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Affordable and Localized Plastic Sheet Press Machine for Sustainable Manufacturing

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My Name is Kenny Harris, there are several things to know about myself, being a senior mechatronic engineering student at Vaughn College of aeronautics and technology. However, here are three important items related to myself: I am an eight-year Marine Corps veteran and an immigrant hailing from the island of Jamaica; finally, and most importantly, I make it a duty to participate in engineering related activities such as clubs, conferences and currently serve as a senator of the National Society of Black Engineers at the college. I am always striving for excellence and love to solve problems that are thrown in my direction. It has forever been my motto that: ”no idle life can build a true man.”

Mr. Mahin Rajon Bhuyan, Vaughn College of Aeronautics and Technology

I'm a senior student pursuing a B.S. in Mechatronic Engineering at Vaughn College of Aeronautics and Technology. Additionally, I am treasurer of the Unmanned Aerial Vehicle Club. My engineering interests are mechanical, aerospace, drones, robotics, and 3D printing. I aim to obtain my engineering license while seeking opportunities to learn from various disciplines within engineering to expand my expertise.

Mr. gordon qian, Vaughn College of Aeronautics and Technology

Gordon Qian is a senior Mechatronics Engineering Major at Vaughn College of Aeronautics and Engineering. For this project, their role entailed acting as software lead focusing on the programming of the Arduino Mega in C++ and running the tests with the components alongside electrical. During periods in which programming or tests could not be completed, the organization of both responsibilities per person and items or files based on work completed was established and maintained.

Alaric Hyland, Vaughn College of Aeronautics and Technology
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Dr. Shouling He holds a position of professor of Engineering and Technology at Vaughn College of Aeronautics and Technology, where she teaches various courses in Mechatronics and Electrical Engineering. Her academic and educational interests focus on Robotics and Automation, Machine Learning, and Mechatronics Education. She has authored over 50 papers published in journals and conferences.

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Maker: Affordable PLA Sheet Press Machine Design and Implementation

Abstract

This project aims to design and implement a functional PLA (polylactic acid) press sheet at less than or half of the standard cost, with a focus on helping Vaughn College reuse old PLA materials from various projects. This project's creation is to serve as a solution and a final-year capstone to the members involved. The project is a collaboration between the college's engineering department and its presiding members. Presently, machines and designs are available on the market, most, if not all are overseas, are at prices of $5000 upwards to $12,000 USD each. This project focuses on common materials used for 3D printing such as PLA. This material is used in bulk and during printing either from supports, shaving or failed product scraps. Developing the project can not only save money for the college from a financial standpoint but also can aid environmental efforts in encouraging upcycling and eco-friendly efforts.

Introduction

In recent years, the awareness of the environmental hazards of traditional manufacturing processes often relies on virgin plastic materials, which causes serious pollution and resource depletion. Additionally, the lack of accessible and affordable recycling solutions exacerbates the problem, hindering efforts to transition towards more sustainable manufacturing practices. Considering these challenges, there is a need for the development and implementation of affordable technologies, such as a PLA sheet press machine, to facilitate the recycling of plastic waste materials into recycled PLA sheets for sustainable manufacturing.

This project aims to address the critical gap in recycling infrastructure at Vaughn College. Moreover, we aim to promote the adoption of eco-friendly alternatives in the manufacturing industry, ultimately contributing to environmental preservation and resource conservation.

PLA is a bioplastic made from fermented plant starches found in crops such as corn, cassava, maize, sugarcane, and sugar beet pulp. The fermentation of sugars present in these renewable materials produces lactic acid. Later, the lactic acid is converted into polylactic acid, or PLA [1]. It is also a thermoplastic, meaning it can melt at low temperatures and solidify when cooled [2]. This property allows for easy recycling, as PLA waste can be melted down and used again without losing its quality. PLA is widely used in additive manufacturing applications. In 3D printing, PLA is used for Fused Deposition Modeling (FDM), the process includes the material melted and extruded onto a surface, forming layers that cool and solidify. In this project, we develop a mechanical sheet press that will melt the shredded PLA from failed prints and previous year prototypes into thin sheets to be later cut into rolls for use. These sheet tiles can be used for cabin paneling or even structural elements. The applications offered by these sheets enable a larger practice of upcycling and new opportunities. This will help educational institutes to save money and reduce waste.

Background Research

Plastic sheet presses, sometimes referred to as thermoforming machines, are amazing pieces of machinery that have completely changed the way that plastic goods are made. A flat plastic sheet is heated to a malleable temperature to start the process. Following its transfer to a mold or die, the heated plastic is formed. This could be a straightforward container or a complex piece of machinery for an automobile. The pressure of the press causes the plastic to take on the shape of the mold, and when it cools, it keeps that shape. These presses' underlying technology has changed over time. Modern presses can be fully automated with exact control over temperature and pressure, guaranteeing consistent quality and efficiency, unlike earlier models that were largely manual and labor-intensive. Additionally, there are several varieties of presses available, including twin sheet forming, pressure forming, and vacuum forming, each of which is best suited for a certain set of uses and goods. The environmental impact of plastic production is also a significant concern, and the industry is constantly seeking ways to reduce waste and energy consumption. Innovations in plastic sheet presses include features that allow for recycled materials and more energy-efficient operations. This helps manufacturers not only comply with regulations but also meet the growing consumer demands for sustainable products. By utilizing the manufacturers in the United States, we can significantly reduce production costs compared to outsourcing manufacturing overseas. This is due to factors such as lower transportation expenses, reduced shipping times, and potential savings on labor costs.

Scaling up production and leveraging local supply chains can further drive down costs through economies of scale. As demand for the PLA sheet press increases, unit costs can decrease, resulting in additional savings for both manufacturers and end-users.

Design Concepts

Properly creating plastic sheets requires heat and pressure. PLA becomes soft at 60 degree Celsius and melts fully at 170 – 180 degree Celsius and the maximum pressure PLA can handle is 7250 PSI (pounds per square inch). We will not need the maximum value but need sufficient pressure to put the PLA under compression and form a uniform plate without air pockets or deformations.

Heating plates were originally designed. However, through thermo-simulations we determined the heating rate was too slow to be usable as needed. Heating cartridges were selected as an alternative for the heating element with a model capable of reaching the desired temperature at the range of 170 – 180 degree Celsius during a reasonable time.

The pressure system causes conflict in the properties of the device at several points in physical processing and as such a decision matrix was created to compare the critical situations more directly in creating an ideal mechanical design. (Table #1)

As seen below, the weight table shown in Table #1 compares the three core designs of hydraulic, linear actuator, or hinged press. Whilst the manual pressure methods would not be used due to the lack of uniformity in manual labor, the linear actuator method was deemed the best solution for this project due to its high availability and low cost. Whilst it is lacking in terms of pressure this can be amended with several linear actuators as using several would still be a cheaper alternative to hydraulic.

The weight distribution for the table follows the bias of greatest to least from cost, applied pressure, reliability, availability, and finally size. This metric was chosen as budgeting and parts acquisition to create a reliable yet cheaper alternative to foreign models.

Table #1: Pressure Distribution Weight Table

Comparison of Criteria	Weighted Values	Hydraulic	Linear Actuator	Hinged Press
Applied Pressure	25	1	-1	0
Cost	35	-1	1	0
Availability	15	0	1	1
Reliability	20	1	0	-1
Size	5	0	0	1
Total		10	25	0

Budget/Bill of Materials:

The material bill shown in Table #2 are sourced majority from United States manufacturers due to the fast delivery and reliable supply compared to overseas suppliers that are cheaper, yet their supply chain is slow and cumbersome. All materials, both electronic and mechanical, needed for the completion of this project are mentioned and gave a total sales figure of $834 USD.

