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# Project Number: 14421

## NEXT GENERATION SMART PV PANEL

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### ABSTRACT

Snow accumulation on top of solar panels can lead to a substantial loss in power generation during the winter months. The purpose of this project was to develop a battery-powered system that uses a pattern of conductive ink on the glass of the solar panel to melt snow and prevent accumulation. The system uses an array of sensors to detect the presence of snow on the panel. A temperature sensor senses for whether the temperature is below freezing, while an ambient light sensor tests for how much light the panel is exposed to. The actual voltage output of the panel is also sensed and is compared to what the voltage should be, based off of the light sensor. When snow is detected and conditions are ideal, the system turns on and power from the battery is used to heat the ink so that the snow can melt. The final system is inefficient and must be re-evaluated before there is potential for a profitable prototype. The ink layout lacks robustness and does not operate properly at the required temperatures.

### INTRODUCTION

As solar power is becoming more affordable and the desire for more sustainable energy sources is increasing, a rapidly growing number of solar panels are being installed by homeowners, even in climates that experience significant snowfall in the winter. However, this raises new issues when considering solar panel installation, because when solar panels are installed on roofs, snow retention is detrimental to the power generation of the system. In order to maximize energy production, the panels would ideally be completely exposed and have no snow covering them. Currently, solar panels must be cleared of snow manually and repetitively in order to allow for continual power production. Removing the snow can be dangerous for homeowners or hired workers who are responsible for clearing off this snow.

Advance Power Solutions, LLC, founded by Jasper Ball in 2008, aims to reduce the required maintenance and the risks involved. The company's focus was on developing a heated system that utilized a pattern of conductive ink on the panel that would allow for snowmelt. They utilized a silver-based ink that could be applied to the glass during the manufacturing process which was heated and used to melt the snow. The original prototype was tested for feasibility in manufacturing and the ability to melt snow in a light Georgia snowstorm.

Project P14421 was designed to further test for feasibility of this product and to create a functional prototype that integrates a battery powered sensor system. The scope of this project also included researching and developing an optimized ink formula and ink layout, based on hand-calculations and ANSYS models of heat spread on a glass panel.

## DESIGN PROCESS

This prototype is required to consume a minimal amount of power while simultaneously preventing snow accumulation. A modular system will be developed, meaning that each panel will have an independent, dedicated snow removal system. The system needs to be robust and be able to operate in extreme climate, including under conditions of low temperatures and high wind, and additionally will be able to operate within a desired range of mounting angles to adapt to the installation environment. The system must have an integrated method for detecting snow. Lastly, the expense of the system needs to be minimized, and it must be designed to be put at the front-end of the existing manufacturing process for solar panels.

The prototype was designed to function in Rochester, NY, based on average snowfall conditions. The system was focused on a small-scale design for an average homeowner and was constrained to utilize conductive inks to heat the panel. Snow accumulation is prevented by melting a bottom layer of snow and allowing for snow to slide off of the panel by the force of gravity combined with the angle of the panel. The system was designed so that during times of low power generation, including nighttime and on cloudy days, the system should remain off in order to prevent excessive cost. The system must be stand-alone and therefore runs off of battery power. The system requires a manual system shutdown option. Response time of the system needed to be minimized. Costs needed to be minimized in order to stay within the $1000 budget.

### 1. Heat and Power Analysis

An extensive analysis of heating and power requirements of the system was necessary to meet engineering requirements. Several parameters and assumptions were used when calculating theoretical power consumption. The snowfall and solar data was based on TYM3data, which was collected over the past 30 years. For each individual month, it utilizes the data from the month with the most "average" conditions. The panel efficiently was assumed to be 19%, a relatively high efficiency when considering modern solar technology. For simplicity, the area of the panel was assumed to be four perfect square cells, although in reality the corners of the squares are cut off. The variance in area is small enough that it can be considered negligible.

A heat analysis was conducted to compare how much energy would be required to heat the panel compared to how much extra energy would be generated due to more constant exposure to the sun. The calculations were based upon a requirement of a steady state temperature of 5°C needed across the panel in order to prevent snow accumulation. The cell was analyzed as a fin. The fin calculations were combined with solar flux data for Rochester, NY, along with the convection coefficient, to determine how much extra power could be generated if this system were utilized. It was concluded that in order to be efficient and cost-effective, the yearly power consumption for the system needed to be under 29,111 Wh/m$^2$-year, with a required heat output rate of 54W, resulting in a required snowmelt rate of 9600 cm$^3$/hr. It was predicted that making the system energy efficient and cost efficient was going to be difficult due to the existing design constraints and that the specs may not be met.

