158.47
95	"	153.0	36.1	388.44	176.56
100	"	161.0	40	430.40	195.64

Figure 11 [8]

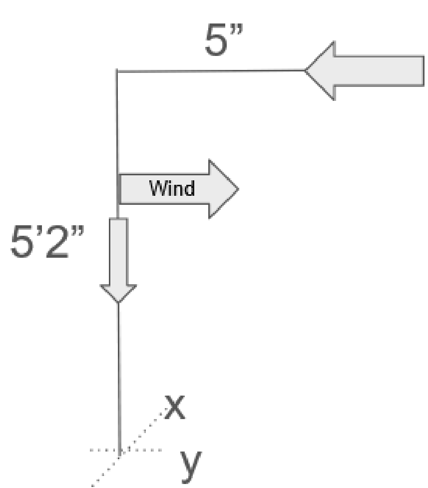


Figure 12

In our second static analysis, we used our assumptions to simplify the free body diagram, focusing on critical aspects such as wind forces and the 3rd law pair of the pump. By representing the top plate and attached motors as point masses and streamlining the modeling of the steel beam, we effectively captured the essential dynamics of the system. While the resultant force from wind was found to be negligible compared to the device's weight in the current configuration, its significance may increase with alterations to the pump or nozzle, warranting consideration for future iterations. Additionally, our second calculation of reaction moments gives us a comprehensive understanding of the device's stability under varying wind speeds, which will help us in subsequent developments and reassure us that our prototype will not fail in basic circumstances.

<u>Analysis 3</u>

In our final analysis, we conducted a SolidWorks Simulation for the failure mode of buckling to assess our material choice for this prototype and determine whether or not it would satisfy our needs.

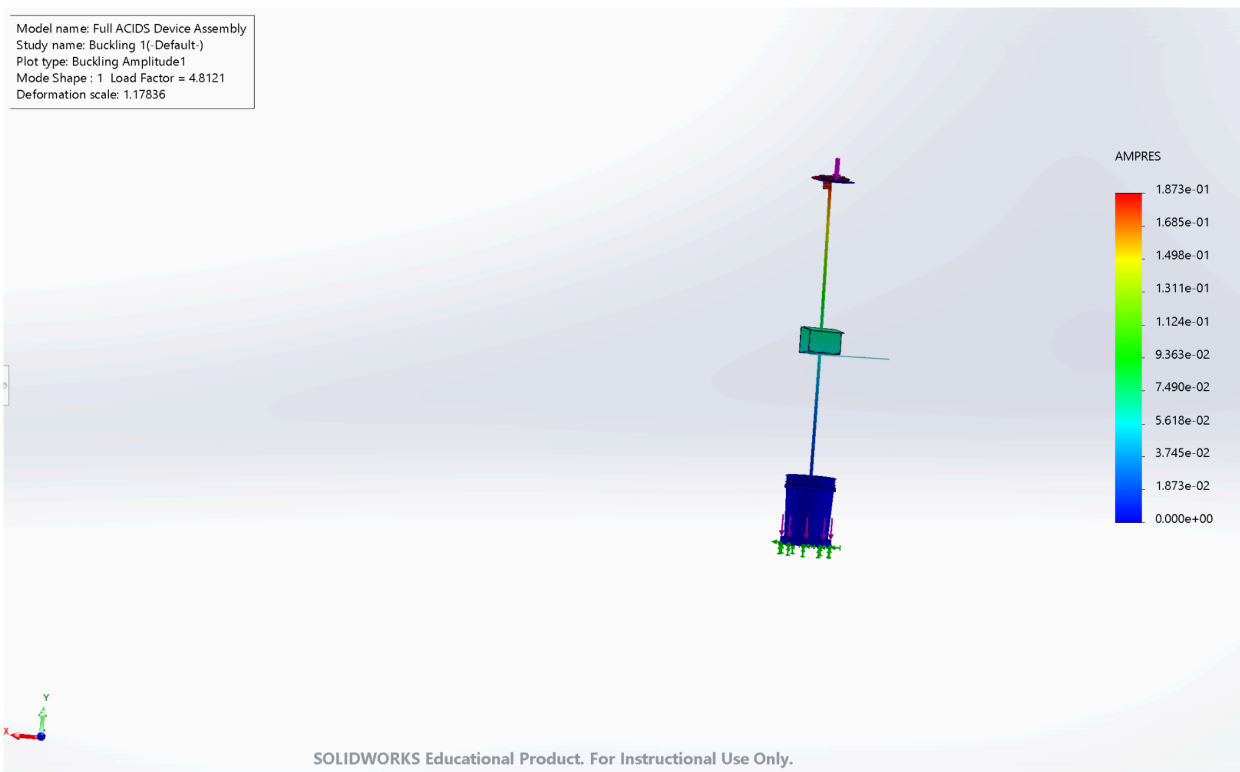


Figure 13

Based on the SolidWorks simulation results indicating a significant "Amplitude Response" (AMPRES) gradient of 1.837e-01 under a load factor of safety 4.3 and applied loads of 50N at the top and 100N at the bottom, it is apparent that the structure exhibits some deformation tendencies, potentially leading to buckling or instability, however, these stresses are concentrated at the top plate, and related to joint issues. This finding underscores the importance of ensuring adequate safety margins to account for such deformations and prevent structural failure. Moving forward, design considerations related to the joints connecting the top plate to the beam should prioritize reinforcement strategies, material enhancements, or geometric adjustments to improve structural robustness and enhance safety margins. Further analyses and refinements such as improving the base mechanism can ensure that the structure can withstand anticipated loads while maintaining an acceptable level of safety. Overall, we can be assured that our prototype will not succumb to buckling