Table #2: Single Level Bill of Materials

SHIPPING TIME	HIPPING COST	PART NAME	DESCRIPTION	QUANTITY/s	UNITS	UPPLIER / MANUFACTURER	LIER / MANUFACTU	IT COST/SUPPLIE	PART COST/ S
3-5 days	$12	Aluminium Frame	Standard Anodized Extruded Aluminum Profile for 3D Printer	1	4	Amazon	AliExpress	$ 8.74	$ 34.99
3-5 days	$12	Glide rode	Linear Bearing Slide	1	4	Amazon	AliExpress	$ 6.50	$ 26.00
3-5 days	$12	Relay	CG Solid State Relay SSR-25DA DC to AC Input 3-32VDC To Output 24-480VAC 25A Single Phase Plastic Cover	1	1	Amazon	AliExpress	$ 9.97	$ 9.97
7-14 days	$14.99	Heating cartridg	TEMPCO Swaged Cartridge Heater: 500 W Watts, 4 in Lg, 10 in Lead Lg, 240V AC, 121W/sq in, 3/8 in Dia	1	8	Amazon	AliExpress	$ 30.62	$ 244.96
3-5 days	$12	Arduino	UNO R3 Board ATmega328P with USB Cable(Arduino-Compatible) for Arduino, Input Voltage 7-12V, 16MHZ,14 Digital I/0 pins Support PWM, SRAW 2KB, Compatible with	1	1	Amazon	AliExpress	$ 12.99	$ 12.99
3-5 days	$12	AC/DC converter	Acxico 5Pcs 5V 700mA Board Module Mini AC-DC 110V 120V 220V 230V to 5V 12V Converter Board Module Power Supply	1	5	Amazon	AliExpress	$ 1.99	$ 9.99
3-5 days	$12	Thermistor	3PCS HT-NTC100K Thermistor Sensor for Creality Ender 3 Upgrade 3x15mm 3950 Thermistor Compatible with E3D V6 Volcano PT100 Ender 3, Ender 5 Pro CR10 3D Printers	1	3	Amazon	AliExpress	$ 4.59	$ 13.79
3-5 days	$12	Fan	2Pcs DC 5V 8010 Fan 3D Printer 80x80x10 Brushless Cooling Fan 80MM for 3D Printer PC CPU Computer Case Fan Cooler	1	1	Amazon	AliExpress	$ 6.99	$ 6.99
3-5 days	$12	LCD screen	BIGTREETECH TFT35 E3 V3.0.1 Graphic Smart Display Panel Board for Ender 3 Compatible with SKR Mini E3 V3.0, SKR 3/EZ, Octopus/Pro/Max EZ, Kraken, SKR Pro V1.2	1	1	Amazon	AliExpress	$ 9.99	$ 9.99
3-5 days	$12	Push button	20 Pcs 6mm 2 Pin Momentary Tactile Tact Push Button Switch Through Hole Breadboard Friendly for Panel PCB	1	20	Amazon	AliExpress	$ 0.29	$ 5.99
3-5 days	$12	Toggle switch	20 Pcs 6mm 2 Pin Momentary Tactile Tact Push Button Switch Through Hole Breadboard Friendly for Panel PCB	1	10	Amazon	AliExpress	$ 0.89	$ 8.99
3-5 days	$12	Heat insulation	Frost King Foil Backed Fiberglass Pipe Wrap, 3"x1"x25	1	1	Amazon	AliExpress	$ 8.98	$ 8.98
3-5 days	$12	insertion nuts	HELIFOUNER 200 Pieces 5 Sizes Metric Hex Nuts Assortment Kit, M3 M4 M5 M6 M8 Stainless Assorted Hex Nuts Set for Screws Bolts	1	200	Amazon	AliExpress	$ 0.04	$ 8.99
3-5 days	$12	Steel plates	ALUINOKI 4Pack 3/16 Hot Rolled Steel Plate A36 Steel Sheet 4in x 4in A36 Square Steel	1	4	Amazon	AliExpress	$ 6.49	$ 25.99
3-5 days	$12	Nut cage	Swpeet 150Pcs Metric 304 Stainless Steel M3 Hex Lock Nuts and M3 Flat Washers with M3 Split Lock Washers Assortment Kit, Hex Lock Nut for Home Automotive	1	150	Amazon	AliExpress	$ 1.74	$ 6.99
7-14 days	$9.99	AC outlet	6.00' (1.83m) Power Cord Black NEMA 5-15P To Cable SVT	1	1	DigiKey	AliExpress	$ 7.93	$ 7.93
3-5 days	$12	Linear actuators	JQDML 12 Inch 12" Stroke Heavy Duty 12V Linear Actuator with Mounting Bracket 3000N/660lbs 5mm/s Linear Electric Actuator for Recliner TV Table Electric Sofa	1	4	Amazon	AliExpress	$ 83.99	$ 335.96
3-5 days	$12	Relay for actuators	CG Solid State Relay SSR-25DD DC to DC Input 3-32VDC To Output 5-240VDC 25A Single Phase Plastic Cover	1	1	Amazon	AliExpress	$ 8.98	$ 8.98
3-5 days	$12	Thermocouple	GalaxyElec 1pcs MAX6675 K-Type Thermocouple Temperature Sensor Temperature 0-800 Degrees Module for Arduino I45	1	1	Amazon	AliExpress	$ 8.98	$ 8.98
3-5 days	$12	Power Supply(Arduino)	GalaxyElec 1pcs MAX6675 K-Type Thermocouple Temperature Sensor Temperature 0-800 Degrees Module for Arduino I45	1	1	Amazon	AliExpress	$ 8.99	$ 8.99
3-5 days	$12	Linear Actuator (Power Supply	NOYITO AC to DC 24V 6A Isolated Power Supply Module AC 120V (85-265V) to 24V 144W Max Power Module with Overcurrent Overload Short-Circuit Protection (24V 6A)	1	2	Amazon	AliExpress	$ 13.99	$ 27.98
3-5 days	$12	Voltage Convertor	110V to 12V Electronic Transformer for Power Efficiency, 160W Voltage Converter with Smart Control, Power Supply Driver for Dimmable Lamps(160W)	1		Amazon	AliExpress		$ -
				22				TOTAL	$ 834.42

The utilization of the heating cartridges in the design is so that the plastic sheet press can provide heat to the PLA in the mold so that it can soften.

Figure #1: DERNORD Immersion Cartridge Heater with 240V & 500W

To convert rotational motion into linear motion, the usage of the linear actuators helps the machine press and apply the pressure of the plate into the mold for shaping.

Figure #2: DC HOUSE 12 Inch 12" High Speed 14mm/s Linear Actuator Motor

The Arduino board will be programmed to control the movement of the linear actuators that will be on the sides of the sheet press machine. It will also allow for the temperature to be monitored with the thermistors and the cooling fan.

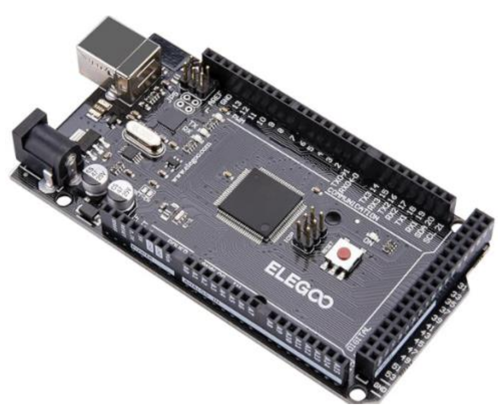

Figure #3: ELEGOO MEGA R3 Board ATmega 2560

The Arduino board will be programmed to control the movement of the linear actuators that will be on the sides of the sheet press machine. It will also allow for the temperature to be monitored with the thermistors and the cooling fan.

Requirements and Constraints
Market Requirements

This product is aimed at smaller-scale community projects or educational ventures. As such, the product must be compact, non-expensive and easy to use. The goal is to promote green practices in PLA usage and expand the interest in the STEM field. The plastic press market requirements can vary depending on the type of plastic products being produced, the target industries, and regional regulations. However, the market requirements for the plastic press include but are not limited to:
Efficient: The plastic press should be efficient in terms of energy consumption, cycle times, and overall production output.

Quality & Safety: The product should produce high-quality plastic tiles with minimal defects while also complying with the safety standards of the school.

Sustainability: The incorporation of environmentally friendly practices, such as recycling, and waste reduction will help benefit the school since there is a high abundance of PLA excess at Vaughn College due to the numerous amounts of 3-D printing. The tiles, the press forms for the aeronautical department of the school can be used for cabin paneling or even structural elements. The applications offered by these tiles enable a larger practice of upcycling and new opportunities.

Technology Integration: During the plastic pressing process, implementing a control system (touchscreen interface) will allow for a more user-friendly and higher precision of the plastic press. There wouldn't be any room for customization in this project because we only plan to have one mold and one type of plastic material (PLA).

Engineering Requirements

To meet the needs of the market and achieve the overall design goals, this product should have technical specifications that comply with the following engineering standards:

1. Microcontroller
   - ∉ Arduino AT Mega 328
   - ∉ 16 Analog Inputs
   - ∉ 13 Pulse Width Modulation (PWM)
   - ∉ 30+ General Purpose Input/Output (GPIO)
   - ∉ Serial LCD Module Display
2. Heating Elements
   - ∉ Cartridge Heater 240V, 500W
   - ∉ Thermistor
   - ∉ Fiberglass Pipe Wrap
   - ∉ 170 - 180 Celsius target temperature

3. Mold: 600 x 600 mm or [23.6" x 23.6"]
4. Weight: ≤ 68kg or [150lbs]
5. Toggle Switch 120 V, 30 Amps
6. Round Rocker Switch AC 125V, 10A; AC 250V, 6A
7. Tactile Tact Push Button Switch
8. Power
    - ≤ 12,500 Watts power outlet
    - Power Supply 348W 12V, 29 A
    - Relay for Linear Actuator 240 V
    - Relay for Power Supply 480 V
9. Brushless 3D printer cooling fan
10. Frame
    - ∉ Materials - Aluminum
    - ∉ 880 x 740 x 1,245 mm^3 (or 35" x 29" x 49") or smaller
11. Motor - Linear Actuator
    - ∉ 12 V DC
    - ∉ Stroke Length 30.5cm (or 12")
    - ∉ Max Push Load – 102kg (or 225lbs)

These engineering requirements are essential for designing and manufacturing a plastic press machine that meets industry standards and customer expectations. Specific requirements may vary based on the machine's intended use and the type of plastic products being produced.

- The mold should be large enough to contain and secure a 600 x 600 mm^2 area.
- The heating element should be able to reach a stable temperature to melt PLA scraps and parts. (220 degree Celsius)
- A stable source of pressure to maintain the plate shape should be consistent throughout.
- Compact and easy-to-use user interface.
- Built-in control systems to maintain consistency on product and maintain fail safes.

Constraints

In developing this project, from the design phase, integration, and implementation, it was evident that the device would be arduous to create in a short period. Developing a plastic sheet press with the aim of a significantly lower working budget compared to existing offerings; while ensuring functionality, reliability and meeting several safety standards gave little time for errors in the process if it was to be developed within one school semester. Several issues arose which caused engineering constraints.

1. Budget constraint: This device must be created for half the current offerings of the available market or below.
2. Mechanical constraints: To ensure consistent and accurate sheet formation, the press and mold are made with structural integrity to withstand the forces involved in pressing.
3. Heat constraint: To ensure appropriate material flow and shaping, the press must be equip ped with a heating system that can reach and maintain the precise temperature range need ed for PLA melting (a melting point between 170°C and 180°C).
4. Electronic constraint: To ensure exact and consistent outcomes, the control system must

precisely manage the pressure and temperature during the pressing operation.

