Introduction to Engineering Design with Professional Development 1

Final Report for
SmartCast

Team: Charlie's Angels
Section 1
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Executive Summary

Within a ten week period, team Charlie's Angels has successfully designed, tested, and constructed the SmartCast, an arm cast which creates a controlled healing environment. SmartCast is an innovative and new cast concept which creates a controlled healing environment by using variable pressure and heating elements to speed up the bone regeneration process after a bone fracture. By controlling the pressure and temperature at the sight of injury, blood flow can be varied at the sight of injury and speed up the rate at which the bone heals. The design of the cast is broken down into seven subsystems: exoskeleton, pressure system, heating system, electric hardware, safety shutoff, user interface, and software/embedded control.

The report below contains detailed information about the design process and how the final project was constructed based off a variety of design considerations and unexpected challenges. Design selections were made by analyzing various models and test results, as well as by trial and error. The use of selection matrices weighed into the final decision choices, as well as the use of graphing of test data to model data reports. The exoskeleton was modeled using NX and 3D printed out of PLA. Electrical systems were modeled and simulated using Upverter and Lucidchart. Lastly, the software was written in arduino, a variant of C++, and was uploaded onto an arduino nano. A HC-05 bluetooth module was used to send data from the arduino nano to the user interface phone app.

The final project met all design requirements and customer needs. The cast had both variable pressure and heating systems within 5% accuracy of calibrated set points. The entire system successfully turns off when peltier plate temperature reaches 40 °C, and when pressure exceeds 1.5 psi, ensuring that this product is safe for all users. The bluetooth module and user interface worked in sync, where the user interface would display immediate pressure and temperature outputs within microseconds of a pressure or temperature change in the cast. The product cost was less than the estimated cost of $250 per unit. With a final prototype production cost of $230 per unit, the SmartCast provides an affordable alternative solution to modern casting methods currently used by orthopedic doctors and surgeons.

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1 Introduction

By: Sierra

Treating broken bones dates all the way back to the dawn of medical practices. With time estimates of 4,500 to 5,000 years ago, historians have found evidence of the use of splints as a method to treat bone fractures on the bodies of ancient Egyptians. The body of a fourteen year old Egyptian girl was found to have had a compound fracture in her right femur, with what appeared to be four splints over the break. The splint was made out of what was believed to be wood wrapped with linen bandages. The first improvement to the ancient method for bone healing was the addition of physical therapy to prevent muscle damage and loss of blood flow while the broken bone was immobilized with stiffened linens. The first stiff/hard casts were made using waxes, starches, eggs, and resins which took hours to dry. The use of plaster casts began in triage units during the wars in the early 1800's. Plaster casts are still used in modern medical practices. The most common type of modern cast is the fiberglass cast. This method of bone immobilization has been used over the past thirty to forty years since fiberglass is the cheapest and sturdiest option. Issues with the fiberglass cast include the weight of the cast and patient discomfort caused by itching or sweating.

The current method of treating broken bones works efficiently, so why change something which has already been proven to be effective for broken bone repair? There is little change in the method in which broken bones have been treated from the Egyptian era to modern day, it is time for change. The answer to this question is that the current method of bone repair is generic and outdated, as well as uncomfortable for those suffering a broken bone. Broken bones require anywhere from one month to six months of limb stabilization, and it is time to shorten this lengthy period of time by customizing the bone repair method. Currently, a doctor will reset the bone into the position it needs to be in, then form a hard cast onto the limb for anywhere upwards of six months. There is no customization to the process other than what color you chose the fiberglass cast to be.

Annually, in the United States alone there are over 7.9 million broken bones. In recent years, a few new types of casts have been attempted, such as a 3D printed spider web-like cast. This cast integrates the use of ultrasound technology to make the bone heal faster, however the use of ultrasound has not been proven to speed up the bone healing process. However, doctors have verified that blood flow is vital to the bone healing process, and applying pressure and heat to a sight of a broken bone are suggested to be efficient in speeding up the process of bone regeneration. Heat and pressure are what need to be integrated into modern broken bone treatment, as well as the discomfort of wearing a cast needs to be eliminated. Creating a cast which will speed up bone regeneration as well as eliminate any discomfort experienced due to wearing a cast is what millions of people will benefit from. The SmartCast is the change which the orthopedic industry needs to see. SmartCast is the future of bone repair and patient satisfaction, as this cast integrates user customization for maximum comfort.

2 Project Objectives & Scope

Project Scope

By: Sierra Carr

In the 10-week allotted time, Team Charlie's Angels has worked to design, build, and test a prototype for SmartCast, an orthopedic cast which creates a controlled healing environment by applying heat and pressure at the sight of a broken bone. In this case, the prototype was built to be an arm cast. To generate a safe pressure, a motor air pump and a pressure sensor are connected to blood pressure cuffs which can inflate or deflate upon command. The heating system integrates peltier plates and temperature sensors to create a safe and comfortable temperature for patients. A 3D printed exoskeleton with removable stability plates forms the mechanical structure of the cast, which is vital for fracture stabilization post injury. The prototype can be controlled using an android phone app user interface and a bluetooth module. The user interface allows for the cast wearer to set a comfortable pressure and temperature of their choosing. The method used to control the pressure and temperature of the cast through the phone user interface is significant for the prototype because this part of the prototype design would be integrated in the final product even if other parts of the prototype fail.

Since this product is a prototype, the dimensions are not completely fit for that of a real human arm. The prototype will also be powered by a series of 9 V batteries, where if the project went to market the use of a rechargeable lithium-ion battery would be more practical. Also the marketed cast would not have breadboards, and would instead have light-weight and smaller customized PCB boards. The cast exoskeleton was 3D printed, with the finalized design a better 3D printer would be used, with a higher percentage infill for quality purposes. The 3D printed cuffs could also be injection molded instead of 3D printed to decrease time and cost of production. The exoskeleton would also have a slight adjustment, in which the cuffs which form the exoskeleton would have clamps allowing for convenient opening and closing of the cast. The prototype was also not tested on humans. In order to go to market, the product would need to be tested on multiple patients, ranging from children to fully developed adults of all ages. However, before human testing, the cast would be tested on dogs to see if the results match the results which are expected with the SmartCast. Expected results are to see a broken bone regenerate quicker using SmartCast compared to using a fiberglass cast.

2.1 Mission Statement

By: Sierra Carr

Objective: To create a bone cast which will speed up the bone regeneration process by creating a controlled healing environment, and to create near optimal patient comfort.

Table 2.1- Mission Statement:

Product Description	An arm cast with controllable heating and pressure systems which will speed up the bone healing process while increasing patient comfort.
Benefits	Shorten the amount of time which a patient needs to wear a cast after breaking a bone, as well as eliminating the discomforts associated with using classic casting methods such as plaster or fiberglass. Patient experiences more breathability, cleanliness, and reduced pain.
Goals	● Present a successful prototype by 12/1/2019 ● Verify that pressure and heat are beneficial for the process of bone regeneration by researching the bone regeneration process ● Make product customizable to each patient's preference of pressure and temperature
Primary Market	● Orthopedic Surgeons and Doctors ● Athletic Trainers ● Physical Therapists
Secondary Market	● Professional athletes ● Body builders
Assumptions	● Must be lightweight and durable ● Can be used for broken bones, and for injured tendons or muscles ● Pressure and Temperatures will not exceed values which as considered dangerous conditions for humans ● Cast will be rigid and impede limb motion forthe bone healing purposes
Stakeholders	● IED Group: Charlie's Angels ● RPI School of Engineering ● RPI Department of Biomedical Engineering

2.2 Customer Requirements

By: Thomas Ranney

The primary customers of our product are medical professionals and centers such as athletic trainers, orthopedics, physical therapists, hospitals or pharmacies. They would need this new ground breaking product to give out as treatment to their patients. As this process would speed up the healing process, it would make many of these people's lives easier.

The secondary customers of our product have broken a bone. As this description is very common, our design needs to fit the requirements of many different groups of people. Many of these people need to support their families, and can't afford to miss an extended period of time from work due to an injury. For other groups of people, their body is synonymous with their profession such as athletes, body builders, or professional fighters. The SmartCast can help heal their injuries faster and potentially prevent career-ending injuries.

The following is a table of the customer needs that we determined were the most important, on a scale of 1-5 (1 being the least important and 5 being the most important). A full list of customer requirements along with their technical requirements can be found in section 11B. The customer requirements were gathered from many groups of people in order to simulate all the different users of our product. These included friends,roommates, family, and some of our professors. Furthermore, the team as stakeholders in the project brainstormed a list of their own desired needs, one such being cost as the team wanted the product to be available to everyone. For the most part the customer needs that we determined were the most important were the ones in making the cast more comfortable and user friendly.

Table 2.2: Customer Requirements

Customer Requirement	**Rating**
Lightweight	5
Ability to adjust temperature and pressure	5
Safe	5
Sturdy	5
Won't impede everyday functions	5

2.3 Technical Specifications

By: Charles Pike

It is not enough to state a device's abilities qualitatively. Numbers must be assigned to characterize the capabilities of a product. Whereas the customers dictate a relatively vague notion of what they want, the engineers must assign numbers with units as goals for the capabilities of their system. Factors such as safety and the capabilities of extant hardware were considered in choosing the ranges of these values, and as knowledge has improved, those values have changed.