7.2. FMEA

Component	Potential Failure Mode	Consequences of Failure	Solution
Battery	The battery fails to hold a charge	System shutdown, inability to operate	Regular battery performance checks and a robust battery management system
	The battery fails to provide enough current to the whole system	Some components will be disabled during the operation	Substitute the current battery for another one with higher-rated power and the same voltage
Stepper Motors	Motor fails to position nozzle accurately	Inaccurate dispensing, potential safety hazards	Quality stepper motors, regular calibration, and real-time monitoring
Nozzle	Clogging or mechanical failure	Inefficient or no dispensing, wasted de-icing fluid	Easy-access design for quick maintenance and clog removal
	The nozzle corroded by the solution	Liquid pressure unstable, solution contaminated	Plating a layer of anti-corrosive coating to the inner side of the nozzle
I2C Communication	Data transmission errors or delays	Miscommunication leading to operational errors	Enhanced error-checking protocols and redundancy in communication
	Transmission data size limitation	The control data transferred will be truncated and generate wrong signals	Mapping the data before transmission and then decode the data after receiving
Pump	Pump failure or underperformance	Inadequate fluid pressure, incomplete ice melting	Use of high-quality pump components and scheduled maintenance

	Producing high noise	Increase user unsatisfaction	Covering soundproof material around the pump or switching to a less noisy pump with a similar power output
Solar Panel	Low power output	Insufficient battery charging, reduced operation time	Installation of high-efficiency solar panels and monitoring system
Raspberry Pi and Arduino Mega	Software bugs or crashes	System crashes or unresponsive behavior	Testing boundary cases, using serial output as a debug method
Supporting Frame	Corrosion or wear	Structural instability, potential system collapse	Use of corrosion-resistant materials and protective coatings
	Unbalanced weight	Device falls over	Add balancing weight to the base, and make the base both larger and heavier to lower the center of gravity
3D Printed Structures	The size of the holes does not match	Unable to connect mechanical system	Adjust the configuration and reprint the structures
	Material susceptible to strong external force	Hardware collapse	Adding stronger support metal frames to the 3D-printed structures

Table 3: FMEA

7.3. Manufacturing and assembly techniques

7.3.1. BOM of Final Prototype:

Parts	Units	Price [$]		Parts	Units	Price [$]
Arduino Mega	1	19.99		Shower Hose	1	19.9
Raspberry Pi 5	1	94.83		Nozzle	1	4.99
Nema 17 Stepper Motor	2	10.99		Solar Panel	1	35.99
9” Rotating Disk	1	9.99		12V 7Ah LiFePO4 Battery	1	25.99
IMX 708 Camera	1	25.00		3D Printed Structural Material	Many	7.00 (Approximate)
85*55 Breadboard	1	2.47		Aluminum Structural Material	Many	5.00 (Approximate)

0.1HP Pump	1	63.59		Wires	Many	2.00 (Approximate)
VL53L1X Time-of-Flight Distance Sensor	2	15.89		Screws	Many	2.00 (Approximate)
A4988 Stepper Driver	2	20.64		Acrylic	Many	5.00 (Approximate)
				Total (Including try-out parts)	/	597.88

Table 4: BOM

7.3.2. Manufacturing Methods for the Final Prototype

1. **3D Printing for Complex Components:** We extensively used 3D printing, particularly for creating intricate parts such as gears within the rotating disk and the housing for the stepper motors. This method allowed for rapid prototyping of complex geometries which would be cumbersome and costly to fabricate using traditional manufacturing techniques. The ability to quickly redesign and reprint components in response to testing feedback was invaluable in optimizing the mechanical assembly and functionality of the dispenser.
2. **Aluminum Fabrication:** Aluminum was used for building the primary structure due to its strength, lightweight, and corrosion resistance properties, ideal for the outdoor deployment of the device. We used manual machining methods including an endmill, drill press, garnet sand water jetting, manual lathe, and laser cutter to construct the frame and mounting brackets that support the entire assembly. This method, although more time-consuming than mass production techniques, provided the durability needed for initial testing and deployment.
3. **Manual Assembly:** Each component was assembled manually, allowing our team members to make adjustments and refinements during the assembly process. This hands-on approach was essential for integrating various subsystems, including the electronic controls housed in an acrylic box, ensuring that all parts fit together seamlessly and functioned as intended.

7.3.3. Manufacturing and Assembly Techniques for Mass Production (DFM)

Our automated ice-melting solution dispenser has been meticulously designed with both the prototyping and mass-production stages in mind. During the prototyping phase, we utilized a combination of 3D printing and manual assembly to create functional units, focusing on flexibility and testing ease. However, for mass production, we propose several advanced manufacturing and assembly techniques to optimize scalability and cost-effectiveness.