5. Constraint connected to PLA: The design needs to take into consideration the unique properties of PLA, namely its low melting point and susceptibility to cooling rates. This entails maximizing the cooling and heating system to attain the appropriate sheet qualities and reduce any flaws.
6. Time constraint: This project must be done in three and a half months to ensure the engineering department has a working device due to their financial backing and sponsoring of this project.

Mechanical Design

This PLA press is designed to meet the college design requirements. The design concept ensures that the machine can be operated under normal circumstances by members of the faculty and student body all while keeping safety in mind that the PLA press includes an audible buzzer while in operation and LED light strips to give a visual warning when a hot surface is detected in normal operations.

As shown in Figure #4, the PLA press is fully extended, with an allowance of 0.5 mm. To prevent any issues during operation, the design considers avoiding over extension of the linear rods, ensuring that the machine does not pull itself apart.

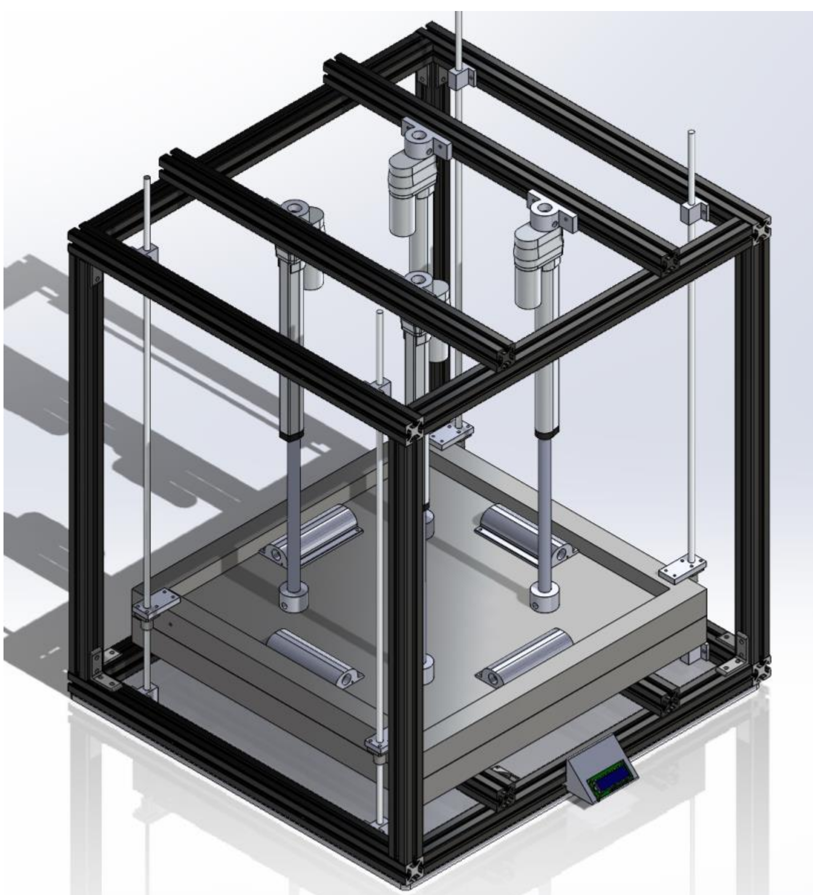

Figure #4: PLA Press with Linear Actuators Fully Extended

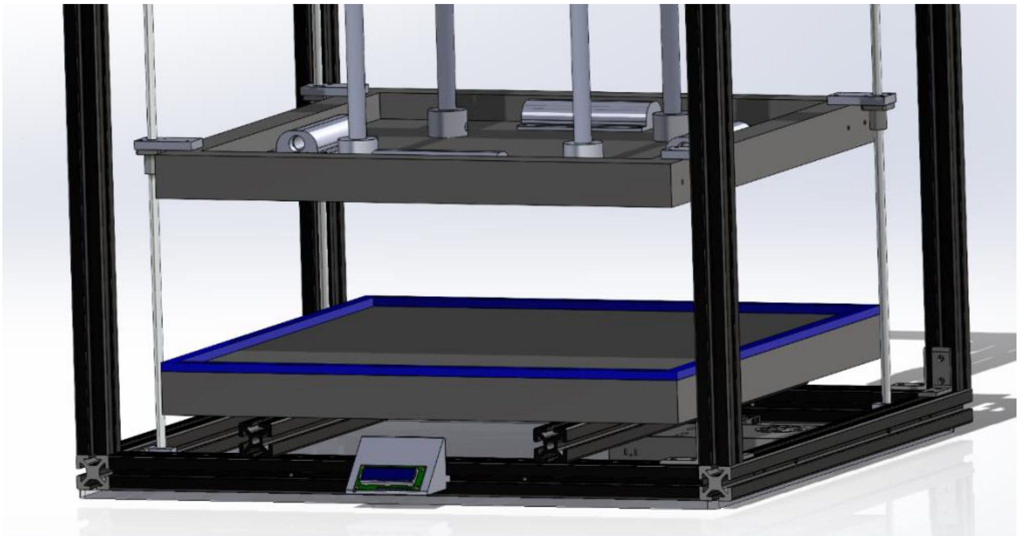

Figure #5: PLA Press with Sheet Mold

Figure #5 illustrates the sheet mold. The mold was designed with clearance around the top plate to ensure a uniform PLA sheet. Additionally, a thin sheet is incorporated to prevent PLA from sticking to the surfaces of the plate.

Specifications for the produced PLA sheet after the machine processing:

- Linear Actuator x1 puts down ≥ 408.233 kilogram-force
- Weight = ≤ 22.68 kg

Processed Sheet:

- Sheet Mold is 600 mm x 600 mm
- 0.5 mm thickness
- (600mm * 600mm * 0.5 mm) = 3600 cm^3
- Density of PLA: ~1.25 g/cm^3
- Weight per plate = 4.5kg
- Machine is 740mm * 800mm*874.2mm

Above are the dimensions required as per the colleges request. While considering the mold thickness and size a weight of 4.5kg of PLA is needed for each sheet.

Analysis of the thermal structure of the sheet press:

Heat - Thermal simulation conducted to test the hypothesis that heating plates will not be sufficient to heat up the PLA, instead heat cartridges will be used to get the desired temperature. (PLA - softens at 60 degrees Celsius and fully melts from 170 to 180 degrees Celsius)
Mechanical Assembly

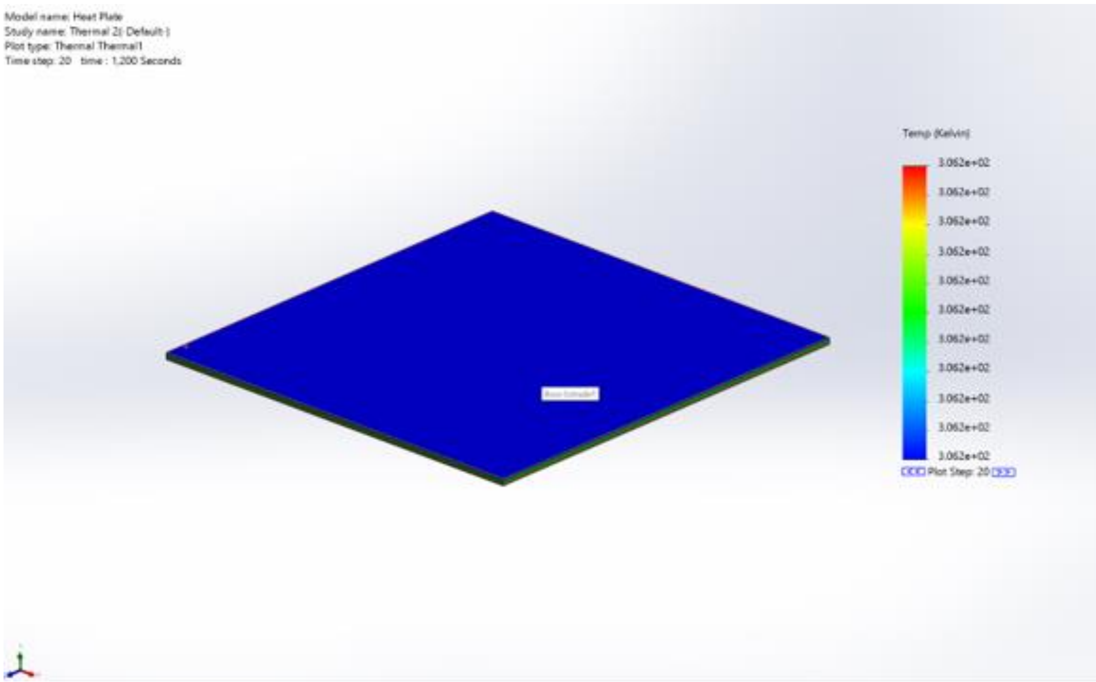

Figure #6: Solid Works Design of Press Sheet

Mechanical assembly can begin once all physical parts are ordered from aluminum extrusions for the frame, top and bottom plates, and mounts for the stepper motors. Testing for the heating cartridge will begin after spring break. The team has CNC'ed a heating enclosure for the heat cartridge and will be able to test the heat transfer and how it performs.

The task of designing and selecting material for the housing of the heating cartridge was completed. With the help of our advisor Alaric Hyland, the cheapest aluminum 6061 material as of now is from fastmetals.com with a 50.8mm x 76.2mm x (1219.2mm long). The design was tailored to the material the team selected from the website to meet the 50.8mm x 76.2mm dimensions, the size of the enclosure was decided by on accounting for the heating cartridge and thermistor, this helped cut cost down and avoid wasting material. The decision behind why aluminum was selected is due to its cost and thermal expansion. The prototype design made of PLA to see what fitment will be like, multiple iterations were done to make sure tolerance was a snug fit for the cartridge as shown in Figure #7.