### 2. Ink Layout

The ink layout was chosen based upon both hand-calculations and ANSYS tests of heat spread across glass. Several ink layouts were theoretically analyzed, with traces at various locations across the panel. The final design needs to be efficient at spreading heat across the panel, while also not obstructing the solar cells. There are gaps between the cells and bus-bars running down the center of the cells, so ideal ink placement is on top of either of the gaps or the bus-bars, because it allows for complete exposure of the solar cells. The ink trace dimensions need to be minimized in order to allow for minimum cost.

Both hand-calculations and ANSYS testing used a thermal conduction value of 1.4W/m-K for glass. The convection coefficient was varied from 5 to 28 W/m$^2$, to be representative of typical winter wind conditions in Rochester. The ANSYS calculations assumed that convection on the back of the panel could be neglected due to lack of exposure to the environment. Figure 1 below shows the results of an ANSYS test of the final ink layout. The convection coefficient was set at 12 W/m$^2$ with a bulk temperature of -5°C, and the ink was raised to 25°C. These conditions allowed for the required heat spread across the panel.

After analyzing multiple ink layouts, both the hand-calculations and ANSYS testing agreed on a pattern which minimized the required amount of ink, allowed for complete exposure of solar cells, and maximized heat spread across the glass. The pattern, which was designed for a 2-by-2 cell panel, would have 5 horizontal heating-traces of ink. These traces would run in the gap between the cells, on the bus bars running in the center of the cells and along the outside edges of the cells. The five heating-traces were to be connected with two vertical traces that had even lower resistance values than the heating-traces, in order to simulate a node condition. The final configuration can be seen below, in Fig. 2.

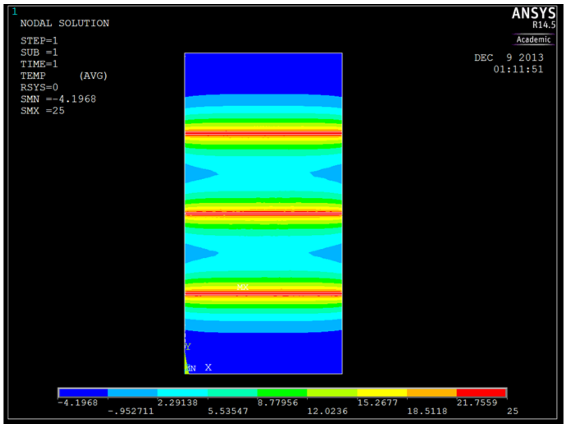

*Figure 1: ANSYS Results of Final Configuration*

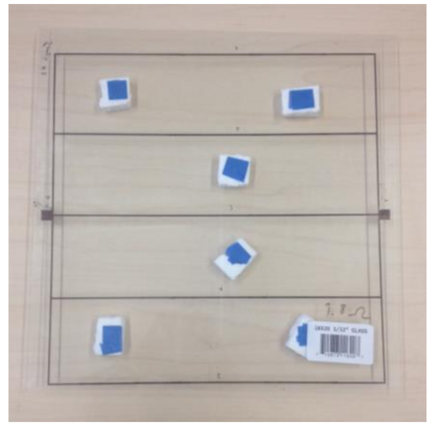
*Figure 2: Glass Panel with Printed Ink Layout*

Once the final ink layout was determined, a custom screen was purchased, which allowed the ink to be printed accurately in the desired layout.

## 3. Ink

The ink was fabricated by Intrinsiq Materials Inc. It is a copper-based ink that is designed to be highly conductive. The ink layout was printed onto three 14” glass panels using the custom screen. After being hand-printed, the ink was baked using a hand-held heat gun. The glass was then transported to Intrinsiq Materials where it was laser-cured. All steps were completed by hand due to the unusual size of the panel, which resulted in numerous imperfections throughout the process. The laser-curing was completed using two separate passes, in order to create nodes out of the vertical traces, while allowing for controlled resistance values in the five heating-traces. Each of the three panels was prepared with the intent to have different resistances, in order to create a range of testing conditions. The overall measured resistances of the three panels measured between 3.3 and 9.8Ω.