Table 2.3.1 : Technical Requirements

Customer Requirement	**Specification**	**Milestone 1 Targets**	**Revised Targets**
Lightweight	Weight	< 4lb	< 3lb
Not bulky	Dimensions	24in. x 6in. x 6in.	24in. x 6in. x 6in.
Doesn't smell	Air flow rate	> 0.3 liters/second	> 0.3 liters/second
Can adjust temperature	Temperature	10℃ - 70℃	20℃ - 40℃
Can adjust pressure	Pressure	0.5psi - 3psi	0psi - 1.5psi
Sturdy	Force withstanded	130lb. - 200lb.	20lb.
Is safe to use	Voltage	< 15V	< 9V
	Current	< 10mA	< 2A
	Shutoff temperature	not considered	50^0C
	Shutoff pressure	not considered	2psi
Doesn't impede everyday functions	Number of joints	1 joint	1 joint
Will not make my skin itch	Coefficient of friction of material to skin	< 0.2	< 0.2
Don't have to charge it often	Power	4W	<4W (quiescent) <18W(transient)

Though there were originally high ambitions for a wide range of temperatures, safety concerns cut the maximum down to 40^0C and the challenges in heat dissipation needed for cooling pushed the lower bound to room temperature. This still allows for a wide control of heating within a safe and therapeutic range. It was decided that any pressure higher than 1.5PSI might be injurious, while low pressures also turned out to be fairly easy to regulate, the new range providing both safety and adjustability. Values for temperature at which the pressure and temperature systems would shut down were also decided for safety purposes.

It was discovered that many subsystems were significantly more power-intensive than initially thought, especially the temperature subsystem. Though power consumption would be limited when the desired temperature and pressure were achieved, large amounts of current were needed in order to reach set values. For such reasons, specifications limiting power were relaxed to be within more achievable bounds. The value of 10mA was chosen for safety reasons, but with the maximum power supply voltage cut down to 9V, the power was insufficient to raise any concern.

Physical materials were also re-evaluated. For prototyping and 3D printing purposes, PLA is an incredibly useful material, and sufficiently lightweight that the weight specification could be made tighter. However, the original specifications for force were deemed far too ambitious, and reduced to a 20lb goal that adequately elucidates the strength of the design. With more time and access to more advanced materials and fabrication tools, the original values may be attainable.

3 Assessment of Relevant Existing Technologies

By: Michael

The short arm fiberglass cast has a low cost and highly efficient model to keep a broken arm in stasis for a period of 1.5 to 6 months. This does not have any additional features however its proven functionality shows that its robust design is popular with customers. This cast allows greater visibility for doctors on x-ray machines allowing the doctors to more accurately assess injury and healing progress. This specific cast achieves the customer goals of safety with its strong and dynamic shape allowing the arm to be protected from nearly any impact that would normally cause reinjury. Additionally, this cast has provisions for comfort as it can be put in water with relative safety, and does not have much volume beyond the arm itself making the cast feel sleek and slim to the body. This cast also comes in multiple colors and therefore can be marketed towards the children who are more likely to break a bone than adults.

The short arm plaster cast is a similarly proven design that has multiple centuries of use and has been the standard of industry. This cast is much more temperamental than the fiberglass alternative as it is not water safe and has problems with itchiness. Despite having many comfort shortcomings as compared to the fiberglass cast it has better functionality as it allows better control of the healing process during the application of the plaster. Despite this the plaster is harder to see through using x-ray technology and has therefore fallen out of favor. Plaster has the additional comfort fault as it feels much bulkier and can have difficulty with maneuvering in an easy manner.

While not in direct competition with these two styles of cast the Futuro arm sling has an abundance of comfort options that surpass the capabilities of the plaster or fiberglass. This cloth cast allows for the customer to sacrifice structure and rigidity for a much more comfortable experience with open air allowed to touch the lightly wrapped arm. This method does not protect the arm from outside damage, but rather allows for the cast to be donned with relative ease and can be removed during sleep. This cast has no problems with itchiness, however, it should not be allowed to get wet and usually is removed while bathing.

Table 3.1 - Competitive Benchmarking

Competitive Product	Title / Description	Relation to this project
Short Arm Fiberglass Cast	This cast is used for distal forearm fractures and occasionally wrist sprains and carpal injuries. Made sing soft padding surrounded by a harder fiberglass shell. This can be applied at home even though it is not recommended.	Creates a solid structure that is protective of the region of injury however it entirely covers the arm and many past users complained about itchiness in and around the afflicted area.
Long Arm Fiberglass Cast	Offers a larger range of colors than many doctors offices and is marketed towards kids using brighter colors. Made using soft padding surrounded by a harder fiberglass shell. This can be applied at home even though it is not recommended.	This cast covers the exact same area as ours does and offers a large range of customizable colors. This has many of the same issues as the short arm cast as it has the same material and doctor requirements.
Futuro Arm Sling	A soft wrapping for the patient's arm that does little for structural stability but is often used after the need for a hard cast has passed.	This cast covers the second half of care that the team aims to provide in the phase after the rigid plates are removed. The primary ideas that this cast excels at are breathability and comfort.
Short Arm Plaster Cast	This is strips of plaster coated cloth that are wet and then allowed to dry around the arm to create a strong and easily molded cast. This allows doctors to create subtle changes that can more easily heal the arm or fracture.	This cast is hard to see through in x-rays and does not allow for its removal without severe strain. This cast struggles with similar problems to the fibreglass, however it is even more sensitive to water and cannot be allowed to get wet.

The patents that were found that included pressure into casts were most clearly exemplified by the patent US4308862A in which tubing was inserted into a plaster cast to allow for ventilation that could flow air between the layer of the plaster and the bandages that are layered underneath. This air pump was external and attached through a tube that would lead outside of the cast to the pump. This design would help to create the idea to ingrain the pump system along the side of the cast to make the whole model more portable, without sacrificing structural integrity.

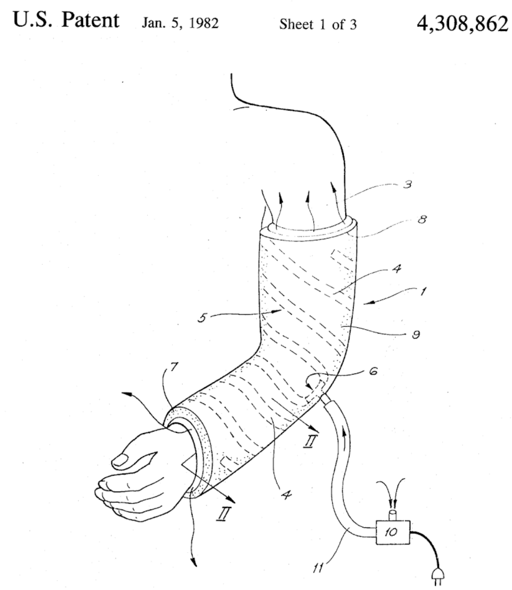


Figure 3.2

The second patent, US6616622B1, that helped with the design was a similar venting device that had tubes running from one half of the arm to the second half that would allow the cast to be ventilated. This would eventually be the same concept that the team put into place to have the pressure pumps gain power from the top half funnelling air down through the elbow to the second half of the cast to inflate the bottom pressure cuff. This device would be inserted between the cast and the skin to create an external ventilation system that does not need to be put in place at the initial wrapping of the cast.

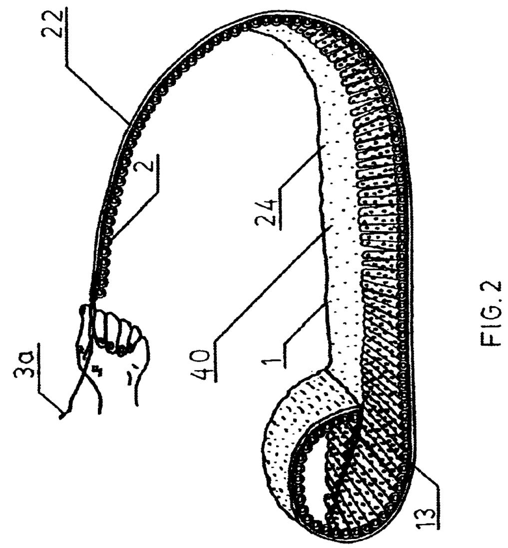


Figure 3.3

The final patent is a conductive heating plate that aided in the positioning and implementation of the heating system. JP354869B2 describes a similar function to a peltier plates and describes a useful implementation in which a second reinforcing plate is placed between the heating element and the structure on which it is being used. This was ultimately not used due to space restrictions leading to direct contact between the peltier plates and the cuffs.

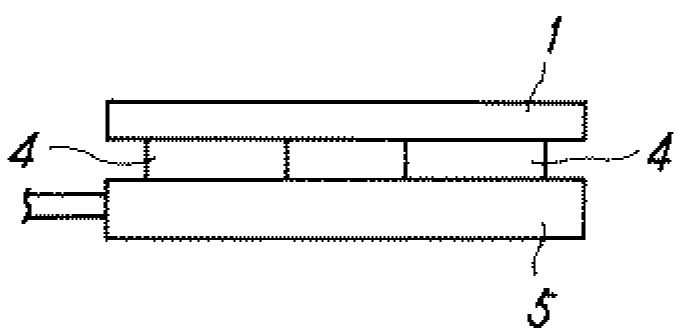


Figure 3.4

Table 3.5 - Patent Research for Related Technologies

Patent Number	Title / Description	Relation to this project
US4308862A	Plaster Cast	This patent claims to solve the airflow problems commonly found with many plaster casts before it. It completely immobilizes the arm and has a pipe that pushes air throughout the arm.
US6616622B1	Surgical cast venting device	This is a ventilation system that allows air to flow through a cast using a strip of cloth that is put inside of a cast that has pores to draw air out through the top of the cast.
JP354869B2	Heat conducting plate for temperature adjustment	This plate is meant to change the temperature of a specific region through the use of copper conducting plates.

4 Professional and Societal Considerations

By: Wei Chen

Our team applied the engineering design process to produce solutions that meet the specified needs with consideration for the topics found in Table 4 - Engineering Solutions Impact.