To ensure the device can be produced on a larger scale, a comprehensive approach involving various strategies will be implemented:

- **Integration of Injection Molded Components:** Initially, the prototyping phase relied heavily on 3D printed parts. These components, while useful for rapid prototyping, often lacked the precision and robustness required for functional deployment, compelling us to simplify our designs to maintain system stability. To address these challenges, transitioning to injection-molded components is crucial. Injection molding not only significantly reduces manufacturing costs but also improves the durability and consistency of the parts. Critical components such as gears and casings, previously made through 3D printing, will be redesigned for injection molding. This shift will not only enhance production efficiency but also ensure greater material uniformity and strength, leading to a more reliable final product.

- **Standardization of Parts:** During the prototype stage, the use of various screws and wiring configurations led to a chaotic assembly process, making it difficult to assemble or disassemble the device using a standardized set of tools. To overcome this problem, we propose to standardize common components like screws, wires, and electronic connectors. The standardization will allow for mass-purchasing, reducing costs and simplifying the assembly line. Furthermore, it facilitates easier maintenance and quality control, ensuring that parts are interchangeable and meet consistent quality standards, which is essential for scaling production.
- **Modular Design:** The current prototype employs a single microcontroller to manage various components, each controlled by different drivers: we have two separate stepper drivers and another driver for the PWM pump. By adopting a modular design approach, we can consolidate these disparate systems into a single, cohesive unit. For example, integrating all drivers onto one printed circuit board (PCB) will streamline both the manufacturing process and subsequent assembly lines. This integration will not only speed up the assembly process but also simplify troubleshooting and repairs, as technicians can identify and address issues more efficiently within a unified system.
- **Automated Assembly Lines:** In our assembly process, the installation of the stepper and the rotating disk was more difficult compared to other parts. This part requires a precise hole localization, with holes that cannot be observed by the human eye when screwing. To streamline the assembly process, it is suggested to implement automated assembly lines that can handle high-volume, high-precision production while reducing labor costs and human error. This includes the use of robotic arms for precise placement of components and conveyor systems for efficient movement of parts through the assembly line.
- **Quality Control Systems:** At the beginning of our prototyping process, some components we bought were of poor quality, and significantly hindered our progress; we had to carefully choose new items and wait for the shipment. Similarly, poor quality control would be a disaster for mass production. Implementing advanced quality control systems will be critical in mass production to maintain the integrity of the product. Automated inspection stations using cameras and sensors will be installed to check the assembly accuracy and functionality of each unit. This will ensure that all products meet our stringent quality standards before shipping.
- **Supply Chain Optimization:** Establishing a robust supply chain will be crucial for managing the logistics of mass production, which includes sourcing raw materials, managing inventory, and coordinating with multiple suppliers to ensure a steady flow of components. We will also need to develop backup suppliers to mitigate any risks associated with supply chain disruptions.

The adoption of these strategies—integration of injection molded components, standardization of parts, and modular design—will collectively enhance the manufacturability, durability, and maintainability of the device. By focusing on these areas, we can ensure a seamless transition from prototype to mass production, ultimately leading to more cost-effective and reliable products that are competitive in the market. This strategic approach underscores our commitment to innovation and quality, positioning us as leaders in our industry.

7.3.4. Key Challenges in Manufacturing and Assembly for Mass Production

Transitioning from a highly customized, prototype-focused manufacturing process to a streamlined, cost-efficient mass production system presents several significant challenges. Addressing these will be critical to achieving the scalability required to meet market demands effectively.

1. **Facility Readiness and Equipment Investment:** One of the primary challenges is preparing facilities for large-scale manufacturing, which includes investing in new machinery for injection molding and automated assembly lines, requiring significant capital outlay. Setting up these facilities also involves designing efficient workflows that minimize downtime and optimize the use of space and resources. Ensuring that the facilities comply with industry regulations and environmental standards adds another layer of complexity.
2. **Material Quality and Supply Chain Reliability:** As we scale production, maintaining the quality of materials becomes increasingly challenging. The prototype phase allowed for close control over small quantities of materials; however, mass production demands consistent quality across much larger volumes. Establishing a reliable supply chain with trusted suppliers who can deliver high-quality materials on time is crucial. Moreover, the risk of supply chain disruptions needs to be mitigated through strategic stockpiling and the development of alternative supplier relationships.
3. **Cost Management and Pricing Strategy:** Cost management is another critical challenge. While mass production typically reduces the per-unit cost, the initial investments in tooling, equipment, and facility upgrades are substantial. Balancing these upfront costs with the pricing strategy to ensure the product remains competitive while still profitable requires careful financial planning and market analysis.
4. **Labor Skills and Training:** The shift from manual assembly to automated production lines will require workforces that are skilled in operating and maintaining sophisticated machinery. Providing adequate training to ensure the workforce can meet these demands is essential. Additionally, retaining skilled labor in a competitive market poses a challenge, necessitating a focus on worker satisfaction and retention strategies.
5. **Technological Integration and User Privacy:** As we incorporate advanced technologies such as camera systems and connectivity into our ice-melting solution dispenser, ensuring the privacy and security of user data becomes a paramount concern. The device is designed to operate in private properties, capturing images to function effectively. This raises significant privacy issues, as the data involves visual information about private premises which could be sensitive. It is crucial to implement robust data protection measures including data encryption for images and operational logs, both in transit and at rest, to safeguard against unauthorized access.
6. **Regulatory Compliance and Environmental Concerns:** Ensuring compliance with both domestic and international manufacturing regulations can be daunting, which includes adherence to safety standards, environmental regulations, and labor laws. Furthermore, as environmental sustainability becomes more critical to consumers, developing production processes that minimize environmental impact while still being cost-effective is essential.
7. **Customer Expectations and Market Adaptation:** As we move to mass production, aligning our manufacturing capabilities with market expectations is crucial, which includes not only meeting demand in terms of volume but also adapting quickly to changes in consumer preferences and