There were many imperfections and inconsistencies in the final ink layouts due to the custom nature of the process. Directly after being printed, two of the three panels had notable imperfections in the ink pattern. The resistances of the individual heating traces on each panel also varied, leading to a variance in voltage and current at different areas of the trace. All of these imperfections led to poor performance of the ink and reduced efficiency in heat spread. Furthermore, the ink was required to have a lifetime of 25 years. A realistic way of testing for the ink lifetime wasn’t able to be determined, but it is assumed that this requirement would not be met, due to the lack of robustness exhibited since the ink was printed.

## 4. Heat Testing

The most important requirements of the system were its ability to melt snow while using a minimal amount of power. Without these requirements being met, the system cannot be a viable marketable product. Several rounds of heat testing were conducted under varying conditions, which included different voltages and different operating temperatures. A list of conducted tests can be seen below (Table 1.)

| Test | Voltage (V) | Ambient Temp. (°C) |
|---|---|---|
| 1 | 3 | 23.7 |
| 2 | 6 | 23.7 |
| 3 | 9 | 23.7 |
| 4 | 9 | 25.4 |
| 5 | 12 | 25.4 |
| 6 | 3 | 24.6 |
| 7 | 3 | 0 |
| 8 | 6 | 0 |
| 9 | 9 | 0 |
| 10 | 12 | 0 |

*Table 1: Test Matrix of Heat Testing*

The tests were conducted using a portable power source that was able to reach the required voltage of 12V. Images of testing can be seen in Fig. 3 and 4 below. All room-temperature testing was conducted on a panel with an overall resistance of 3.3Ω, while a panel with an overall resistance of 9.8Ω was used for testing at freezing temperatures. The ink layout came out best on the 9.8Ω, and its higher quality as desired for the important testing. Temperatures at designated points across the glass were measured and recorded using a set of four thermo-couples attached to a four-channel data-logger thermometer. The thermocouples were held onto the glass with painters tape Wires were then either soldered or taped onto the glass, depending on what was available at the time. The wires were attached to the power source and current was applied to the ink. Temperatures were recorded manually. The engineering requirements set a maximum ink-heating time of 300 seconds, which deemed using a computer to record measurements at a high collection-rate to be unnecessary. In all tests, temperatures were recorded every 30 seconds.

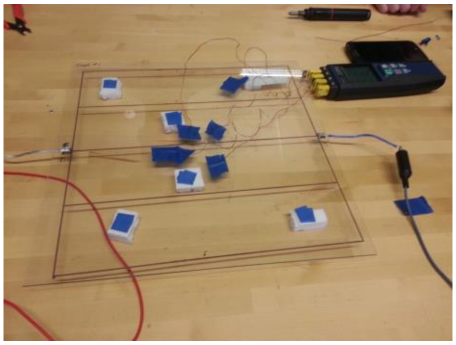

*Figure 3: Testing at Room Temperature*

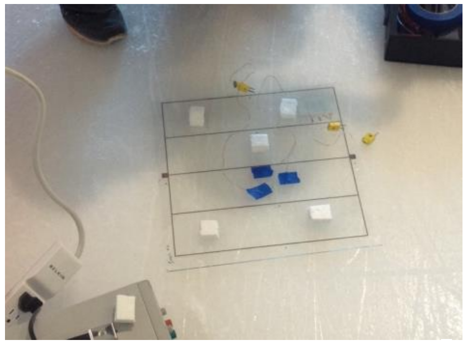

*Figure 4: Testing on Ice Rink, Glass at 0°C*

Testing at room temperature tested the feasibility of the system while also modeling heat spread across the glass. Testing on the ice rink both provided feasibility testing and allowed for the ink to be put under realistic conditions. In Test 10, the temperature of the glass increased by approximately 2°C at the trace, but the rest of the glass remained at a constant 0°C. The results of the ice-rink (Test 10) and room-temperature (Tests 4 and 5) testing data can be seen in Figures 5 and 6 below, respectively.