Figure #7: PLA Prototype of Heating Enclosure

Table #3: Thermal Expansion for Steel vs Aluminum

Steels		
Material	Coefficient of Thermal Expansion	
	10^{-6} (°C)$^{-1}$	10^{-6} (°F)$^{-1}$
Plain Carbon and Low Alloy Steels		
Steel Alloy A36	11.7	6.5
Steel Alloy 1020	11.7	6.5
Steel Alloy 1040	11.3	6.3
Steel Alloy 4140	12.3	6.8
Steel Alloy 4340	12.3	6.8

Aluminum Alloys		
Material	Coefficient of Thermal Expansion (CTE)	
	10^{-6} (°C)$^{-1}$	10^{-6} (°F)$^{-1}$
Aluminum Alloy 1100	23.6	13.1
Aluminum Alloy 2011	23.0	12.8
Aluminum Alloy 2024	22.9	12.7
Aluminum Alloy 5086	23.8	13.2
Aluminum Alloy 6061	23.6	13.1
Aluminum Alloy 7075	23.4	13.0
Aluminum Alloy 356.0	21.5	11.9

After consulting Alaric about choosing aluminum 6061, the issue brought up was to investigate how the material warps before reaching 580 Celsius, the table above shows the thermal expansion of aluminum vs Steels. 6061 is approximately double the expansion of steel. There will be 4 mm expansion approximately. Thermal expansion was important in the design and operation of heat cartridges to have a proper fit, heat transfer, precise temperature control. Using Partially Threaded M5 Steel Socket (McMaster) and Spring Lock Washers (McMaster) for a M5 throughout this assembly. The block was a 50.8 mm x 76.2 mm x 152.4mm aluminum costing $46.77 given to our group by Professor Rachid. The design from CAD was finally manufactured and figure #24 is the result of the heating enclosure. The steel alternative is going to come out to be more expensive than aluminum, but it does have a higher melting point which would be a more optimal as a material for the plate. Steel is often preferred over aluminum for a PLA sheet press due to its superior strength and durability. The pressing process involves high pressures and temperatures, and steel can handle these conditions better than aluminum. Steel's higher strength helps ensure the press can withstand the forces involved without deforming or breaking. Additionally, steel has better heat resistance, allowing for precise temperature control during the pressing process. While aluminum has its own advantages, such as being lightweight and corrosion-resistant, steel is a more suitable choice for the demanding requirements of our PLA sheet press.

Electrical Design

The schematic for this project is depicted above. Care is taken when handling 220VAC. The converter module will be insulated, so as not to touch any low voltage parts [4]. The heater to the relay and the relay to the main 220v input with a mains wire. The same input is connected to the 5-volt power supply. The Arduino is connected to the LCD, and the thermocouple is connected to a module which leads back to the Arduino. The heating cartridges are then connected to the 220 VAC to consume sufficient current. To directly control the power in the entire system, a power switch is then employed. The power supply then converts the 220 AC TO DC current. Both DC and AC current are controlled from this switch. The temperature is controlled through feedback of the thermistors employed in each press plate. This turns each individual cartridge to heat up and cool as needed using a PID controller saved on the Arduino. The temperature readings and process status can all be viewed on the LCD display.

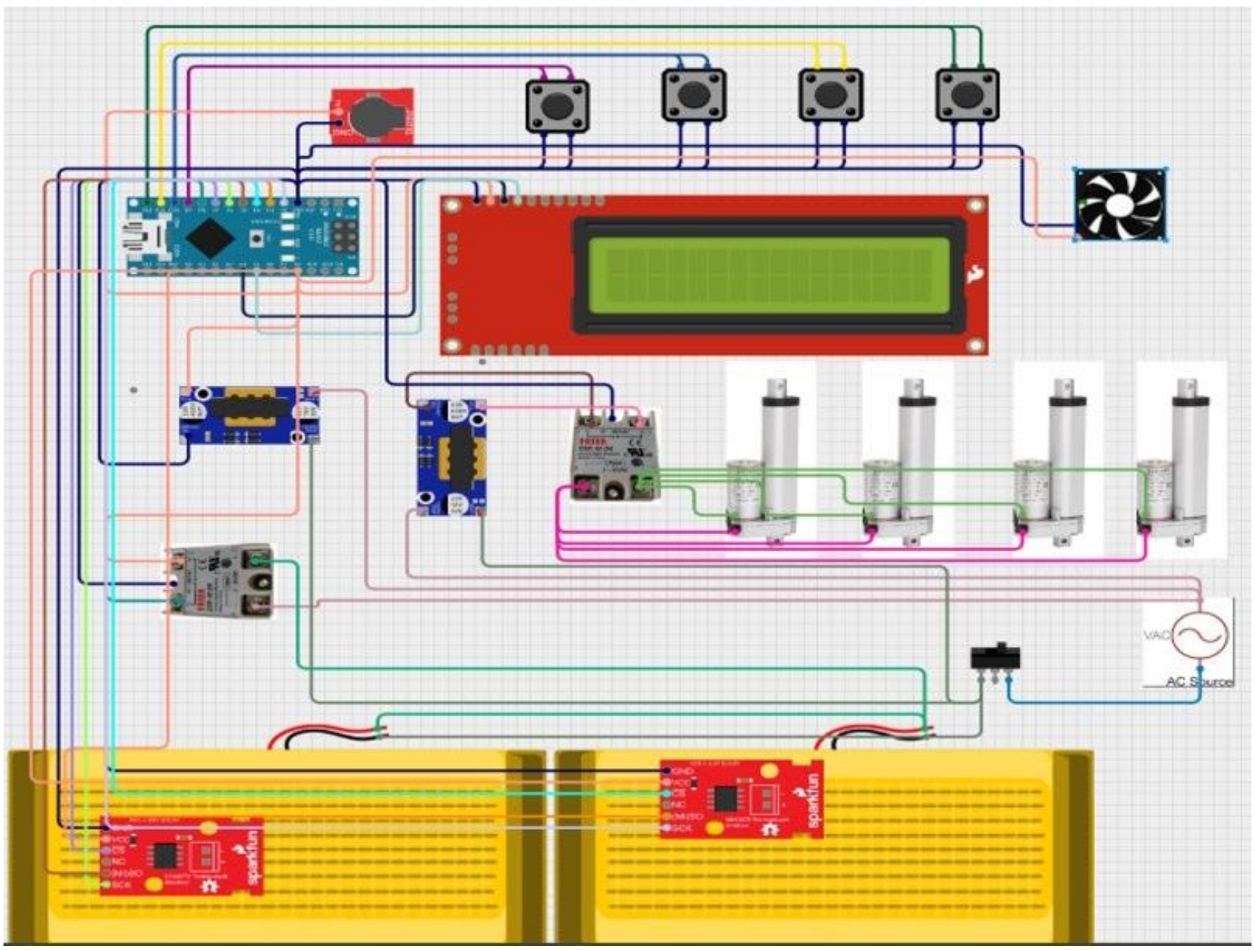

Figure #8: Projected Schematic of the Electrical Circuit

The current wiring for the schematic is intentionally left out as the final wiring and integration takes place. The team prioritizes labelling and connecting the electronic devices as the final integration brings all the hardware pieces together. All electronic devices are, however, included in the current diagram.