technological advancements. Ensuring our product remains relevant and desirable in a competitive market requires ongoing innovation and responsiveness to customer feedback.

Addressing these challenges requires a well-coordinated effort across multiple aspects of the business, from operations to HR to sales. By anticipating these challenges and planning effectively, we can ensure that the transition to mass production not only meets the current needs of the market but also positions us for future growth and success.

8. Final Design Description

8.1. Design problem

When discussing our project with the professor, we realized that our device may have environmental impacts on the plants in the surrounding areas, such as grasslands, flowers, and trees. When shooting ice-melting solutions to the plants, the solution may pollute and cause damage to the plants.

We noticed that some of the ice-melting solutions are labeled “environment friendly”. While these types of solutions may protect the environment to some extent, not all solutions are environment-friendly, therefore still posing a threat to plants.

To address the issues, we thus decided to add the functionality that the user can select specific areas to shoot solutions, which can eliminate most of the potential threats to the plants. To achieve this function, we promoted a computer vision algorithm to detect the depth information of the image. With each pixel’s 3D coordinate information of the user-selected region, the Raspberry Pi can generate proper control signals to Arduino Mega, so that our nozzle will only shoot solutions to the desired location and avoid spraying to vulnerable grasses.

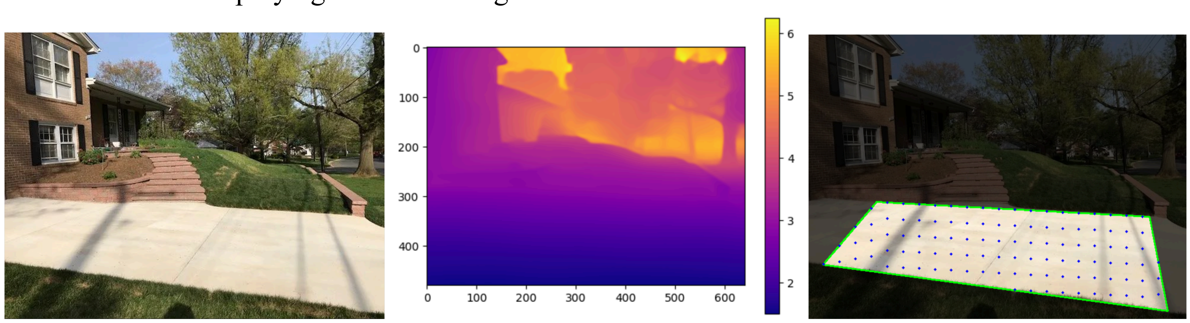


Figure 14: Depth info and dots generation

Standard	Description	Application to A.C.I.D.S

ISO 14001	Environmental Management Systems – Requirements with guidance for use. This standard helps organizations improve their environmental performance through more efficient use of resources and reduction of waste.	Ensures that the development and operation of the A.C.I.D.S project consider environmental impact, particularly in minimizing potential harm to plant life and surrounding ecosystems.
ANSI/ISEA Z358.1	American National Standard for Emergency Eyewash and Shower Equipment. This standard provides guidelines for emergency eyewash and shower equipment.	Relevant in ensuring that safety measures are in place during the manufacturing and operational phases of the device, especially where chemical handling (i.e., ice-melting solutions) is involved.
ASTM D1179-16	Standard Test Methods for Fluoride Ion in Water. It describes the methods to detect and measure fluoride levels in water, which can be a component of some deicing agents.	Applicable for testing the runoff water if fluoride-based deicing agents are used, ensuring that the levels are safe and within environmental compliance limits.

Table 5: Standards

8.2. Demonstration of the design

8.2.1. Mechanical Subsystem

After Prototype 1, the original poorly performed two-servo driven gimbal system was replaced with two Nema 17 Stepper motors, each performing up to 42 N·cm torque. One motor was designed to drive a rotating plate, which provides horizontal angle adjustments of the nozzle. The other motor directly connects to a bracket that holds the nozzle and provides vertical angle adjustments. This design aims to provide sufficient torque to operate the 2 DOF movement and more precise angle control than servo motors.