Table 4 - Engineering Solutions Impact

Area of Impact	Impact	Description of Impact
Public Health and Safety	Yes	Improves health and safety
Global	No	N/A
Cultural	No	N/A
Societal	No	N/A
Environmental	Yes	Materials used to make the product cause environmental harm
Economic	Yes	Introduces a new product to compete with companies selling traditional casts

Of the five areas engineering solutions may impact, three are relevant and need to be considered. The first is public health and safety. The SmartCast was conceptualized to facilitate the healing process of broken bones. Throughout its development, new purposes such as healing muscle injury and massaging sore spots were included to its original motivation. The summation of these possible uses mean there is a significant impact on public health and safety. It will not prevent injury, but it will lessen the recovery period for those who use the cast. The next area of impact is environmental impact. In its current iteration, the cast is made primarily of plastic and uses batteries to supply power to its electronic components. Neither of which is good for the environment. Plastic is non-biodegradable which means disposing of the cast after it is finished being used is difficult; it will be permanent litter. Similarly, batteries contain toxic or corrosive materials which can harm the environment if disposed of improperly. Overall, there is a large negative impact on the environment from the cast, though it may be mitigated by recycling. The last important area to consider is the economy. As of right now, there are no other products on the market with the same capabilities as the SmartCast. Part of its market share overlaps with traditional casts, and if the SmartCast can be sold for below $500, which is the typical cost of a traditional cast, it can threaten to overtake traditional casts in the market. Considering the cost of production is well below $200, it is a very real possibility. The last three areas of impact, global, cultural, and societal are not relevant to consider because the effect on them is bordering zero.

5 System Concept Development and Selection

By: Casey Schmidt

The process of going about concept development and selection for the smart cast was quite research intensive due to its idea being surprisingly absent in the medical world. In a sense, our team had to begin from a square one of what was practically a new innovation for the modern world. To begin with, we analyzed what controllable variables could be used to expedite bone growth and regeneration. During the first stage of the broken bone healing process the body experiences what is known as acute inflammation. This stage normally lasts between 1-3 weeks and causes the patient to experience swelling, and subsequently pain. A way to counteract this is through the process of stimulating blood flow and applying cold temperatures to reduce the present swelling. Both these symptoms solutions can be controlled electronically through the use of a system that offers both variable temperature and pressure. Overall, the goal of the product we wanted to created was to make a cast that both increased recovery time while also being more comfortable and patient friendly.

Some of the concepts that we developed to achieve this goal included having the whole system be remotely controlled by the wearer's smart phone in order to provide a familiar terminal to interact with the cast. In addition, by using an app to control the cast, this allowed for a more simple input system for the user as the code could handle the bulk of the tasks needed to change the pressure and temperature via a bluetooth module communicating with a chosen microcontroller. For the cast design itself, the most appealing idea was a 3-D printed mesh as this method provided both flexibility in its construction and a comfortable design. Furthermore, it made sense to use the growing commercialization of 3-D printing as the backbone for the structure of a "smart cast" built for the modern world's health industry.

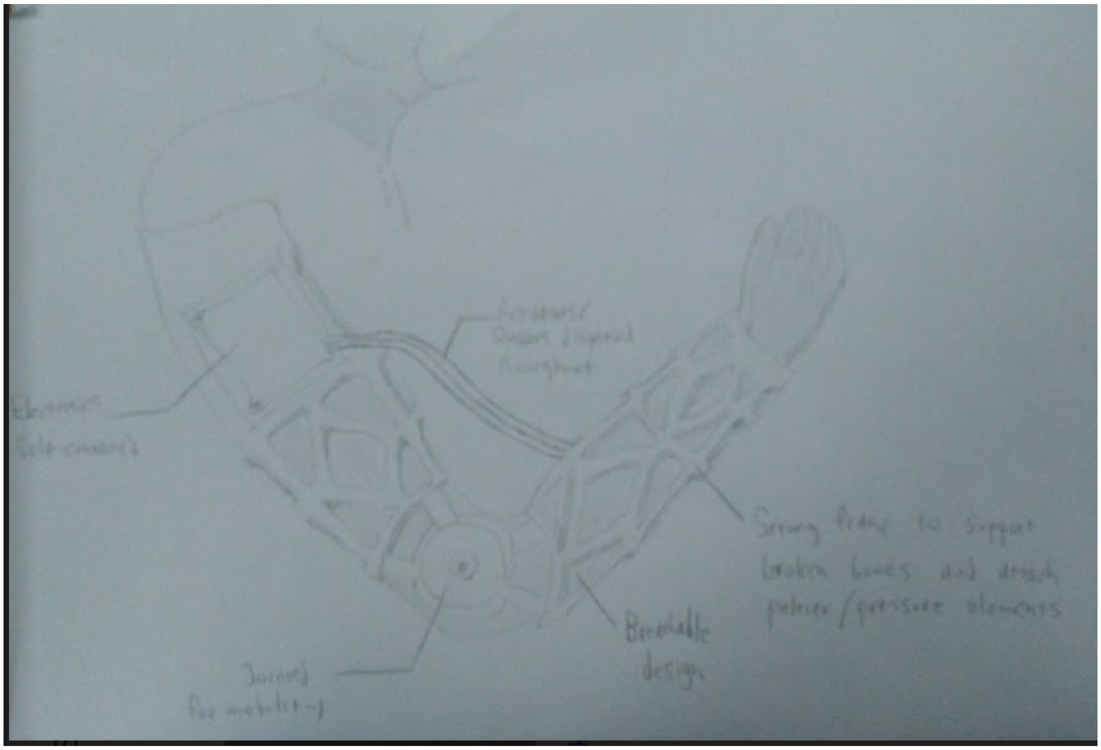


Figure 5.1: Rough Draft of Smart Cast

For the variability control systems (temperature and pressure) their were a multitude of options on how to go about constructing and integrating them into the cast. For the pressure it was decided that the pumps would be electrically driven by a microcontroller to inflate a rubber bladder or a cuff. Also, it was decided that a pressure sensor would then be used to read the pressure, where it could then be transformed into digital data by the circuit. For the heating and cooling that we planned to have for the cast apparatus, the choices for how to go about implementing this variable involved using a peltier plates or a water based system. Due to their overall simplicity and convenient size it became overbearingly obvious that the peltier plates were the best choice for controlling temperature within the medical device.

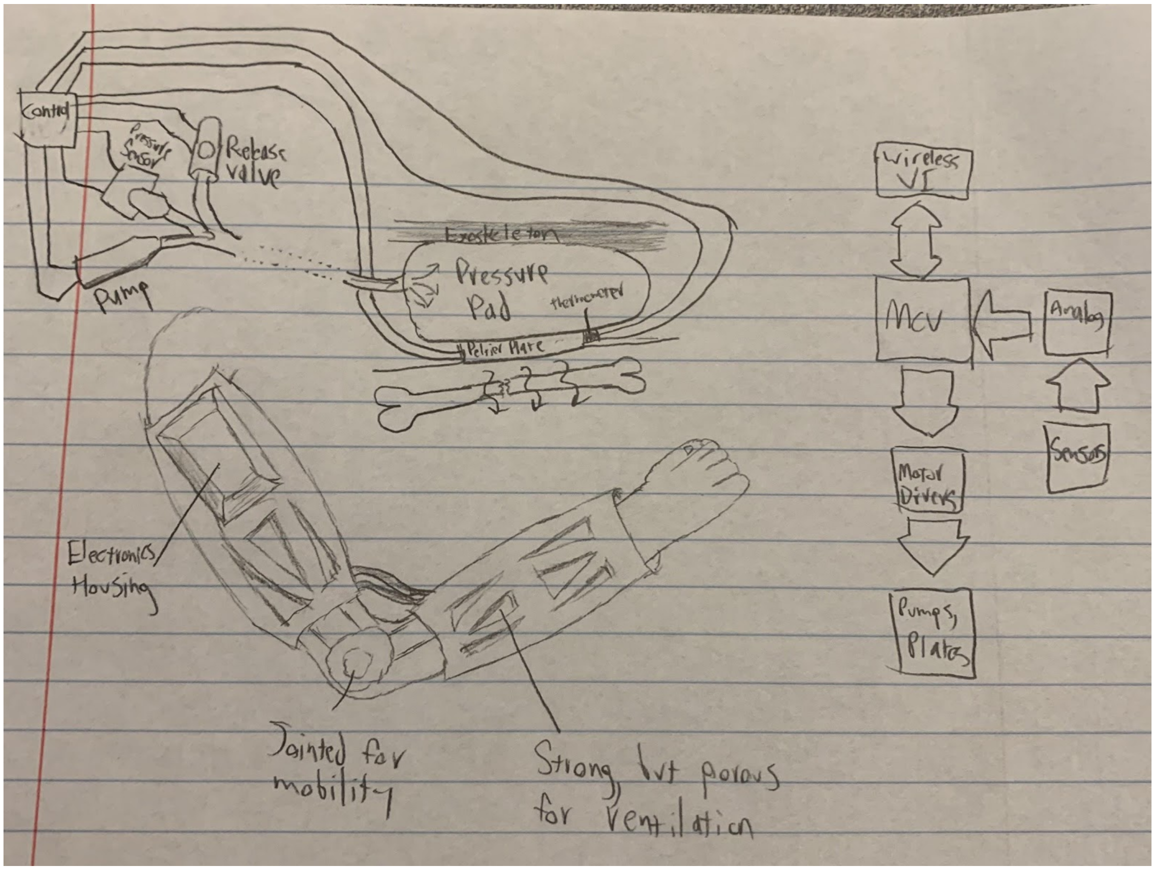


Figure 5.2: Sketch of Subsystem Integration

To control everything in the system it was eventually decided to use an arduino that would communicate to motor drivers in order to control both the peltier plates and the electric pumps. Then using a bluetooth module the arduino could interact with the smart phone app and vice versa. As shown in Figure 5.2, the microcontroller is responsible for taking in data from both the temperature and pressure sensors, interpreting it, and then sending data to the app via bluetooth. While doing this is must also be micromanaging the motor drivers to adjust the pumps and peltier plates to reach the variables in their perspective subsystems that the code tells the arduino to set them to.