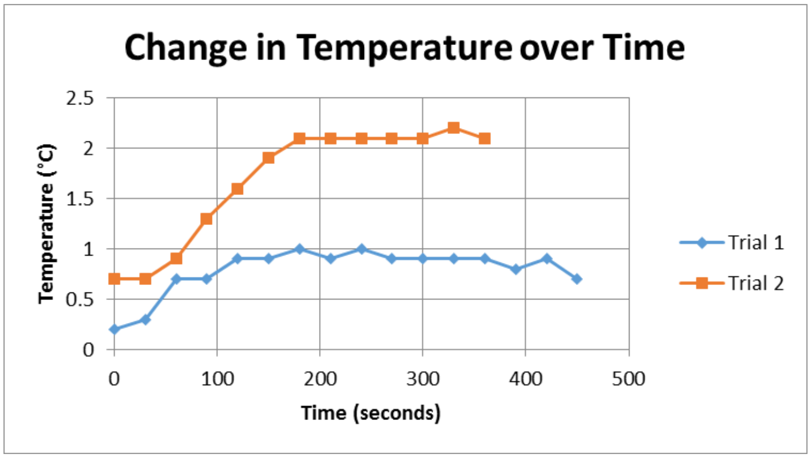


*Figure 5: Temperature of glass at trace vs time for Test 10 (see Table 1)*

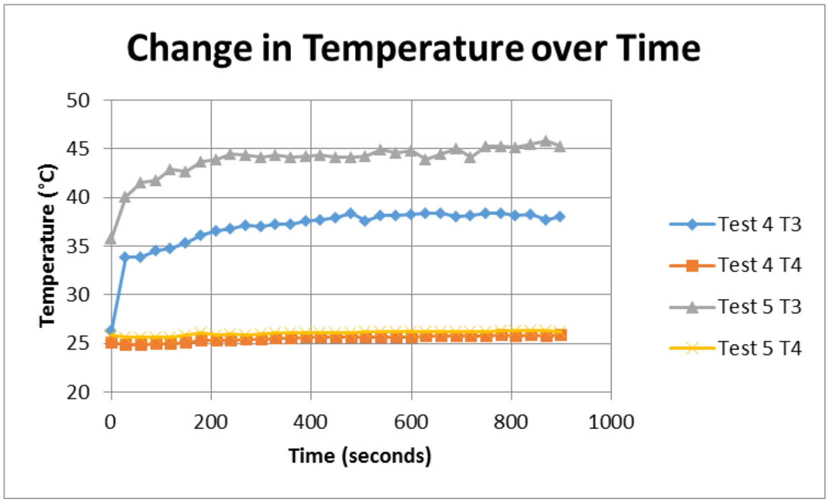

*Figure 6: Temperature of glass vs time for Tests 4 and 5 (see Table 1)*

Figure 5 shows the temperature that was recorded at the center heating-trace for Test 10. The overall glass temperature stayed constant, while the temperature of the trace increased by a maximum of 1.5°C. This testing was conducted at 12V, where the resulting current varied between .10 and .13A, which is equivalent to an average of 1.2W of power flowing through the ink.

For Tests 4 and 5, thermocouple 3 (T3) was placed directly next to the trace, while T4 was placed at the midpoint between two traces, and testing was conducted at room temperature of approximately 25°C. The ink was able to increase by 12°C at 9V, where a current of .4A was maintained. At 12V, the ink temperature rose to 45.5°C, equivalent to 20°C above room temperature, and maintained a current between .50 and .54A. Both of the previous conditions were at T3. The temperatures reached a steady state after approximately 300 seconds. The temperature at T4 showed negligible increase.

Heat output rate varied from test to test, based on the original resistance of the ink traces and the voltage being applied to the ink. Heat output rate was maximized during Test 3, where a maximum amperage of 1.72A was achieved, resulting in an output rate of 15.5W, compared to the requirement of 54W. Heat did not spread through the glass as efficiently was predicted through hand calculations and ANSYS-testing. This is most likely due to the inefficiency of the ink along with errors caused by assumptions made when making predications.

## 5. Power Electronics

The power electronics focus on supplying power to sensor conditioning circuits, the system controller and, most importantly, the ink to heat up the panel. The first step when considering the power electronics was choosing the correct type and capacity for the battery. The type of battery that was chosen was an absorbed glass mat (AGM) battery. This type of battery is preferred in standalone photovoltaic systems because it needs very little maintenance. The next step was to choose the capacity of the battery so it could provide power for a sufficient amount of time. Taking into consideration the efficiency of the battery in cold weather, a 100 amp-hour battery was chosen. A 110AH AGM sealed battery was supplied by Renewable Rochester. The duration of time that the battery can supply power to the system will vary depending on how bad weather conditions are and how much power is being used to heat the ink.