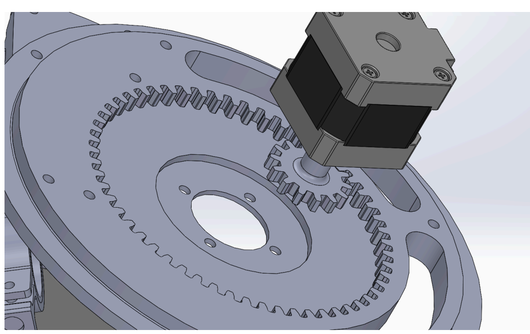


Figure 15

Figure 15 is the detailed mechanism of horizontal movement, the inner gear plate is mounted to the rotating plate, and the gear ratio is 4:1, which amplifies the motors' torque four times, preventing any movement issue caused by insufficient force.

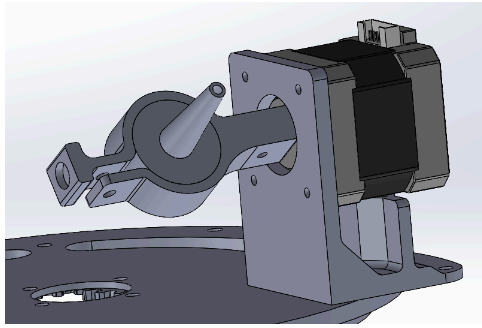


Figure 16

Figure 16 is the detailed mechanism of vertical movement. High precision can be obtained when the nozzle is directly connected to the stepper motor, as stepper motors can perform micro steps. The following link is a video to demonstrate the 2 DOF movement:
https://youtube.com/shorts/silHO3gvK_Q

8.2.2. Sensing & Control Subsystem

The sensing subsystem utilizes a Pi camera to capture the image. The Raspberry Pi with the pre-trained deep learning model ZoeDepth [3] can receive the image and estimate the distance from the camera to each pixel in the image. Our tests found that the estimated value does not represent the real distance from the camera to the points. However, after measuring and comparing the actual distance from the camera to the points using laser measurement, we discovered that although the estimated value is not perfectly accurate, they form a perfect linear relationship with the actual distance value. Figure 17 shows the relationship and points measured, the deep learning model even found some outliers of actual distance because the material of the surface can influence the laser measurement. This behavior indicates that all the estimated values can be mapped to their corresponding real values by measuring only the real distance of two pixels on the camera.

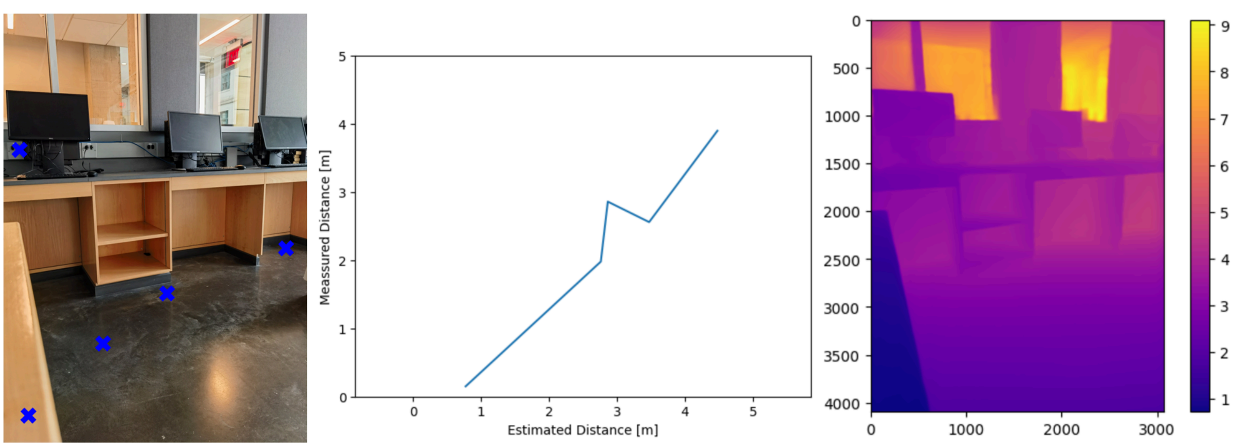


Figure 17:. Relationship between estimated value and measured (Blue markers are points measured, some offset exist on the graph because marker coordinates are estimated)

With further experiments, we tried to utilize the ultrasonic sensor to provide distance information to points, but its accuracy was drastically lower than our requirements. Therefore, to accurately calibrate the estimated values, two VL53L1X Time-of-Flight Distance Sensor was integrated into the sensing subsystem, to provide ground truth values that can calibrate the values. The following link leads to the video of the VL53L1X.
https://www.youtube.com/watch?v=mDJDvO6LOrw

Furthermore, we can generate control signals from the distance to pixels through a series of computer vision algorithms that will be explained in later sections. The control signals were sent from Raspberry Pi to Arduino through I2C communication, providing a secure and fast data exchange. To our convenience, both Raspberry Pi and Arduino support I2C communication with their dedicated SCL & SDA pins. The control signals of all points in the user-selected regions sent by Raspberry Pi will be stored in an array in the Arduino Mega. By suspending the execution of certain portions of the code, we can ensure the system will not start to spray until receiving control signals from all the selected points, which greatly enhances the safety and reliability of our system. The only limitation of the I2C communication is its limited data size, as it only supports byte-to-byte transmission, so each integer value should be within the interval of 0-255, we have to map the large data value to this interval on the Raspberry Pi before transmission and then decoded the map on Arduino Mega. This method is effective, but the control accuracy is unavoidably slightly lowered during the mapping and unmapping process.