In terms of the physical cast itself, it was hoped that the cast brackets would have the ability to open and close, at which they could then be locked in position once set around the patient's arm. This idea can be seen in the prototype in Figure 5.3 which include two separate portions of a cast bracket, which could rotate about a common axel to allow for the process of opening and shutting the apparatus. Furthermore, due to the need for a large amount of circuitry, wiring, and a microcontroller, it was decided to make a circuit mesh that would have its own spot on the upper portion of the smart cast.

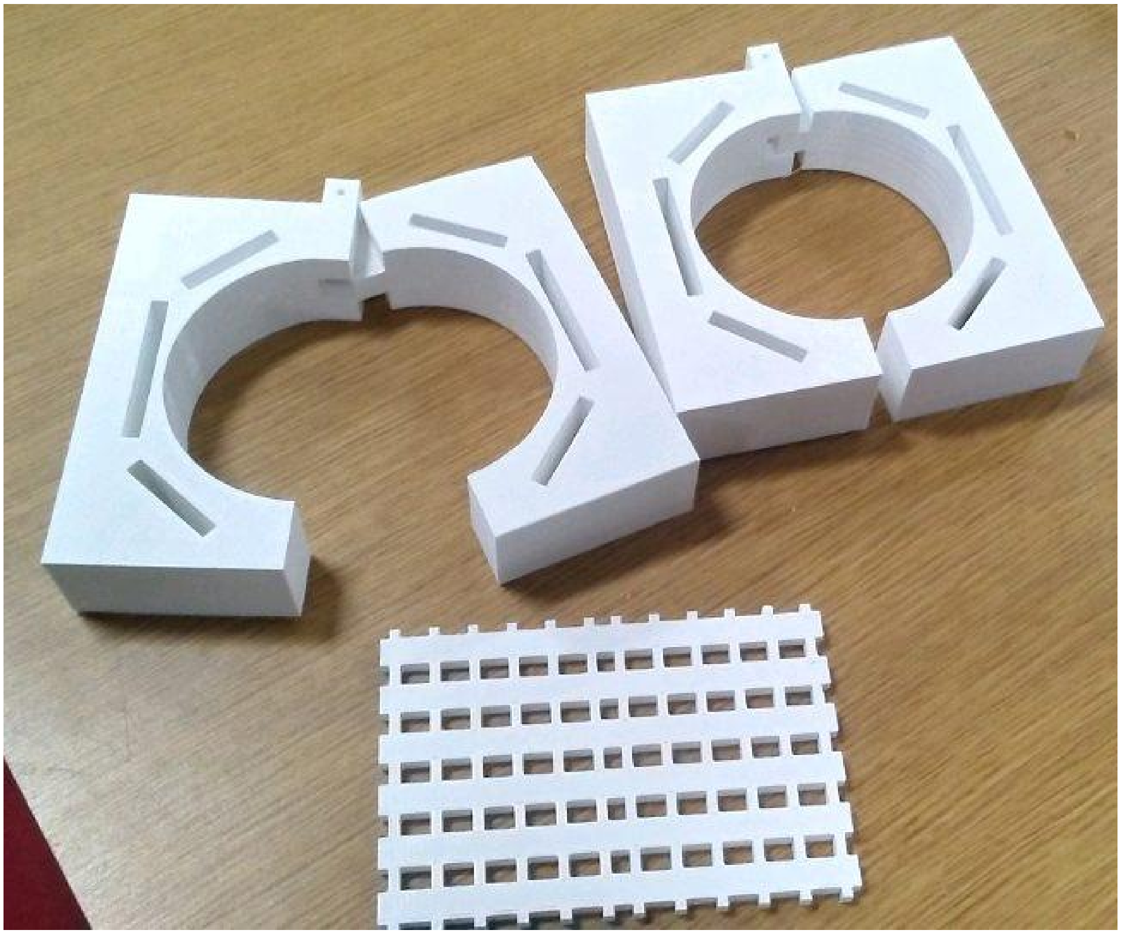


Figure 5.3: Print of Prototype Cast Brackets and Circuit Mesh

For the pressure system, the original intention was to include an automatic pumping system to raise the pressure in the apparatus, a pressure sensor to receive data from the inflatable vessel, and an automated release valve to lower pressure. All these aspects of the pressure system would have to be rigged up though tubing located along the exterior of the cast as well as allow for multiple branch off points for the various connections needed. The clear goal of the system however was to create a way to control the variable pressure present on a limb in order to increase the blood flow to a broken bone or fracture.

6 Subsystem Analysis and Design

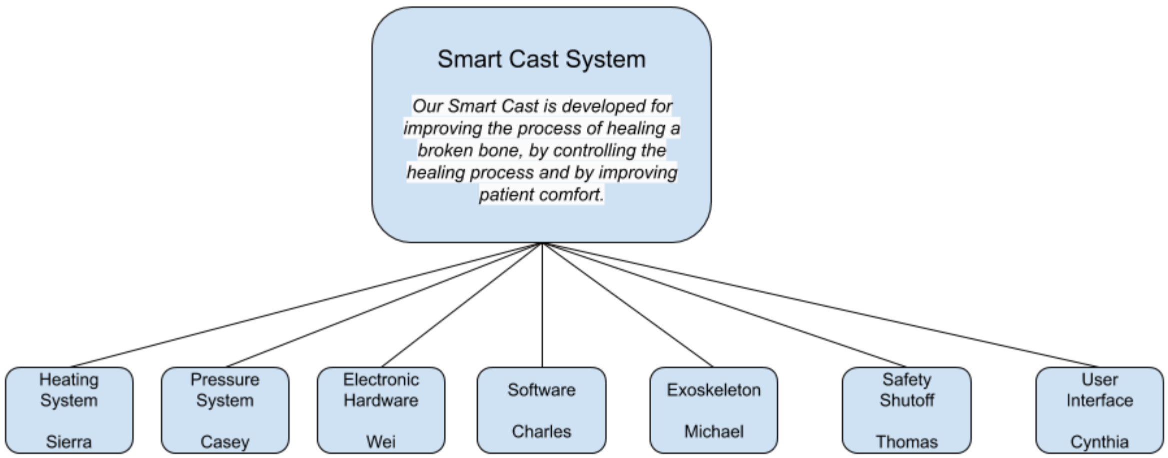


Figure 6.1: Subsystem diagram

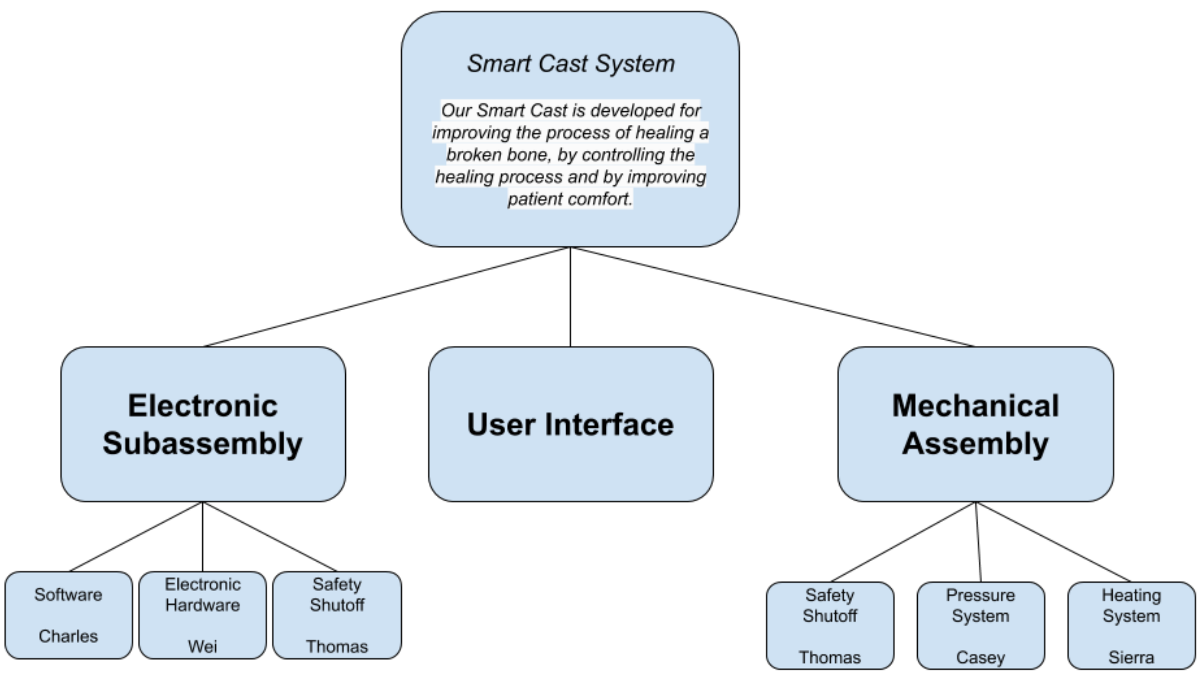


Figure 6.2 : Hierarchical Subsystem Diagram

6.1 Exoskeleton

By: Michael Sweitzer

The process for designing the structure and exoskeleton of the cast went through two major phases the pre-prototype and post-prototype. Before the creation of the first prototype many of the design specifications had not been finalized as the dimensions needed for the circuit and the mechanical capabilities of the cuffs was in question. Through being the most inherently adaptive and the most rigid it was imperative that to create an accurate prototype to test the other aspects of the physical design. Because of the reliance on not only customers for design specifications but also other subsystems the communication of the specifications leads to many complicated design considerations and choices.