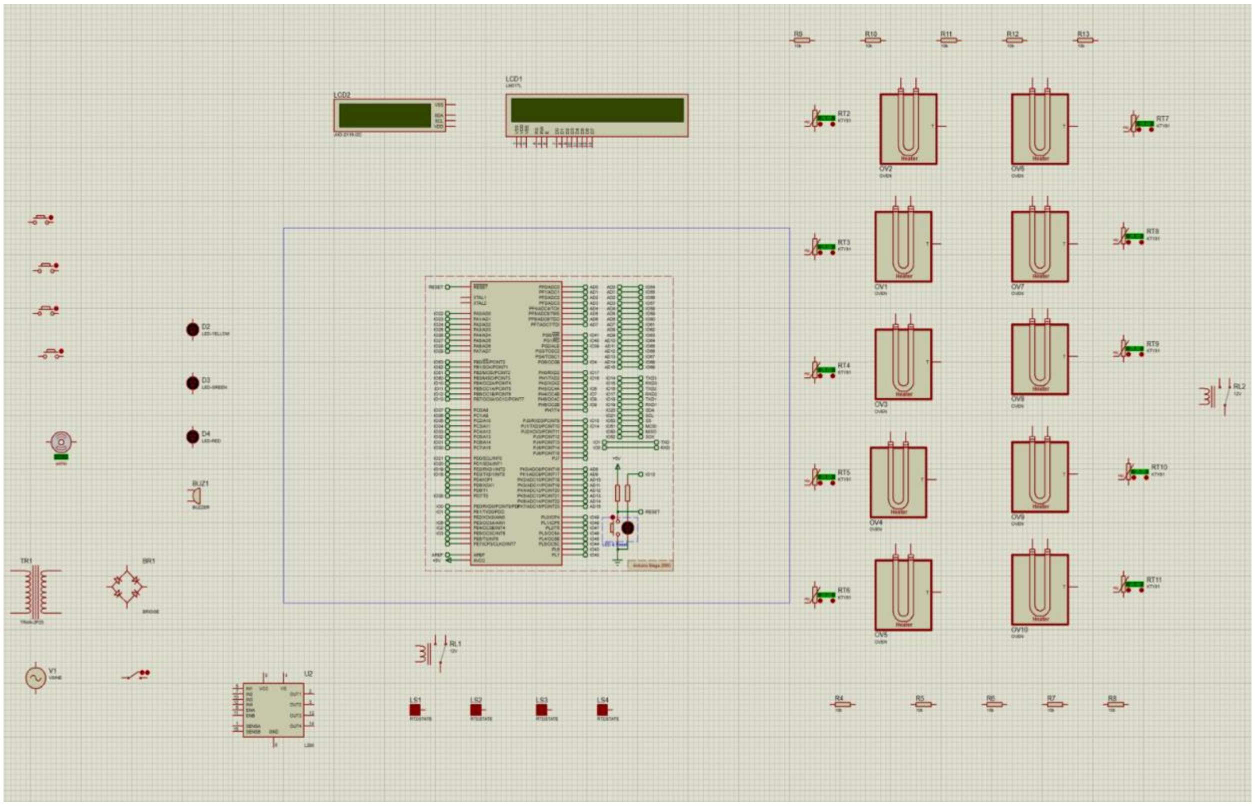

Figure #9: Updated Electrical Circuit Schematic

The electronic design for this project requires both AC and DC at multiple instances to control various components in sequence within the controlled process. At the heart of this machine sits a 5Vdc Arduino ATmega microcontroller. All inputs from the user will be entered through four push buttons connected directly to an analog pin along the analog side of the microcontroller and all selections will be viewed on the serial LCD display. All four Linear actuators are 12 Vdc and will be powered using a power supply module. This power supply steps down and regulates the input from 220 VAC to 12 Vdc output. As such, this power supply module energizes the 12-volt Linear Actuators. However, a motor driver is first added to the actuators connection to extend and retract the actuators length. To control these actuators a 12 volt relay is added between the lead (live) wire of the linear actuators and the Arduino signal port. This is due to the current difference of the Atmega board of 5 Vdc and the actuators of 12 Vdc.

Two 5Vdc fans will cool the electronics from the lower storage bay of the sheet press; by doing this, a constant supply of air is supplied throughout the operational process. Both 5Vdc fans will be connected directly to the Arduino power output and thus will not need to be wired to a signal port. The warning lights and buzzer module will be connected to the 12 Vdc power supply and grounded in that manner to the power supply. To control or trigger this device, four leads from

the Arduino's signal ports will interface a dc-to-dc relay module. These wires are then connected to the lead (live wires) of the warning lights/buzzer module.
To finally heat the PLA, heating cartridges are employed (10 to be exact) and connected to the 220 Vac. To control the heating cartridges the live wire is connected to a dc to ac relay and triggered through a specified pin from the signal port from the Arduino Atmega. To successfully control the desired temperature for melting the PLA material, thermistors are added to enable a reading from the heating cartridges all while creating a feedback loop.

Software Development

Software development started with the creation of an excel sheet of the variables needed and a flow chart to organize and plan out the desired goal and the most effective path to achieve it. An example of what is recorded in the variable tracker is shown in Table #4, whilst the logic flow chart denoting how the system will handle the actual logic is shown in Figure #10.

Table #4: Software Variable Tracker Sample

Name	Function	Pin
Button 1	Up Arrow, Toggle up	D3
Button 2	Down Arrow, Toggle down	D2
Button 3	Menu Navigation	D0
Button 4	Select	D1
LCD	Liquid Crystal Display Output	Several wires: 20, 21
RED_LED	Red Light	D22
YLW_LED	Yellow Light	D24
GRN_LED	Green Light	D26
BUZZER	Buzzer Alarm	D28
Thrmstr_1	Thermistor Readings	A5
Thrmstr_2	Thermistor Readings	A4

This logic dictates both the core loop of the mostly autonomous system with a focus on convenience and safety. The left portion dictates the desired loop for a plate and the component states during that stage. On the right side of the flow chart is the modification of settings for future iterations to include different thermoplastic types beyond PLA. With the values hard coded and only requiring the user to select it and begin the core loop.

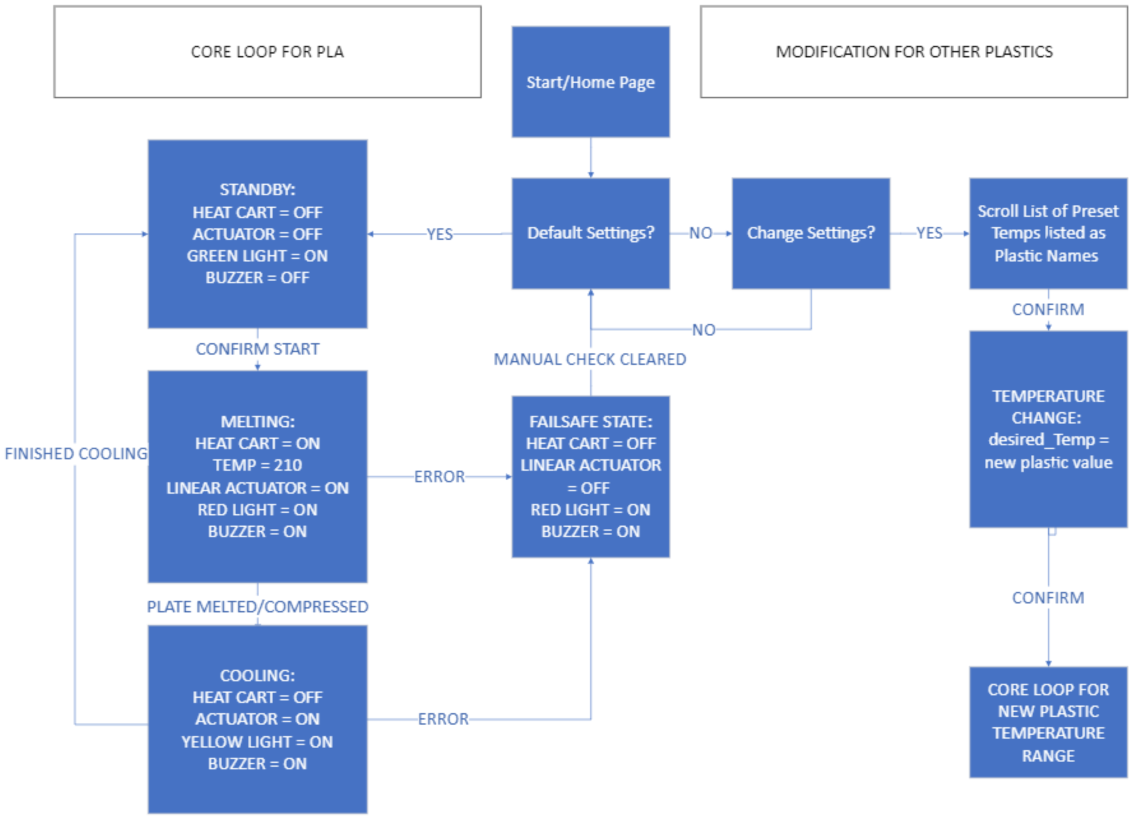

Figure #10: Software Logic Flow Chart

The micro controller for the project is an ELEGOO MEGA R3 Board ATmega 2560 with its code written in C++ with custom libraries for certain components (LCD I2C display). Initial software development began with proto code to test the components the team received. Isolated systems for each component were created to test them in which once initial testing was completed and labeled, and the code was used as a reference to integrate various sub-systems.

System testing started with seven tested and labeled thermistors, an example of which can be seen in Figure #11. To test the heat range of the thermistor and the code for accuracy the team utilized a heat gun set at 100 degree Celsius. The written code was screenshot and placed in the appendix refer to Figure #16. Within the code there are several lines that have been commented out and were utilized to check values and corrected as needed. This holds true for many of the test code shown in the appendix.

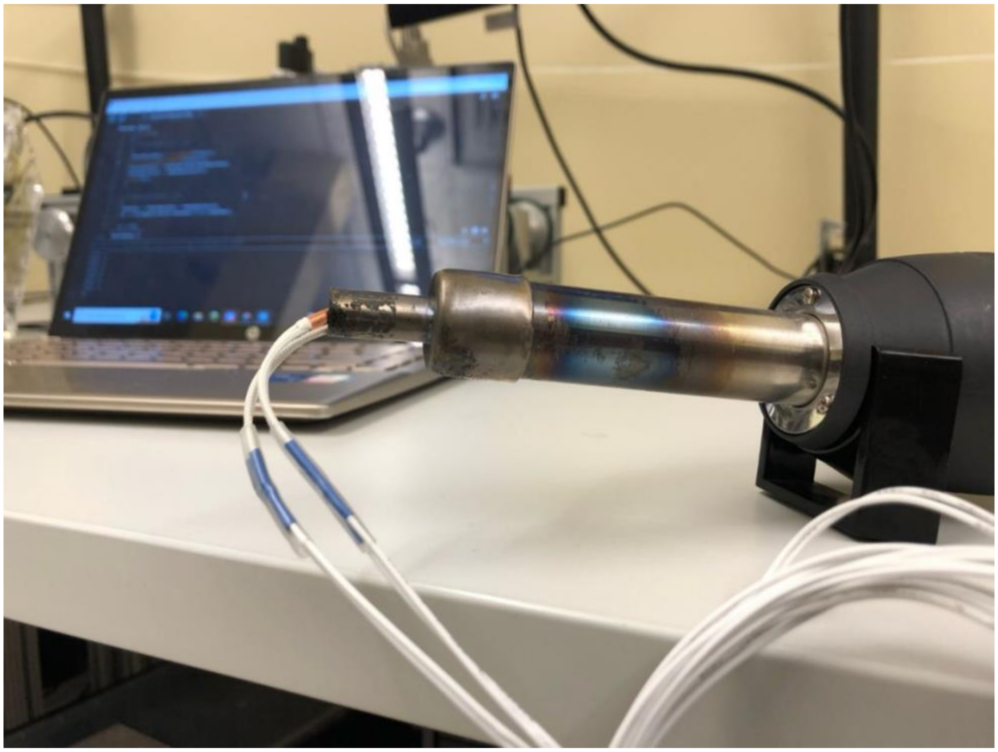

Figure #1: Thermistor Test

LCD with I2C integration of a test phrase written on the display in Figure #12. The code was simplified to the I2C library add on for Arduino. This code can be seen in the appendix Figure #18.