8.3. Testing and results

8.3.1. Maximum coverage range

To test the performance of the pump, we set up experiments to measure the range of coverage of our PWM pump. We set up three angles for testing: 45 degrees (upward), 0 degrees (horizontal), and -45 degrees (downward). Based on the gravitational force and physics governing projectile motion, we concluded that the solution will shoot at the maximum range of positive 45 degrees (upward).

We set up tape measures on the ground as reference positions and sent seven different PWM signals to the pump: 255, 225, 200, 175, 150, 125, and 100. We connected the battery and tested it with these seven hardcoded PWM values.

The testing results showed that at 45 degrees with 255 PWM, the maximum range is 304 inches or 7.72 meters, which meets our expectations of the maximum range. We also noticed that the minimum activation PWM is 125 for our pump, indicating that the minimum achievable range is 50 inches or 1.27 meters measured at -45 degrees with 125 PWM. Figure 18 shows the testing result of the coverage range.

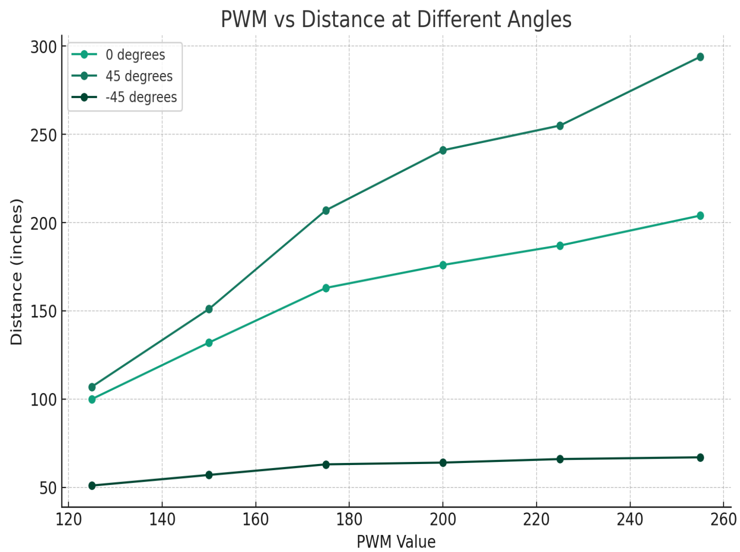


Figure 18: Coverage range

8.3.2. Computer vision on area selection

The region selection has the exact outcome demonstrated in Figure 17, where the user can left-click on the captured image and select points as the border of the desired region, and right-click to end selection. Then the algorithm will create a polygon and determine all the points within, then mesh the polygon according to its size to obtain a reasonable amount of points to dispense. This link is the video of how the region selection works.

With the depth information collected, the other step is to convert it to 3D coordinates relative to the camera, where the camera's intrinsic matrix [2] is utilized. Here, the IMX 708's intrinsic matrix (K) is:

$$\begin{bmatrix} 3386 & s & 2304 \\ 0 & 3386 & 1296 \\ 0 & 0 & 1 \end{bmatrix}$$

Where "s", the axis skew was set to be zero. The conversion from camera coordinates to real 3D coordinates follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = Depth \cdot K^{-1} \cdot \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}$$

Where u and v are the x and y coordinates of points in the camera's frame.

To determine the accuracy of the distance, we developed an interface that outputs the point's 3D coordinates when clicking on a point, where the y-coordinates are the most intuitive metric to quickly determine the precision. This link is a video that demonstrates this action. In this video, there is an error in y coordinates, and its value is not consistent. This inconsistency is due to the intrinsic matrix, there are some unknown skew "s", that it should not be zero. Despite the error, the coordinate measurements are still acceptable because they remain in a small range, and the water splash can compensate for this error.

8.3.3. Shoot to the selected area

With the process we made from previous prototypes, we are able to conduct tests on the integration of different components. We thus decided to test if our system can shoot water to the selected region. Before writing control signals to draw the specific region, we used the data measured in the above-mentioned distance test with seven distinct PWMs to generate a function through polynomial regression. The following polynomial function shows the relationship between the shooting distance as output versus the vertical stepper motor angle and pump PWM as input.

$$\boldsymbol{Distance = -\,0.00381 \times PWM^2 + 2.218 \times PWM + 0.01444 \times PWM \times Angle - 1.078 \times Angle - 0.01239 \times Angle^2 - 114.751}$$