6.1.1 The Shackle

The shackle system was created above the other options due to the desire to create a breathable, cost efficient, and structurally rigid. These specifications came from our surveys of previous cast users and their needs. The shackle system provides more rigidity than the soft cast models that are cost efficient and breathable, while also providing a more cost efficient and breathable model than the hard shell cast. The decision to 3D print the cast shackles came from a desire to reduce cost and have an easy production of both the prototype system and the actual design. The need to create a lightweight yet sturdy structure made PLA an obvious choice. This also allowed for the costs to be kept down and complexity of each part to increase.

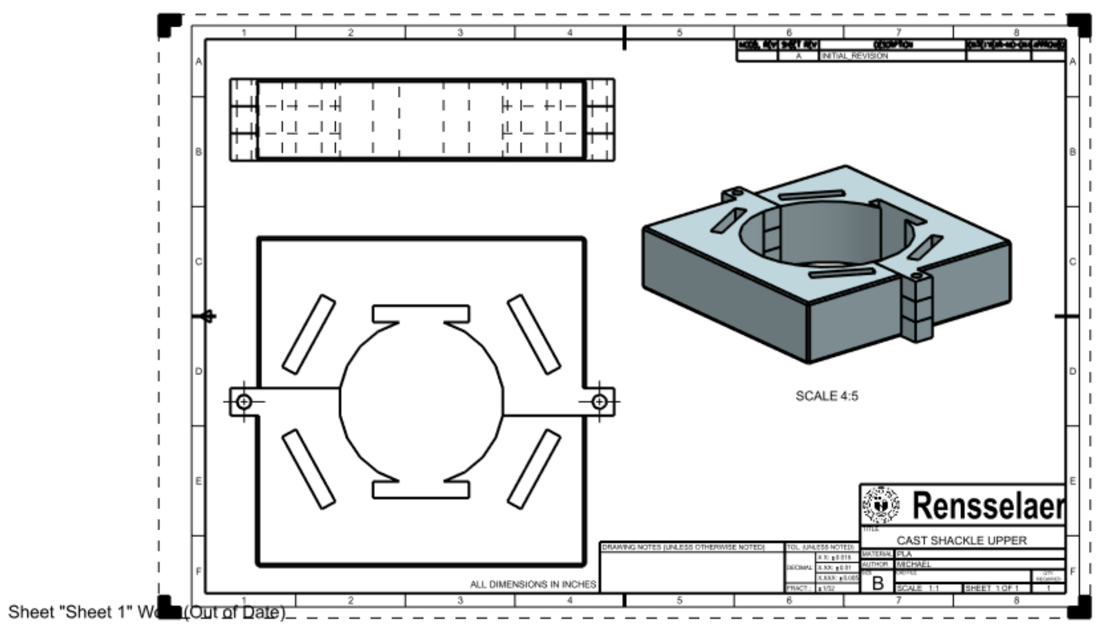


Figure 6.1.1

The main shackle as seen in figure 6.1.1 appears four times on the upper shoulder, middle bicep, middle forearm, and wrist. These four have the same square shape with side hinges that allow for the structural rods to run through them. These were created to be square to allow for the circuit to be placed on a mesh of PLA between the first and second cuffs while allowing for more circuit space should it be needed on the bottom two cuffs as well. The outer diameter for each of the cuffs was equal so that the plates would be in the same position relative to the outside of the cast this allows for more consistent and reliable dimensions. Every shackle has four slots for wooden rigid plates that could be removed at the user's leisure. These were positioned equidistant from each other in position so they could provide structural support without interfering with any of the necessary mechanical responsibilities of the cuff.

Initially each shackle was going to be able to opened around a single hinge that would allow easy access to the cuff and allow for the cast to be donned with ease. This led to design issues stemming from the need for velcro to keep the cuff closed while in use and the need for more support between each of the cuffs without the plates inserted. This was then replaced with the two hinge model that is represented in the final build. The opening of the cast was found to threaten the safety of many of the circuits and electronic components of the cast in turn this aspect was removed in favor of a solid single shackle that would be slid on and off.

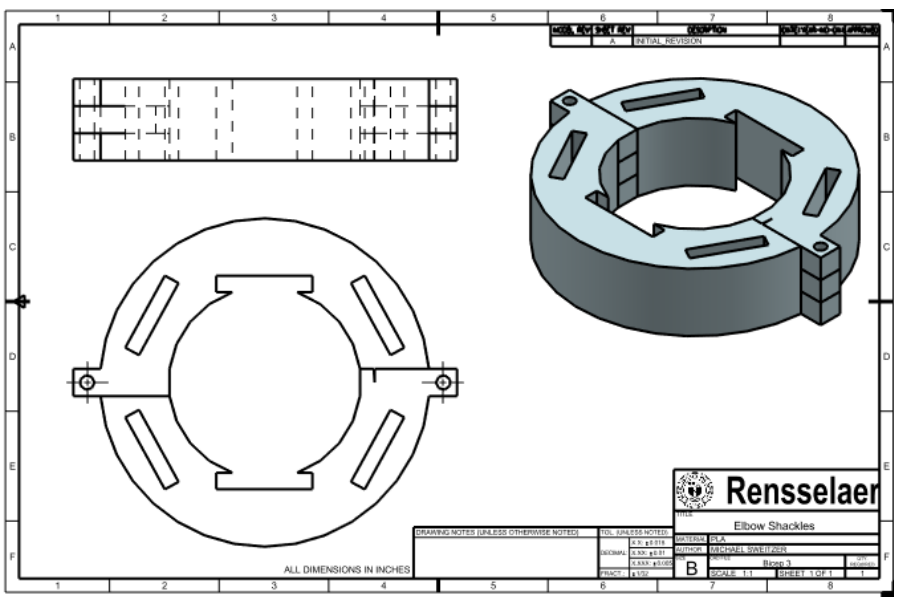


Figure 6.1.2

The secondary shackle is positioned around the elbow on both the lower bicep as well as the upper forearm. This shackle follows a circular outer radius that was designed without the need to support the large circuit mesh between either of these cuffs. This allowed for the turning down of the edges to reduce volume and therefore cost for printing of the cuffs. These circular cuffs had the same slots for the rigid plates that the main cuffs had however these also had multiple openings for the positioning of peltier plates to be flush against the skin while the main shackle only had one. This was to open up more space for the circuit mesh that was not required on the elbow cuffs.

6.1.2 The Rigid Plates

The system of rigid plates was created as a result of the need to have a strong structure to implement while the healing process of the broken bone was in its vital first few weeks of setting. During the stage of hematoma in which the fracture does not have structure and there are many problems with inflammation and swelling, it is necessary to have an external rigid system to allow the following stages to occur properly. During the following stages of granulation tissue formation and callus formation the structure is vital to not reinjure the vulnerable region. These stages required the cast to provide a structure that could be put in place to keep the areas of the arm stable and still.

While these stages did put forth the need for a rigid structure in the cast the desires of comfort from the customers were interpreted to mean for the cast to be flexible as well which lead to a design that allowed the plates to be removable. This was achieved through crafting the rigid plates separate from the cuffs and using wood rather than PLA. Due to the simplicity of the plates shape the use of wood was quite easy simply cutting the rectangles out of a board of plywood using a laser cutter. The use of PLA was inhibited by the needed size of the prints that would be hard to print consistently. Additionally the availability of the printers needed to craft these pieces was limited to the team’s use. Due to these difficulties, the use of wood allowed for strong structural stability without sacrificing the low cost of materials that the customers want.

These plates were set into the cast slits and were stopped from sliding all the way through using a top made out of felt that would act as a handle and a grip to pull the plates out of the cuffs. The four plate system was chosen because it had enough plates for structural integrity while not being too difficult to put into place and to prevent any material deficiencies. Other options were rounded plates that were tight to the skin, however this had complications with crafting rounded wooden pieces. Using alternative materials such as aluminum would have similar machining difficulties for rounded plates and would not add much additional support. The use of PLA in printing these pieces would have also posed a challenge and the wooden supports were finalized as the final design.

6.1.3 The Circuit Mesh

In order for the cast to hold the many important systems and capabilities it has there is a need for a large amount of circuitry. The way that this was implemented into the physical design was through a mesh that was placed in between the top most and the middle bicep cuffs. This web of interlocking plastic allowed for the circuit to rest with relative safety above any of the heat from the peltier plates or any intrusion of the rigid

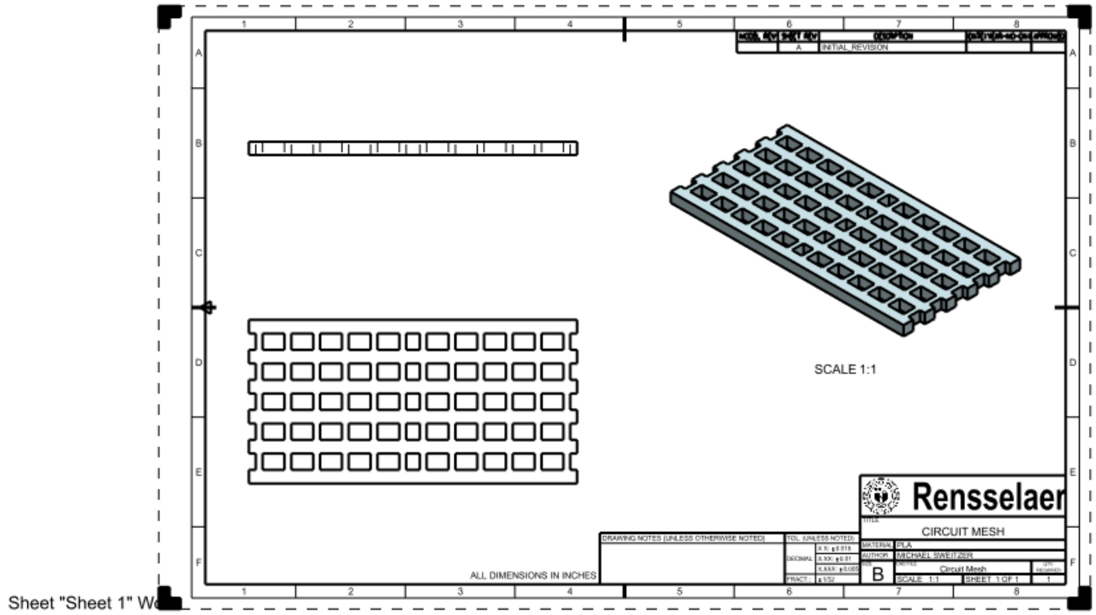


Figure 6.1.3

plates. The mesh was used to attach the circuit to the main body of the cast and to act as an additional structural boon in the area that the sensitive circuitry would be. The initial design had a system of connected rectangles that ended in points on all four sides with 4 by 6 inch dimensions. This was adapted to two bars along the top and bottom of the mesh to allow for easier adhesion to the cuffs and for better stability for the circuit to rest on.