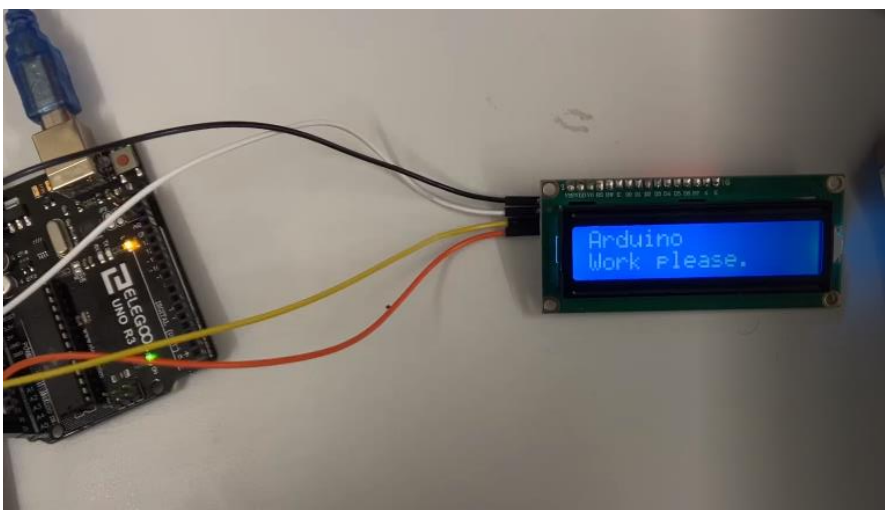

Figure #12 LCD I2C Display Test

Then linear actuators and motor relay in which we determined an integrated circuit could reduce the analog pins required by half. Starting with a single linear actuator, confirming its movement in both directions, we moved onto two linear actuators connected to one motor relay.
An example of the test with dual linear actuators is shown in Figure #13. The code can be found in appendix Figures #22 through #24.

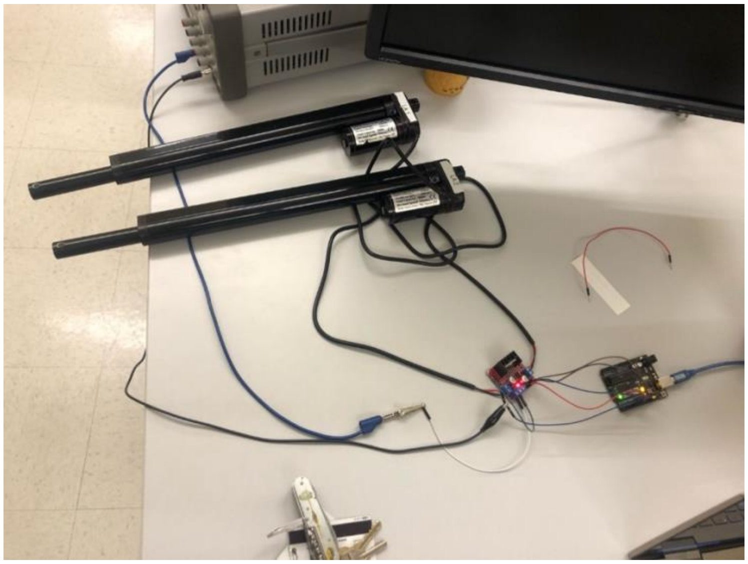

Figure #13: Linear Actuator Testing

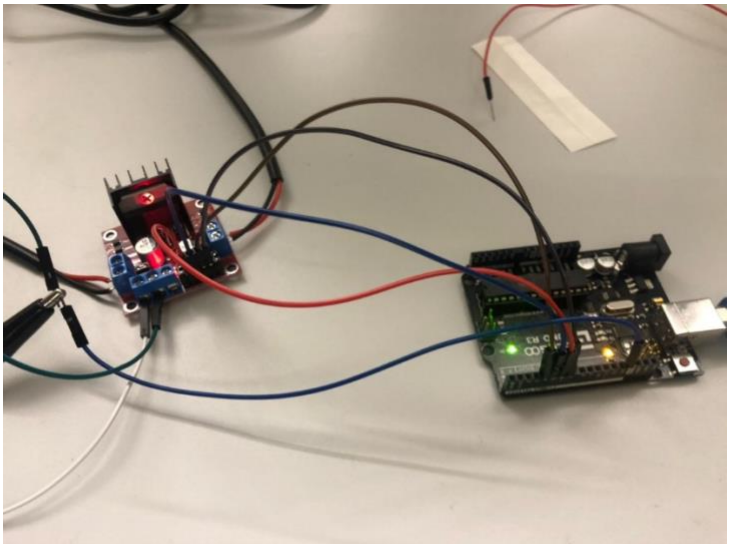

Figure #2: Linear Actuator Relay Wiring

The next test was the LED buzzer as heating cartridges could not be tested safely without a proper casing. This made use of a 12V relay utilizing four digital pins to correspond to each light and buzzer. An image of the test is shown in Figure #15 with the code found in appendix Figures #19 through 21.

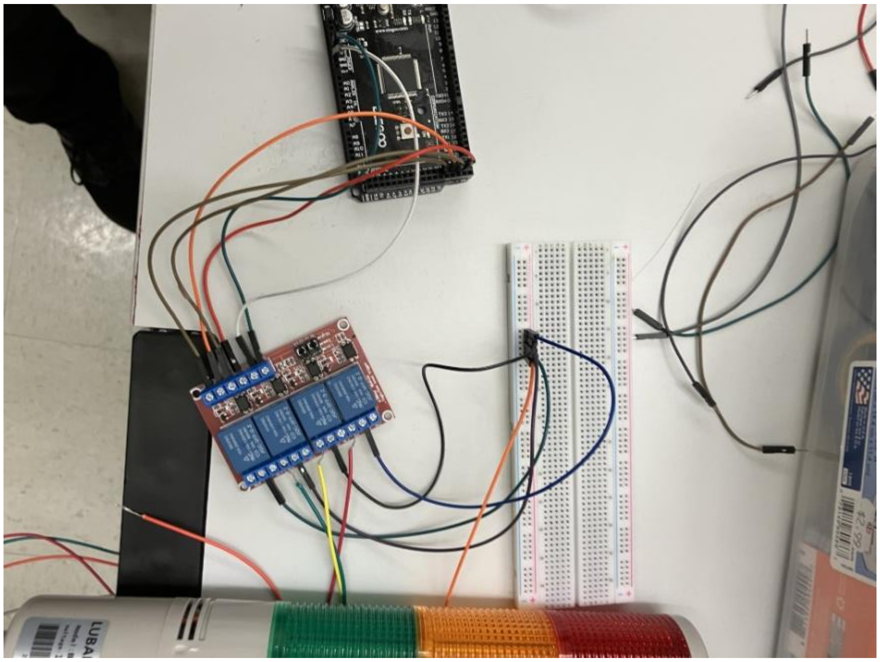

Figure #3: Safety LED Testing

The final isolated test was the heating cartridge [7], in which it utilized a casing designed by the mechanical lead. This test was conducted to test not just the heating cartridge and casing but the thermistor and built in safety of the code. An example of the test can be seen in Figure #16. With the code found in the appendix Figures #27 through 30.

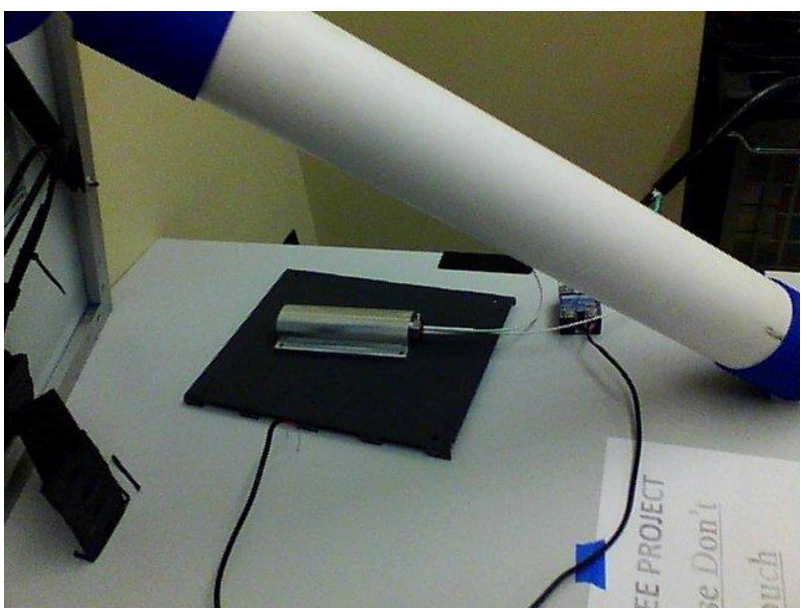

Figure #16: Heating Cartridge/Casing Test

Finally bringing these all together into a single network through iterations and incorporating a simple UI for navigation led to the completed prototype of the project. With the wiring and software demonstrated in several tests. An example of such test is seen in Figure 17 below and the code is found in appendix Figures #31 through 39.