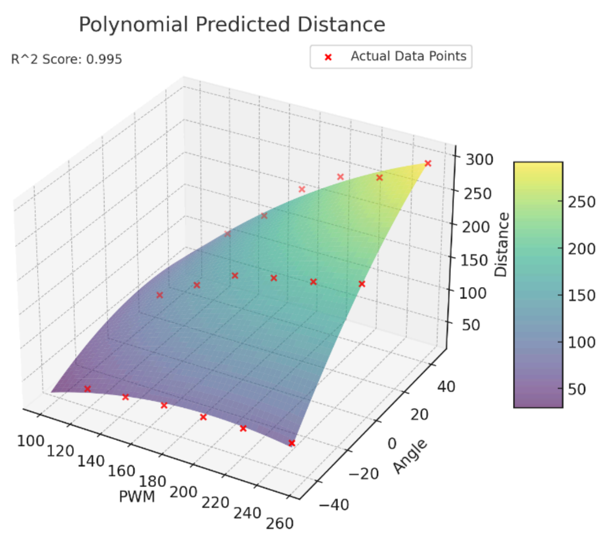
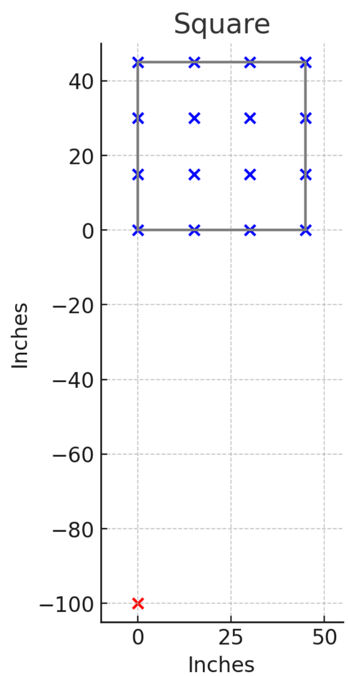


Figure 19: Simulated relationship

The above graph shows the simulation results of three variables, and the red dots represent the real data we measured in the first test. The R^2 score of the regression model reaches 0.995, indicating that our model generates an accurate simulation and prediction of real distance.

We then used this function to calculate the angle and PWM lists required to draw a square. To make the process easier, we fix the vertical stepper motor at a horizontal degree and divide the square into dots so that we can save more water.



Dot Position (X, Y)	Distance (inches)	Adjusted Angle (degrees)	PWM Value
(0, 0)	100.0	0	122.7
(15, 0)	115.0	0	134.9
(30, 0)	130.0	0	148.0
(45, 0)	145.0	0	162.5
(0, 15)	101.1	8.5	123.6
(15, 15)	116.0	7.4	135.7
(30, 15)	130.9	6.6	148.8
(45, 15)	145.8	5.9	163.3
(0, 30)	104.4	16.7	126.2
(15, 30)	118.8	14.6	138.1
(30, 30)	133.4	13.0	151.2
(45, 30)	148.1	11.7	165.7
(0, 45)	109.7	24.2	130.4
(15, 45)	123.5	21.4	142.2
(30, 45)	137.6	19.1	155.1
(45, 45)	151.8	17.2	169.7

Figure 20: Parameters

Table 6

In Figure 20, the red dot represents the position of the device, which is 100 inches away, and the blue dots show the location we want to shoot to cover as a square. By calculating every angle between blue dots, red dots line and y-axis, we can acquire the horizontal stepper motor angle. By using the formula we get from polynomial regression, we can acquire the PWM value needed to cover the blue dots. Table 6 shows the corresponding value for the horizontal stepper motor angle and pump PWM.

We then tested these data by hardcoding the horizontal stepper motor angle pump PWM into the Arduino Mega and using a tape measure on the ground for reference of position.

By connecting the power, the system shooted water to each dot one by one, and roughly covered a square area on the ground. The whole operation time is 1 minute and 20 seconds, and the system can operate full-time without human interaction. The testing results thus met our expectations. The following link leads to the video of this test.
https://www.youtube.com/watch?v=PLr0PryQqO8

9. Conclusions

9.1. Teamwork Lessons

From this project, our team learned the value of a user-centered design approach, utilizing iterative cycles that integrated repeat revision for continuous improvement. This building process taught us flexibility and the importance of adapting to new insights.

From our early mistakes in component selection, we also learned that effective planning and preparation were crucial to save time and ensure steady progress. Although we established a detailed timeline to allocate each team member’s work and time for each task, the improperly selected components and our inexperience with certain drivers greatly disrupted and procrastinated our planned timeline. Additionally, we also learned that even if each subsystem works as intended separately, it does not necessarily mean the whole system can work as intended. During our design process, the control signal algorithm on Arduino and the depth-sensing algorithm on Raspberry Pi were done by Haoran and Jianhao respectively, and although each of these two microcontrollers worked well during its own tests, there were problems when these two worked together due to the complicated data mapping issue during transfer. We underestimated the time and effort to combine these two microcontrollers, so we did not leave enough time to address the potential issue, resulting in only a partially working final prototype at the Expo.

These collective lessons we learned will enrich our technical and strategic skills and prevent us from making the same mistakes again in the future. After this project experience, we will be better prepared for future engineering challenges.

9.2. Different Choices and Potential Improvements

After reviewing the design as a whole, we realized that there are some key selections we could make to make our product better:

1. ***High-precision 3-D printed components***
   The precision of our 3-D printed components did not meet our expectations, as sometimes the 3-D printed components jammed with each other. High-precision 3-D printed components could greatly promote stability.

2. ***Wifi connection to the local forecast to activate the spray***
   We expect the device to start itself and spray the ice melt solutions before the snow so our system will be fully autonomous, eliminating the need for manual activation. Additionally, the pre-emptive spray will also save people’s effort to plow through the snow before activating the device.

3. ***Phone App interface***
   We expect the users can use the phone App to directly control our design, like real-time images, remote switching on, and manually aiming on the phone app.