The idea of the circuit mesh became the premier solution when the idea to create a fluid circuit board that would wrap around the arm was dismissed as an idea due to lack of space. In order to optimize the space usage the circuit would have wrapped around the arm using multiple perfboards to form a loose sleeve that would encircle the arm. The problem arose when the circuit would not be able to move fluidly as it would need to while encircling the arm and additionally it would cause many problems with the space that the pressure cuff was already demanding tight to the skin. The mesh was the solution that was then devised to protect the circuit and allow it an easy place to rest.

6.1.4 The Elbow

The elbow piece is a system of four parts that attach the middle two cuffs and act as a hinge for the elbow to rotate about. This system was 3D printed that allows for cheap production and for a simple, low friction design. The system consists of two plates that connect to the cuffs, a hinge that is attached to the cap, and a second cap that completes the hinge system.

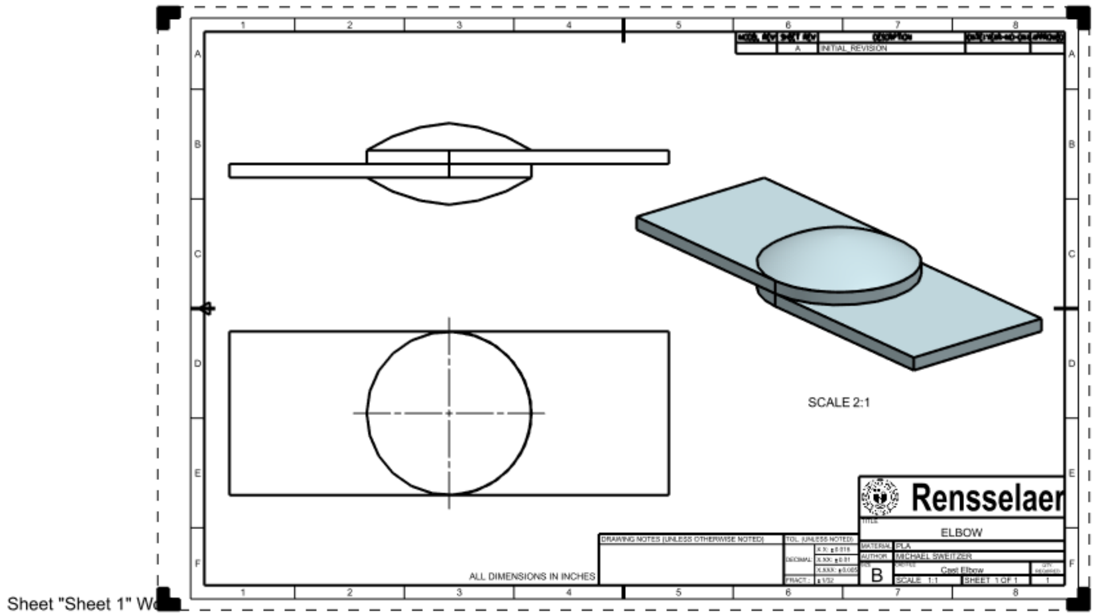


Figure 6.1.4

Each of the plates was a quarter of an inch thick, allowing for a strong structure to be formed; keeping the two halves of the arm together. This elbow hinge would have had a second counterpart that sat on the underside of the are while this piece sat on top, however, due to multiple printer failures and repeated unreliability from the prints only one of the hinges was created. The use of PLA was ideal due to the light weight, low cost, and low friction which allowed the cast arms to rotate freely and not be hindered as wood or aluminum may have been.

6.2 Pressure System

By: Casey Schmidt

The pressure apparatus was one of the two variable systems implemented into the smart cast (the other being the heating element) in order to set it apart from casts currently found in the medical world. Designing the pressure subsystem involved a multitude of design decisions to figure out the most optimal route to go about its blueprint. However, the end goal remained the same, which was to create an apparatus that could both lower and raise the sitting pressure experienced on the cast held arm. Its purpose is to create the ability to increase blood flow to a region of the arm to accelerate the body's natural healing process of fractured or broken bones.

6.2.1 - Research

By increasing the blood blow to the region where the fracture or break occurred, the body is able to speed up the rate at which oxygen, nutrients, and new cells reach this area of the body. Scientifically, increasing the pressure around specific portions of a human's limb should be expected to give these results as blood, just like any fluid can have its flow quantified as volume per time. This is determined as the cross sectional area of the vessel or tube, and the velocity of the liquid (blood), which is hence dependent upon the current applied pressure. The present relationship is expressed in a formula known as Poiseuille's Law which is derived from the Navier-Stokes equation for flow of Newtonian fluids.

$$Q = \frac{\pi r^4 \Delta P}{8 \mu L}$$

Figure 6.2.1.1: Poiseuille's Law for Newtonian Fluids

In this equation flow rate (Q) is given as a function in terms of the radius of the tube (r), the differential pressure acting upon the walls of the vessel (ΔP), the viscosity constant of the fluid (μ), and the length of the tube itself (L). Even though blood is not a true Newtonian fluid due to it being non-homogeneous, the relationship illustrated shows that blood flow is proportional to the applied pressure and radial size of the vessel. As such it is safe to make the hypothesis that by causing constriction about a limb using pressure cuffs, it should be possible to increase blood flow to specific parts of the body. This in turn has been proven in research to expedite the bone healing process as listed by the factors previously stated. By providing this ability to increase the healing speed, the smart cast can stand as a powerful alternative to the current methods for broken bone regeneration and mending.

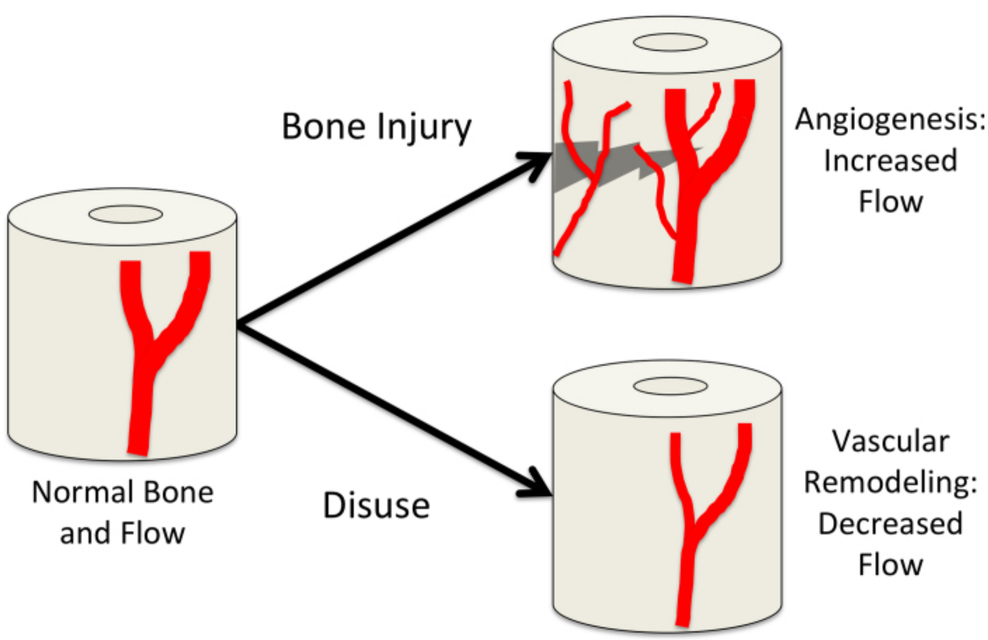
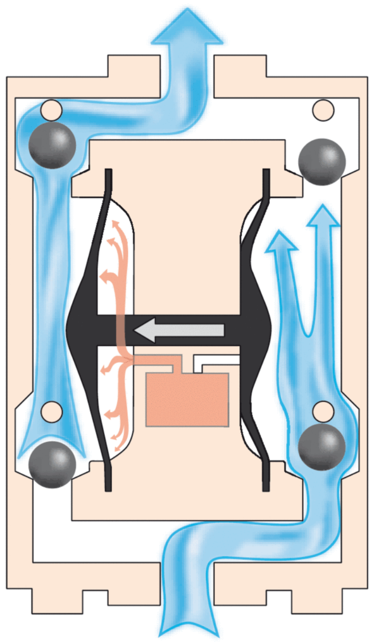


Figure 6.2.1.2: Increased Blood Flow Brings nutrients and Fresh Cells to a Fracture

6.2.2 - Concept Development

One of the first major choices that had to be made for the design was figuring out what the medium of inflation would be. Through systemic research the two choices that appeared the most advantageous to the overall design, were a rubber bladder or inflatable cuff. An advantage that the rubber bladder held was the ability to create differential pressures in opposite sides of the arm simultaneously through the use of multiple bladders. In addition, the rubber bladders were a significantly more cost effective option than the inflatable cost when taken my themselves. Unfortunately, disadvantages plagued this option as the to accommodate differential pressure and multiple bladders, the pressure apparatus would have to be more expensive, complex, and be significantly bulkier to to added pumps and tubing. On the other hand, the inflatable cuffs were abundantly more convenient in design for the cast system we had proposed. This was due in fact to their intended commercial purpose as a sphygmomanometer (blood pressure reader) meant that by construction they were built to be worn comfortably around an arm. Furthermore, even though they lacked the ability to create differential pressure, functionally they could create evenly distributed pressure at any point along the arm (depending on where they were set up on the cast). Due to the advantages stated previously, as well as their relative simplicity, it was decided that the inflatable cuffs would be the medium of choice rather that the rubber bladders.