Figure #17: UI Iteration 7 Test

Conclusion

This project is to develop and implement an affordable PLA sheet press for sustainable manufacturing offer various environmental, economic, and social benefits. Thus, by effectively implementing technologies such as this PLA machine, we can mitigate the adverse impacts of plastic pollution on ecosystems and human health. By transforming the waste plastics at the college and many other areas of society into PLA sheets, this technology holds numerous promising benefits for transformative change. Particularly, this innovative technology significantly impacts the environment by reducing plastic pollution and significantly reduces the dependency and production of virgin plastic production. On an economic scale, plastic recycling from a PLA press creates new opportunities for stimulating innovation and reducing production costs. Furthermore, this technology's continuous adoption promotes opportunities for small-scale manufacturers and entrepreneurs to engage in sustainable practices. The adoption of this PLA technology thus raises awareness about the importance of waste management and sustainable manufacturing practices, paving the way towards a greener and more equitable future.

References

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[6] Amazon. (n.d.). MAOPINER Linear Actuator 900N 300mm Stroke Electric DC Motor for Recliner TV Table Lift Massage Bed Electric Sofa Linear Actuator Mounting Brackets Included [Linear actuator]. Retrieved from https://www.amazon.com/MAOPINER-Actuator-Mounting-Recliner-Automation/dp/B0BZHLZPP8 Accessed February 2024 https://www.amazon.com/MAOPINER-Actuator-Mounting-Recliner-Automation/dp/B0BZHLZPP8 Accessed February 2024

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Appendix

```
int Thrmstr1 = A5;
int Thrmstr2 = A4;
//int Thmrstr[10] = [A5,A4,];
float Temp = 0; //Current temp derived from Thermistor readings
float desired_Temp = 210; //Temperature desired set by user, Default to 210 (PLA Value)
float True_Max = 250; //Absolute max temperature before fail safe to ensure no risk of harm
long Heat_Cart = 0; //Heating Catridge control

long R1 = 100000;
long VoltageDividerR1 = 10000;
float a, b, c, d;
float e = 2.718281828;
float tempSampleRead = 0;
//float tempLastSample = 0;
float tempSampleSum = 0;
float tempSampleCount = 0;
float tempMean;

float BValue = 3950;
float T1 = 298.15;
float T2; //Temperature reading
float R2; //current resistance (Thermistor value)
```

Figure #4: Thermistor Test Code (part 1)

```
void loop()
{
 if(tempSampleCount < 10)
 {
 tempSampleRead = analogRead(Thrmstr1);
 tempSampleSum = tempSampleSum+tempSampleRead;
 tempSampleCount = tempSampleCount+1;
 delay(100);
 }

if(tempSampleCount == 10)
 {
  tempMean = tempSampleSum / tempSampleCount;
  //Serial.print(tempMean);
  R2 = (VoltageDividerR1*tempMean)/(1023-tempMean);
  //Serial.print(R2);

  a = (1/T1);
  //Serial.print(a, 5);
  b = log10(R1/R2);
  //Serial.println(b, 5);
  c = b/log10(e);
  //Serial.println(c);
  d = c/BValue;
  T2 = (1/(a-d))-273.15;
  Serial.print(T2);
  Serial.println(" °C");

  tempSampleSum = 0;
  tempSampleCount = 0;
 }
```

Figure #19:5 Thermistor Test Code (part 2)

```
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);

void setup()
{
 lcd.init();
 lcd.backlight();
}

void loop()
{
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.print("Arduino");
 lcd.setCursor(0, 1);
 lcd.print("Work please.");
 delay(2000);

 lcd.clear();
 lcd.setCursor(0,0);
 lcd.print("Is it working?");
 lcd.setCursor(0,1);
 lcd.print("Holy shit!");
 delay(2000);
}
```

Figure #620: LCD Test Code

```
/*#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);*/

int RED_LED = 22; //red wire
int YLW_LED = 24; //yellow wire
int GRN_LED = 26; //green wire
int BUZZER = 28; //orange wire

void setup()
{
 pinMode(RED_LED, OUTPUT);
 pinMode(YLW_LED, OUTPUT);
 pinMode(GRN_LED, OUTPUT);
 pinMode(BUZZER, OUTPUT);
 Serial.begin(9600);
 /*lcd.init();
 lcd.backlight();*/
}

void loop()
{
 Serial.println("Select Case for Red, Yellow, or Green Light");
 //lcd.print("Select color case:");

```

Figure #21: 7 LED Code (part 1)

```
digitalWrite(RED_LED, LOW); //default
digitalWrite(YLW_LED, LOW);
digitalWrite(GRN_LED, HIGH);
digitalWrite(BUZZER, LOW);

while (Serial.available() == 0 ) {}
int menuChoice = Serial.parseInt();

switch(menuChoice)
{
 case 1:
 digitalWrite(RED_LED, HIGH);
 digitalWrite(YLW_LED, LOW);
 digitalWrite(GRN_LED, LOW);
 digitalWrite(BUZZER, LOW);
 //lcd.print("CAUTION! HOT!");
 Serial.println("RED");
 delay(5000);
 break;
 case 2:
 digitalWrite(RED_LED, LOW); //default
 digitalWrite(YLW_LED, HIGH);
 digitalWrite(GRN_LED, LOW);
 digitalWrite(BUZZER, LOW);
 //lcd.print("CAUTION! COOLING!");
```

Figure #22:8 LED Code (part 2)

```
  //lcd.print("CAUTION! COOLING!");
  Serial.println("YELLOW");
  delay(5000);
  break;
  case 3:
  digitalWrite(RED_LED, LOW);
  digitalWrite(YLW_LED, LOW);
  digitalWrite(GRN_LED, HIGH);
  digitalWrite(BUZZER, LOW);
  //lcd.print("On Standby");
  Serial.println("Green");
  delay(5000);
  break;
  case 4:
  digitalWrite(RED_LED, LOW);
  digitalWrite(YLW_LED, LOW);
  digitalWrite(GRN_LED, LOW);
  digitalWrite(BUZZER, HIGH);
  //lcd.print("BUZZ TEST");
  Serial.println("Buzzer");
  delay(1000);
  break;
 }
 delay(100);
}
```

Figure #923: LED Code (part 3)

```
//const int ENA_PIN = 9; //endabler pin (Supposed to be unnecsary)
const int IN1_PIN = 6; //OUT1 Parallel
const int IN2_PIN = 5; //OUT2 Parallel
const int IN3_PIN = 7; //OUT3 Parallel
const int IN4_PIN = 4; //OUT4 Parallel
int t = 0; //time constant variable

void setup()
{
 //pinMode(ENA_PIN, OUTPUT);
 pinMode(IN1_PIN, OUTPUT);
 pinMode(IN2_PIN, OUTPUT); //*/
 pinMode(IN3_PIN, OUTPUT);
 pinMode(IN4_PIN, OUTPUT); //*/
 Serial.begin(9600);
}

void loop()
{
 digitalWrite(IN1_PIN, LOW);
 digitalWrite(IN2_PIN, LOW); //*/
 digitalWrite(IN3_PIN, LOW);
 digitalWrite(IN4_PIN, LOW); //*/
 delay(5000);

```

Figure #24:10 Motor Code (part 1)

```
digitalWrite(IN1_PIN, LOW); //counter-clockwise = outward for OUT1/OUT2
digitalWrite(IN2_PIN, HIGH); //counter-clockwise */
digitalWrite(IN3_PIN, HIGH); //clockwise = outward for OUT3/OUT4
digitalWrite(IN4_PIN, LOW); //clockwise

for(t=0; t<=3500; t++) //timer: Full draw time at 255 speed is in 3300 ~ 3500 ms range
{
 //digitalWrite(ENA_PIN, 255);
 delay(10);
 Serial.println(t);
}
//delay(1000); //*/

digitalWrite(IN1_PIN, HIGH); //clockwise = inward for OUT1/OUT2
digitalWrite(IN2_PIN, LOW); //clockwise */
digitalWrite(IN3_PIN, LOW); //counter-clockwise = inward for OUT3/4
digitalWrite(IN4_PIN, HIGH); //counter-clockwise
for(t=0; t<=3500; t++)
{
 //digitalWrite(ENA_PIN, 255);
 delay(10);
 Serial.println(t);
}
delay(1000); //*/
```

Figure #1125: Motor Code (part 2)

```

digitalWrite(IN1_PIN, HIGH); //clockwise = inward for OUT1/OUT2
digitalWrite(IN2_PIN, LOW); //clockwise */
digitalWrite(IN3_PIN, LOW); //counter-clockwise = inward for OUT3/4
digitalWrite(IN4_PIN, HIGH); //counter-clockwise
for(t=0; t<=3500; t++)
{
 //digitalWrite(ENA_PIN, 255);
 delay(10);
 Serial.println(t);
}
delay(1000); //*/

digitalWrite(IN1_PIN, LOW);
digitalWrite(IN2_PIN, LOW); //*/
digitalWrite(IN3_PIN, LOW);
digitalWrite(IN4_PIN, LOW); //*/
delay(2500); //*/
}

```

Figure #1226: Motor Code (part 3)

```
#include <Wire.h>
#include <math.h>

int Thrmstr1 = A5; //Current Read value
//int Thrmstr2 = A4;
int HEAT_C1 = A4;
float Temp = 0; //Current temp derived from Thermistor readings
float desired_Temp = 210; //Temperature desired set by user, Default to 210 (PLA Value)
float True_Max = 250; //Absolute max temperature before fail safe to ensure no risk of harm

long R1 = 100000; //Thermistor base resistance
long VoltageDividerR1 = 10000; //10k Resistor
float a, b, c, d;
float e = 2.718281828;
float tempSampleRead = 0;
float tempSampleSum = 0;
float tempSampleCount = 0;
float tempMean;

float BValue = 3950; //From thermistor specs paper
float T1 = 298.15;
float T2; //Temperature reading
float R2; //current resistance (Thermistor value)
```