A Morningstar SS-20L 20 charge controller was selected to control the charge levels of the battery. An AGM battery is intolerant to an overcharge. This charge controller works with a 12V battery as specified in the engineering requirements and allows for a load current of up to 20A which is more than enough for powering the ink. The charge controller uses the voltage from the solar panel to charge the battery which will power the connected load (Fig. 7).

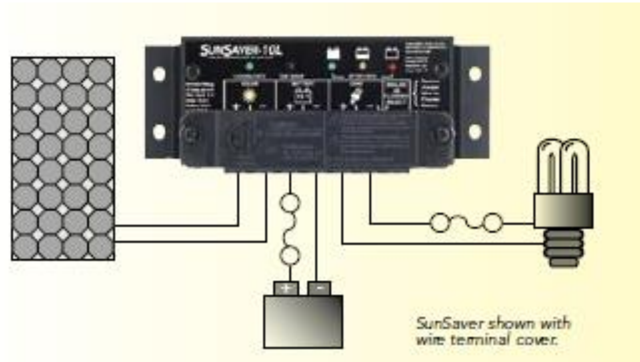

*Figure 7: Charge Controller Connections*

A +5V, +3.3V, and a -5V linear regulator were chosen to power the sensors and microcontroller. The linear regulators were chosen with relatively high efficiencies to avoid unnecessary use of power. The main element of the power electronics is the solid state relay (SSR), which is responsible for supplying the power to heat the ink. This is where the majority of the system's power is being utilized. The selected SSR is the crydom series 1- DC D1D20. This SSR is rated for up to 20A and the output can be controlled by the selected microcontroller. The duty cycle of a 490Hz 5V square wave determines the output level of the SSR. The duty cycle and therefore the output of the SSR will be determined from the sensor outputs.

## 6. Sensor System

The prototype required a sensor system that was integrated into the system that could help determine whether or not the system should turn itself on. Three environment variables – ambient light (GA1A2S100LY), ambient temperature (LM35), and panel output voltage (direct monitor) – are monitored to sense the presence of snow on the panel. Each of these signals is then passed through conditioning circuitry which shifts and scales the signals to the 0-5V range of the analog inputs on the Arduino. The individual signals then drive comparators implemented with hysteresis. The outputs of the individual comparators then drive transistor-transistor logic, which sends an interrupt signal to the Arduino.

When considering the three environment variables, the presence of snow can be accurately determined when the temperature is below freezing and the output of the panel voltage is low (no light gets through to the panel). If those two variables are in the correct state, ambient light is observed. If the ambient light level is high enough so as to produce a reasonable amount of power with a fully-exposed panel, then the interrupt signal will wake the Arduino, which will then apply voltage to the resistive ink, in order to heat the panel.

## 7. Control System

The control system needed to be able to process signals from various sensors in order to make a decision to melt or not while consuming a minimal amount of energy. It also needed to be able to output a pulse-width modulation signal to interface with the SSR cube to apply various amounts of power to the ink.

The controller consists of Atmel's flagship microcontroller, the ATMEGA328P, which was selected for its ease of use and cost effectiveness. It is featured in the popular Arduino Uno breakout board. It includes an 8-bit with system programmable flash. This enables the controller to be programmed on a printed circuit board with the use of the breakout board. It has ample I/O peripheral pins with 6 dedicated to analog-to-digital conversion that can be interfaced with various conditioned signals from the sensors. It also features a very low power consumption mode that uses interrupt capability to resume program operation. Successful and reliable operation was tested and proved using a standalone configuration validation test.

In order for the system to operate properly, the Arduino must output a pulse-width modulation signal to heat the ink in a timely manner once an interrupt is received. As observed when testing the system as a whole, the system response time (i.e. time between interrupt signal and melt signal) was so quick that it was immeasurable by the methods available. As such, it can be determined the response time is below the required .5 second threshold.