Another major design decision that had to be addressed was the pump system that would be used to drive the pressure into and out of the inflatable cuffs. The two choices that appealed to the schematics of the structure were a diaphragm pump and a vacuum pump. While both electronically driven motors could be used to create pressurized vessels by drawing air from a vent and out of a nozzle, they differentiated in terms of advantages and disadvantages. Diaphragm pumps use an electronically powered geared motor driver, which creates a reciprocating action upon a rubber or teflon diaphragm, to force air through non return check valves. A compelling advantage of these pumps is their efficiency, as they are able to run for long periods of time while drawing minimal power from the supply source. A downside to these pump systems is their slow flow rate, which would lead to a moderately lethargic inflation speed. The other type of pump that held potential for integration into the pressure system, was vacuum pumps. Differential pressure is achieved through the use of a Roots type blower, which is a positive displacement lobe pump which operates by pumping a fluid with a pair of meshing lobes resembling a set of stretched gears. This is driven by a simple electric motor which allows for the lobes to displace air from the intake and force it through the outlet. Due to this design, the motors had a relatively high flow rate and the intake nozzle allowed for variability in where the air could be taken in from. A downside held by this type of motor was its high power intake as it drew quite a significant current to properly operate. In consideration that neither motor held distinct leverage over the other in terms of practicality (and were relatively cheap), it was decided to purchase and test both systems.



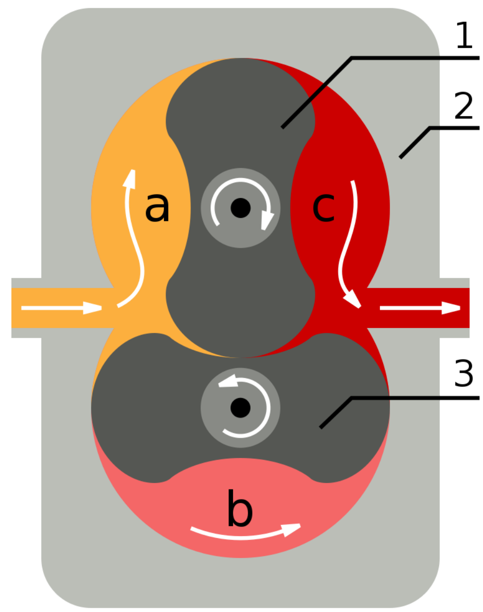


Figure 6.2.2.1 (left): Diaphragm Pump, Figure 6.2.2.2 (right): Roots Type Blower Vacuum Pump

Table 6.2.2.3: Chart Comparing Vacuum and Diaphragm Pumps

	Operating Voltage	Amperage Draw	Max Pressure	Flow rate	Cost
Vacuum Pump	9 Volts	300 mA	5 psi	4.5 liters/min	$2.50
Diaphragm Pump	9 Volts	40 mA	7psi	0.8 liters/min	$7.00

6.2.3 - Pressure Sensor

The final part required for the full integration of the pressure apparatus to the smart cast, was the pressure sensor itself. This device would allow for the circuit to have a comprehensible shift in voltage which could be converted into digital data that could be interpreted by the code and thus be communicated to the app. For the specific pressure sensor we utilized, it operated by reading a differential pressure created by a passive leak between the input tube and the circuit itself. Its body was made up of 6 pins and an air intake tube section as seen in Figure 6.2.3.1. Three of the pins were used to measure the differential voltage created under changing pressures, 2 where for the 5 volt power supply and ground for the small device, and one of the pins was redundant, only needed to structurally attach the sensor to a breadboard or perf board. By reading the potential voltage change when the pressure alternated, it was possible to compute a linear correlation between the two data sets and produce a function that could be employed by the circuit.

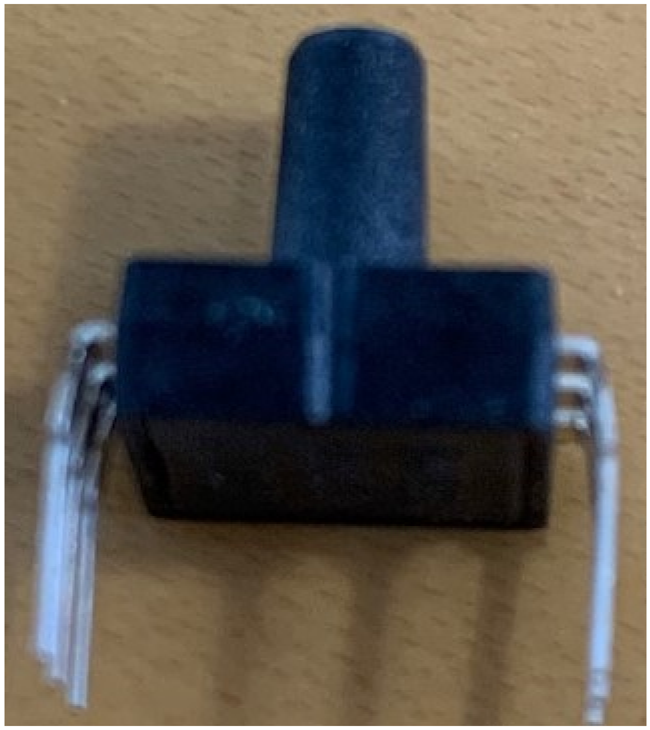


Figure 6.2.3.1: Variable Pressure Sensor

To attach the pressure sensor to the tubing, a junction was required to link the two systems while also allowing for air flow to reach the inflation vessel (pressure cuffs). In order to overcome this issue, by utilizing CAD software, it became possible to create a virtual rendering of the attachment system and then 3-D print it to a customized fit. The newly printed piece allowed for the attachment of two sections of tubing as well as the pressure sensor. Another portion of the pressure apparatus that was digitally designed and printed, was tubing connection points that could allow for the ability to link two separate tubes together with an airtight seal. Both designs were created on the program NX 12.0 from which they were converted to files that could be printed off of Prusa 3-D printers. The material they were printed in was PLA, which has fairly high stress tolerances especially when the infill (percent of print which is material and not air) is raised.

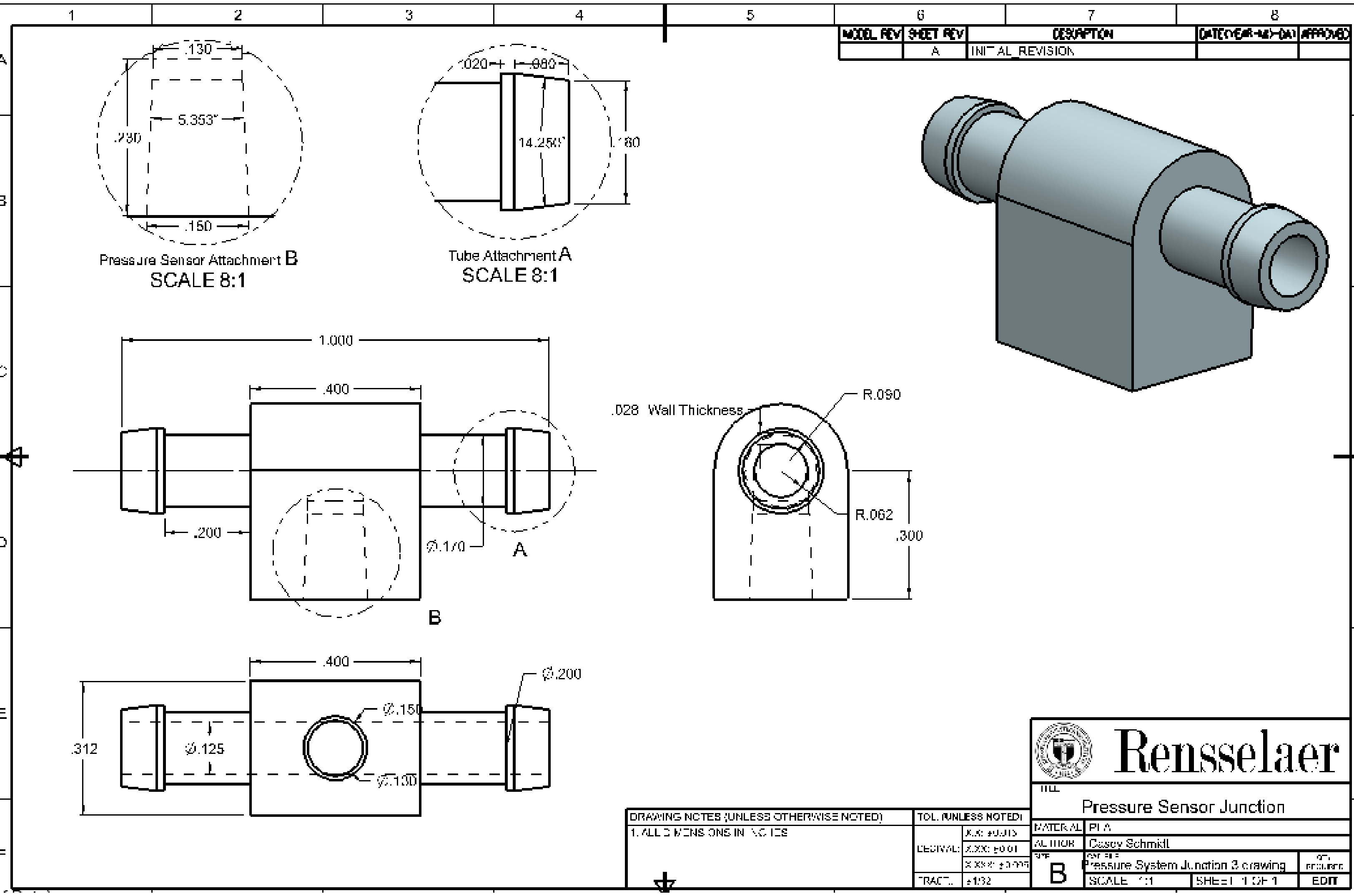
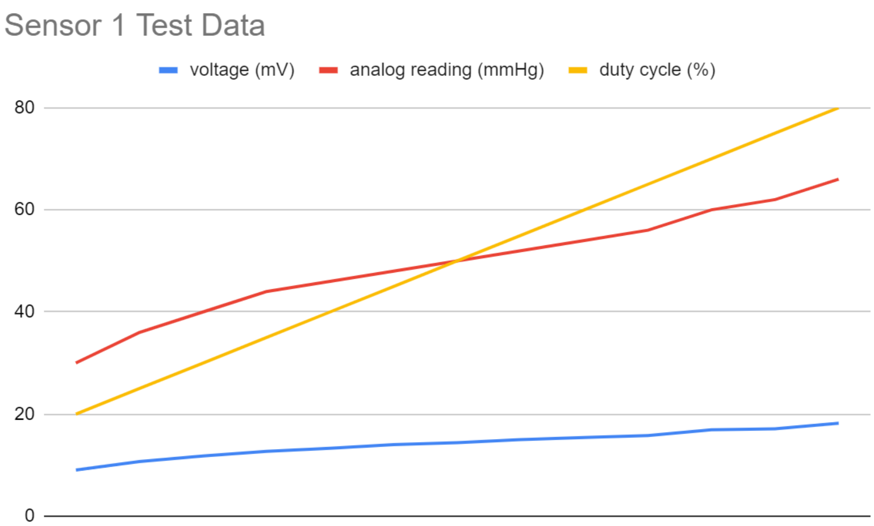