9.3. Unresolved Issues

In our final prototype, we encountered specific unresolved issues that did not fully meet our initial expectations. One significant limitation was related to the data transfer capabilities between the Raspberry Pi and the Arduino. Due to I2C communication constraints, the system could only transmit a single byte at a time, rather than the entire user-generated shape directly. This restriction limited the efficiency and responsiveness of our targeting system.

Additionally, the power supply proved inadequate for our needs. The 12-volt battery was unable to sustain all components simultaneously, necessitating a secondary power source to ensure that the Raspberry Pi operated effectively during our final demonstration. This issue highlighted the need for a more robust power management strategy to accommodate the simultaneous operation of multiple high-demand components within the system.

These challenges underscore the necessity for further refinement in communication protocol and power management systems to achieve a fully operational and reliable prototype.

9.4. Suggestions for Future Group

We suggest the future group who wants to continue working on the project to:

1. Choose strong components and do not care too much about the small price difference
   The components with sufficient performance will significantly help you save lots of time and effort. If the components do not perform well in the early prototype, the timeline will be significantly disrupted, and you still need to purchase stronger components, which will cost more than buying these components at the start.

2. Use a computer for computation instead of Raspberry Pi
   Since the Raspberry Pi is only used for the first time setup, considering the complexity of the wire connection of Raspberry Pi, we would suggest the next group just use the computer as a computation source and send necessary signals directly to the microcontroller. The microcontroller can then be switched to a much cheaper one instead of Arduino. For example, the ESP32 is 5 times cheaper than Arduino, and can directly communicate with computers through Wifi or Bluetooth.

Citation

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Appendix A: Survey Questions

This appendix lists the survey questions administered to homeowners to assess their needs and perceptions regarding automated ice removal and salt dispensing systems. The survey was conducted among various homeowners, as detailed below:

1. Demographic Information:
    - What is your name? (Identified for the purpose of the survey, not published.)
    - How long have you owned your home?
    - How many properties do you own?
2. Experience with Ice Removal:
    - Do you struggle with ice removal/salt dispensing?
3. Interest in Automated Solutions:
    - Would you be interested in an automated system for ice removal and salt dispensing?
4. Installation Preferences:
    - How much time would you be willing to spend on installing a device for automated ice removal?
5. Aesthetics:
    - Does the aesthetics of the ice removal device matter to you?
6. Operational Preferences:
    - If you had this device, how would you prefer to refill it with salt? (Options included pouring salt into a dispenser slot, tipping a container to refill salt, emptying salt into a bag, or transferring salt using a funnel spout.)

This summary provides a comprehensive view of the questions designed to gauge the practical and aesthetic considerations homeowners have regarding automated ice removal systems. The answers to these questions will guide the design and implementation strategies for the Automated Stationary De-Icer Dispenser (A.C.I.D.S)

Appendix B: Individual Technical Contribution:

Members	Mechanical System	Control System	Sensing System	Power System
Jianhao	• Final prototype design • 3D printed parts' fabrication	• Stepper motor control algorithm development	• The camera setup on Raspberry Pi, • Depth estimation algorithm development • User interface development	/
Haoran	• Prototype construction	• Stepper motor control • Pump control	• I2C communication • Laser distance sensor • Raspberry Pi Data conversion to Arduino	• Linear regulator
Haoen	• Prototype construction	• Stepper motor control • Pump control • System Integration	/	• Linear regulator • Solar Panel
Zhaonan	• Prototype construction	• Stepper motor control • Pump control • System Integration	• I2C communication	/
Shawn	• Prototype construction • Prototype supporting structure design and manufacture • CAD for prototyping	/	/	• Solar Panel

Table 7: Work Distribution

Appendix C: Pseudocode for Final Demo:

```
Initialize:
  Set SLAVE_ADDRESS for I2C
  Configure pins for stepper motors and PWM
  Initialize serial communication at 9600 bps
  Set initial positions for stepper motors
  Enable motor driver inputs
  Register I2C receive event

Main Loop:
  If new data is received:
    Parse data into a matrix
    Increment rowIndex for new data
    If all expected data is received:
      Process each row of the matrix
        Calculate the movement required for each stepper motor
        Move stepper motors to new positions
        Update current positions to new values
        Log completion of job

Function - I2C Data Reception (Triggered by I2C event):
  If the byte count is correct:
    Read bytes into the matrix at the current row and column
    Advance column index
    If the end of the row is reached:
      Reset column index
      Increment row index
  Else:
    Log error: Incorrect byte count received

Function - Move Stepper Motors:
  Calculate degrees to move based on target and current positions
  Set direction based on whether the movement is positive or negative
  Convert degrees to steps
  Perform movement:
    For each step:
      Set pin HIGH, wait, set pin LOW, wait
  Update current position

Function - Initialize System:
  Set pin modes (OUTPUT)
  Set PWM pins to LOW initially
  Enable driver circuits
  Delay in system stabilization

Function - Log Data:
  Send data to the serial port for debugging and monitoring purposes

Loop Forever:
  Keep processing incoming data and moving motors accordingly
  If no new data:
    Continue monitoring
```

Appendix D: CAD Design for Initial Prototypes:

Figure 21: CAD