A simulation was performed in order to test the sensors' ability detect snow. The test setup included a solar panel with a method in which to cover it, a beaker of ice water to change the temperature of the sensor, and a light source. The thresholds first had to be set in the control program to tell the Arduino when to turn on the heating source and the potentiometers were set for these points. The threshold values that were used were 1.75V for ambient temperature, 1V for ambient light, and 3V for the panel voltage. The signal from the Arduino to the SSR was monitored to see when the system would start melting snow. The presence of snow was simulated by covering up the panel and putting the temperature sensor in the ice water. A light was shone on the light sensor to simulate that it is sunny outside and the snow should be melted. The Arduino sent the pulse-width modulation signal to the SSR once the light was turned on. The temperature sensor was then heated up and as predicted, the Arduino turned off because it was not cold enough for snow to potentially be the cause of the panel coverage. The panel temperature feedback system was also tested. As the panel temperature increased, the Arduino lowered the duty cycle of the pulse-width modulation since less power was needed. When performing this test outside, the threshold values would have to be adjusted.

### 8. Enclosure

The enclosure needed to be able to fit all components of the system and weatherproof the components against the elements. The selected enclosure measures 22"H x 16" W x 10" D, with the capacity to hold one 110Ah battery. The enclosure includes hinges, latches, a door gasket, and is made of .063" aluminum that has a riveted construction to meeting NEMA 3R standards.

### 9. Final Assembly

All subsystems were mounted into the enclosure. The layout can be seen in the figure below. Additional holes were drilled in the enclosure in order to allow for wires to connect the internal subsystems to the solar panel and ink layout, as well as to allow for the mounting of switches. The system required a manual on/off button which is mounted on the outside of the enclosure, along with a switch that allows the user to manually force the system to be in a melting state.

*Figure 8: Subsystems within Enclosure*

## RESULTS AND DISCUSSION

The ink layout on the panel was designed for maximum heat spread across the panel. The sensor system was designed to determine whether conditions meet the requirements to justify the system being turned on. Non-ideal conditions could lead to excessive amounts of power being wasted to heat up the panel.

It was desired that the ink would be able to survive the manufacturing process. After conducting ink testing, it was evident that the ink layout is not robust and would not survive the manufacturing process. The ink scratched easily which led to a lack of current flow through entire traces. At room temperature, when the power was set to 9.0V or higher, even with a low current flowing, the ink on the low resistance panel began to burn. It was noted that during high-voltage testing the current values decreased as time went on. This is believed to be due to the degradation of the ink during heating.

Furthermore, when testing was conducted at freezing temperatures, the temperature of the glass directly next to the trace only increased by around 2°C, as seen in Fig. 5, and the overall panel temperature stayed constant. With 12V of power being sent through the ink, there was a maximum of 1.2W of heat output, compared to the calculated 54W that was needed to melt the snow. Therefore, neither the required snowmelt rate of 9600 $cm^3$/hr or required minimum power consumption of 29,111 Wh/$m^2$-year was achieved. It is evident that the current ink formula is not able to withstand the freezing temperatures and doesn't maintain its low resistive properties. Lower resistance is needed to produce more power but when resistance values are lower, the traces are more likely to burn, as exhibited in prior tests.

It was originally desired to know how much of the heat output was being transferred to the snow and how much was actually being used to melt the snow, however, due to the lack of successful test results, this requirement was not able to be explicitly tested.

## CONCLUSIONS AND RECOMMENDATIONS

The goal of this project was to create a functional prototype of a snowmelt system that could be perfected and sent to production. The project was constrained to use a conductive ink based system without any mechanical or moving parts.

Many aspects of this project need to be thoroughly considered before this product is proposed to be manufactured on a large scale and sold commercially. Although the project was within budget, it does not meet the requirements set forth by the customer. The current system design isn't energy efficient and the consumer may not end up saving money, which defeats the purpose of the product. Additional thought must be given to the design in order to take it from a small-scale system to a large-scale application on a solar farm or other large-scale setup. Furthermore, the ink is not robust and will not be able to withstand the manufacturing process or being exposed to the elements.

Overall, the system does comply with the most important customer needs and fails to meet the majority of the specified engineering requirements. However, it was already predicted during the end of the design stage that the requirements may not be met, based upon the results of initial analyses. Although the project is not currently ready to be built on a larger scale, the data collected and knowledge gained throughout this project will help future teams to tackle pinpointed issues and further improve the system. The future of this project is largely dependent on the further understanding and improvement of the ink technology required for this concept. Future iterations of this project would ideally begin during spring so that the improved system will be ready for testing once it begins to snow.

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