Figure #1327: Heat Cartridge Code (part 1)

```
void setup()
{
 pinMode(HEAT_C1, OUTPUT);
 Serial.begin(9600);
}

void loop()
{
 if(tempSampleCount < 10)
 {
 tempSampleRead = analogRead(Thrmstr1);
 tempSampleSum = tempSampleSum+tempSampleRead;
 tempSampleCount = tempSampleCount+1;
 delay(100);
 }

 if(tempSampleCount == 10)
 {
  tempMean = tempSampleSum / tempSampleCount;
  //Serial.print(tempMean);
  R2 = (VoltageDividerR1*tempMean)/(1023-tempMean);
  //Serial.print(R2);
```

Figure #1428: Heat Cartridge (part 2)

```
  a = (1/T1);
  //Serial.print(a, 5);
  b = log10(R1/R2);
  //Serial.println(b, 5);
  c = b/log10(e);
  //Serial.println(c);
  d = c/BValue;
  T2 = (1/(a-d))-273.15;
  Serial.print(T2);
  Serial.println(" °C");

  tempSampleSum = 0;
  tempSampleCount = 0;
 }

 if(T2 >= 250)
 {
  digitalWrite(HEAT_C1,LOW);
  delay(5000);
 }

 if(T2 <= (desired_Temp-15) && T2 >= (desired_Temp+15))
 {
  digitalWrite(HEAT_C1,LOW);
  delay(1000);
 }
```

Figure #1529: Heat Cartridge (part 3)

```
if(T2 >= 250)
{
 digitalWrite(HEAT_C1,LOW);
 delay(5000);
}

if(T2 <= (desired_Temp-15) && T2 >= (desired_Temp+15))
{
 digitalWrite(HEAT_C1,LOW);
 delay(1000);
}
if else(T2 <= (desired_Temp-15) )
{
 digitalWrite(HEAT_C1,High);
 delay(1000);
}
delay(1000);
}
```

Figure #30: 16 Heat Cartridge Test Code (part 4)

UI_Iteration_7.ino

```
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);

//Tactile buttons
int Button1 = 23; //buttons
int Button2 = 25;
int Button3 = 27;
int Button4 = 29;
int Button5 = 2;
int buttonTemp1, buttonTemp2, buttonTemp3, buttonTemp4;
int menuChoice = 0;
int Temp = 210;
int t = 0;

//LED & Buzzer
int RED_LED = 22; //red led wire
int YLW_LED = 24; //yellow led wire
int GRN_LED = 26; //green led wire
int BUZZER = 28; //orange led wire

//Linear Actuators
const int IN1_PIN = 8; //OUT1 Parallel
const int IN2_PIN = 9; //OUT2 Parallel
const int IN3_PIN = 10; //OUT3 Parallel
const int IN4_PIN = 11; //OUT4 Parallel
```

Figure 17#31: UI Iteration 7 (part 1)

```
void setup()
{
 pinMode(Button1, INPUT);
 digitalWrite(Button1, HIGH);
 pinMode(Button2, INPUT);
 digitalWrite(Button2, HIGH);
 pinMode(Button3, INPUT);
 digitalWrite(Button3, HIGH);
 pinMode(Button4, INPUT);
 digitalWrite(Button4, HIGH);
 pinMode(Button5, INPUT);
 digitalWrite(Button5, HIGH);
 pinMode(RED_LED, OUTPUT);
 pinMode(YLW_LED, OUTPUT);
 pinMode(GRN_LED, OUTPUT);
 pinMode(BUZZER, OUTPUT);
 pinMode(IN1_PIN, OUTPUT);
 pinMode(IN2_PIN, OUTPUT); //*/
 pinMode(IN3_PIN, OUTPUT);
 pinMode(IN4_PIN, OUTPUT);
 pinMode(heatRelay_1, OUTPUT);
 attachInterrupt(digitalPinToInterrupt(Button5), cease, LOW);
 Serial.begin(9600);
 lcd.init();
 lcd.backlight();
}
```

Figure #32: 18 UI Iteration 7 (part 2)

UI_Iteration_7.ino

```
void loop()
{
 lcd.setCursor(0, 0);
 lcd.print("Start");
 lcd.setCursor(0, 1);
 lcd.print("Current Temp:");
 lcd.setCursor(13, 1);
 lcd.print(Temp);

 buttonTemp1 = digitalRead(Button1);
 buttonTemp2 = digitalRead(Button2);
 buttonTemp3 = digitalRead(Button3);
 buttonTemp4 = digitalRead(Button4);

 standbyState();
 menuChoice = 0;

 if(buttonTemp1 == LOW)
 {
  menuChoice = 1;
  Serial.println(menuChoice);
 }
 if(buttonTemp2 == LOW)
 {
  menuChoice = 2;
  Serial.println(menuChoice);
```

Figure #33:19 UI Iteration 7 (part 3)

UI_Iteration_7.ino

```
switch(menuChoice)
{
 case 1:  //Start
 lcd.clear();
 lcd.print("Begun");
 meltingState();
 delay(5000);
 if (buttonTemp1 == LOW)
 {
  coolingState();
 }
 delay(5000);
 break;

 case 2:
 lcd.clear(); //temp up
 Temp = Temp + 10;
 lcd.print("Current Temp:");
 lcd.setCursor(13, 0);
 lcd.print(Temp);
 delay(1000);
 lcd.clear();
 break;
```

Figure #34: 20UI Iteration 7 (part 4)

UI_Iteration_7.ino

```
  case 3:
  lcd.clear(); //temp down
  Temp = Temp - 10;
  lcd.print("Current Temp:");
  lcd.setCursor(13, 0);
  lcd.print(Temp);
  delay(1000);
  lcd.clear();
  break;

  case 4: //emergency stop
  lcd.clear();
  lcd.print("CEASE");
  delay(1000);
  failsafeState();
  break;
 }
}

void meltingState()
{
 lcd.clear();
 lcd.setCursor(0,0);
 lcd.print("Heating");
```

Figure #35: 21UI Iteration 7 (part 5)

UI_Iteration_7.ino

```
lcd.print("Heating");

//RED ON, Buzzer ON
digitalWrite(RED_LED, HIGH);
digitalWrite(YLW_LED, LOW);
digitalWrite(GRN_LED, LOW);
digitalWrite(BUZZER, HIGH);
delay(1500);
digitalWrite(BUZZER, LOW);
delay(1500);

//LA Extension
digitalWrite(IN1_PIN, LOW);
digitalWrite(IN2_PIN, HIGH);
digitalWrite(IN3_PIN, HIGH);
digitalWrite(IN4_PIN, LOW);
for(t=0; t<=3500; t++) //timer: Full draw time at 255 speed is in 3300 ~ 3500 ms range
{
 delay(10);
 Serial.println(t);
}

//Heating ON
digitalWrite(heatRelay_1, HIGH);
}
```

Figure #36:22 UI Iteration 7 part 6

UI_Iteration_7.ino

```
void coolingState()
{
 digitalWrite(RED_LED, LOW);
 digitalWrite(YLW_LED, HIGH);
 digitalWrite(GRN_LED, LOW);
 digitalWrite(BUZZER, HIGH);
 delay(2000);
 digitalWrite(BUZZER, LOW);
 delay(1000);

 //LA Extended
 digitalWrite(IN1_PIN, LOW);
 digitalWrite(IN2_PIN, HIGH);
 digitalWrite(IN3_PIN, HIGH);
 digitalWrite(IN4_PIN, LOW);
 for(t=0; t<=3500; t++) //timer: Full draw time at 255 speed is in 3300 ~ 3500 ms range
 {
  delay(10);
  Serial.println(t);
 }

 //Heating OFF
 digitalWrite(heatRelay_1, LOW);

```

Figure #2337: UI Iteration 7 (part 7)

UI_Iteration_7.ino

```
void standbyState()
{
 digitalWrite(RED_LED, LOW); //default led
 digitalWrite(YLW_LED, LOW);
 digitalWrite(GRN_LED, HIGH);
 digitalWrite(BUZZER, LOW);

 //LA Recline
 digitalWrite(IN1_PIN, HIGH);
 digitalWrite(IN2_PIN, LOW);
 digitalWrite(IN3_PIN, LOW);
 digitalWrite(IN4_PIN, HIGH);
 /*for(t=0; t<=3500; t++) //timer: Full draw time at 255 speed is in 3300 ~ 3500 ms range
 {
  delay(10);
  Serial.println(t);
 }*/

 //LA Standby
 digitalWrite(IN1_PIN, LOW);
 digitalWrite(IN2_PIN, LOW);
 digitalWrite(IN3_PIN, LOW);
 digitalWrite(IN4_PIN, LOW);

 //Heating OFF
 digitalWrite(heatRelay_1, LOW);
```

Figure #38: 24UI Iteration 7 (part 8)

UI_Iteration_7.ino

```
void failsafeState()
{
 digitalWrite(RED_LED, HIGH);
 digitalWrite(YLW_LED, LOW);
 digitalWrite(GRN_LED, LOW);
 /*digitalWrite(BUZZER, HIGH);
 delay(2500);
 digitalWrite(BUZZER, LOW);
 delay(500);*/

 //Heating OFF
 digitalWrite(heatRelay_1, LOW);

 //LA Recline
 digitalWrite(IN1_PIN, HIGH);
 digitalWrite(IN2_PIN, LOW);
 digitalWrite(IN3_PIN, LOW);
 digitalWrite(IN4_PIN, HIGH);
 for(t=0; t<=4000; t++) //timer: Full draw time at 255 speed is in 3300 ~ 3500 ms range
 {
  delay(10);
  Serial.println(t);
 }
}
```

Figure #25: UI Iteration 7 (part 9)