Figure 6.2.3.2: Pressure Sensor Junction CAD Rendering

6.2.4 - System Testing

With all of the pressure sensors now attached to junctions that could be connected with tubing, it became possible to test the voltage change experienced at different pressures in order to find a readable correlation for the circuit. To test the sensors, they were linked to a tubing apparatus (which included an analog pressure sensor) that originated from the pressure cuffs. Using a waveform generator and dc voltage supply, we were able to test the motors as if they were hooked up to the arduino driven circuit. By using a square wave, the duty cycle could be changed allowing for the pressure being pumped into the system to change and thus allowing for a range of data sets to be taken from the pressure sensor. For the process of reading data from the sensor, a multimeter was used to view the change in voltage experienced at various pressures. To find the correlation, the duty cycle was changed by intervals on 5% and the change in pressure as well as the voltage output were recorded. In order to make the results as accurate as possible, all 4 sensors that could be joined to a junction were tested to find their respective correlations.



voltage (mV)	analog reading (mmHg)	duty cycle (%)
9.05	30	20
10.7	36	25
11.8	40	30
12.7	44	35
13.3	46	40
14	48	45
14.4	50	50
15	52	55
15.4	54	60
15.8	56	65
16.9	60	70
17.1	62	75
18.2	66	80

Figure 6.2.4.1: Sensor 1 Test Data

From the data found during the test on sensor 1 (as shown by figure 6.4.2.1) it was possible to create a linear correlation function between the voltage and the analog reading from the sphygnomonometer. As shown by the chart in figure 6.4.2.2 it is clear that there is a linear correspondence between the recorded voltage from the pressure sensor and the pressure reading from the analog readout.

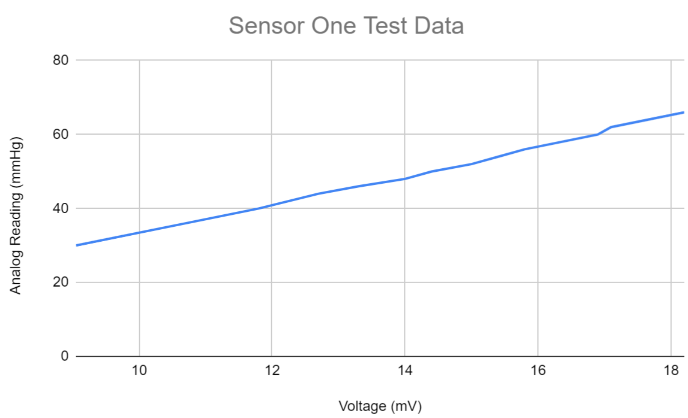


Figure 6.2.4.2: Pressure to Voltage Correlation Graph (Sensor 1)

The function derived from this relationship is y = 3.94x - 6.28 with the x variable being the change in voltage in terms of millivolts and with the y value corresponding to the pressure being read by the sensor. In addition, the R^2 value of the linearity function was found to be .997 proving that the two data sets had a high degree of linear correlation. This test and analysis of data was then repeated for the next three sensors in order to further strengthen the function that would determine the control over the pressure apparatus. Data from these tests was recorded in the table below and the linear correlation between the pressure and the voltage for each sensor is graphed in Figure 6.2.4.4.

Table 6.2.4.3: Test Data from Sensors 1, 2, 3, and 4

Sensor 1	voltage (mV)	analog reading (mmHg)	Sensor 2	voltage (mV)	analog reading (mmHg)	Sensor 3	voltage (mV)	analog reading (mmHg)	Sensor 4	voltage (mV)	analog reading (mmHg)	duty cycle (%)
	9.05	30		9.7	36		8.6	34		10.8	37	20
	10.7	36		11.4	42		10.3	41		12.7	45	25
	11.8	40		12.6	47		11.6	46		14.1	50	30
	12.7	44		13.5	51		12.5	50		15.2	55	35
	13.3	46		14.3	54		13.3	54		16.1	60	40
	14	48		14.8	57		14	56		16.7	62	45
	14.4	50		15.3	59		14.5	59		17.3	64	50
	15	52		15.8	61		14.9	61		17.9	66	55
	15.4	54		16.1	63		15.4	62		18.3	68	60
	15.8	56		16.5	64		15.7	64		18.8	70	65
	16.9	60		16.7	65		15.9	65		19.1	71	70
	17.1	62		17	66		16.1	66		19.4	72	75
	18.2	66		17.3	67		16.3	67		19.7	74	80

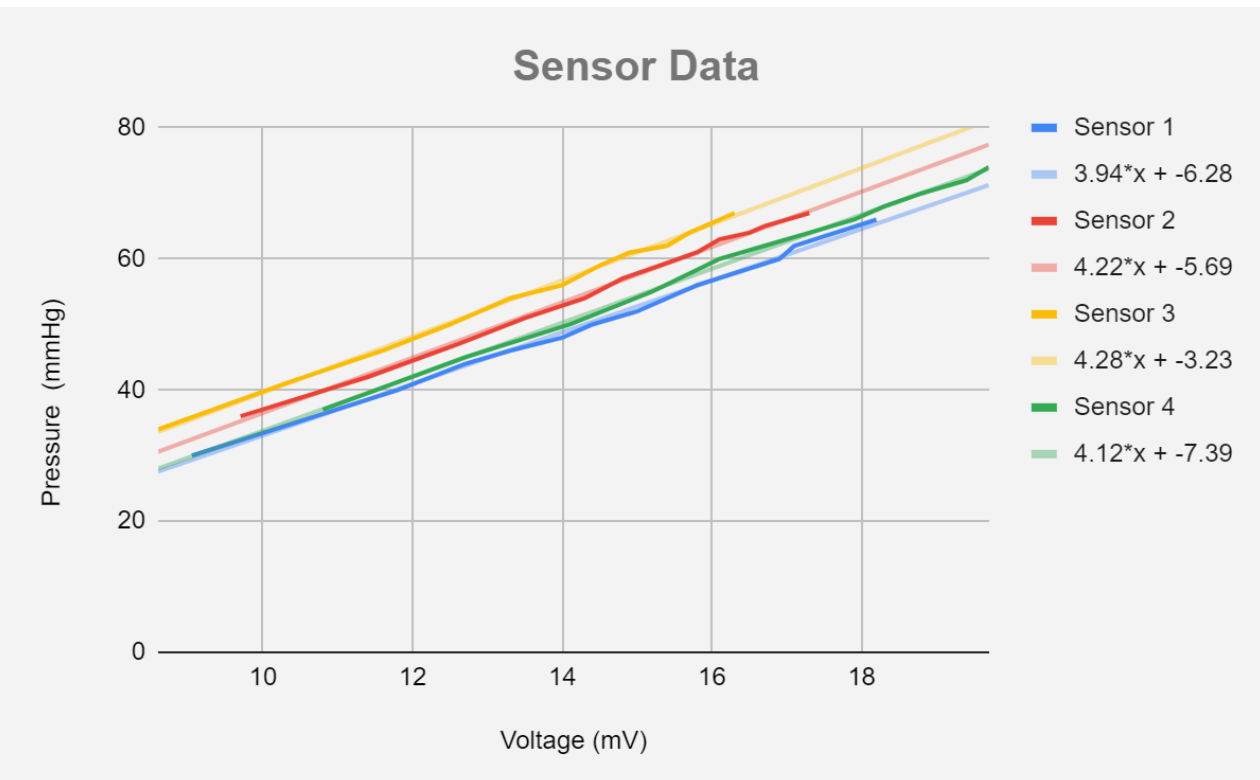


Figure 6.2.4.4: Chart of Linear Functions of the Pressure Sensors

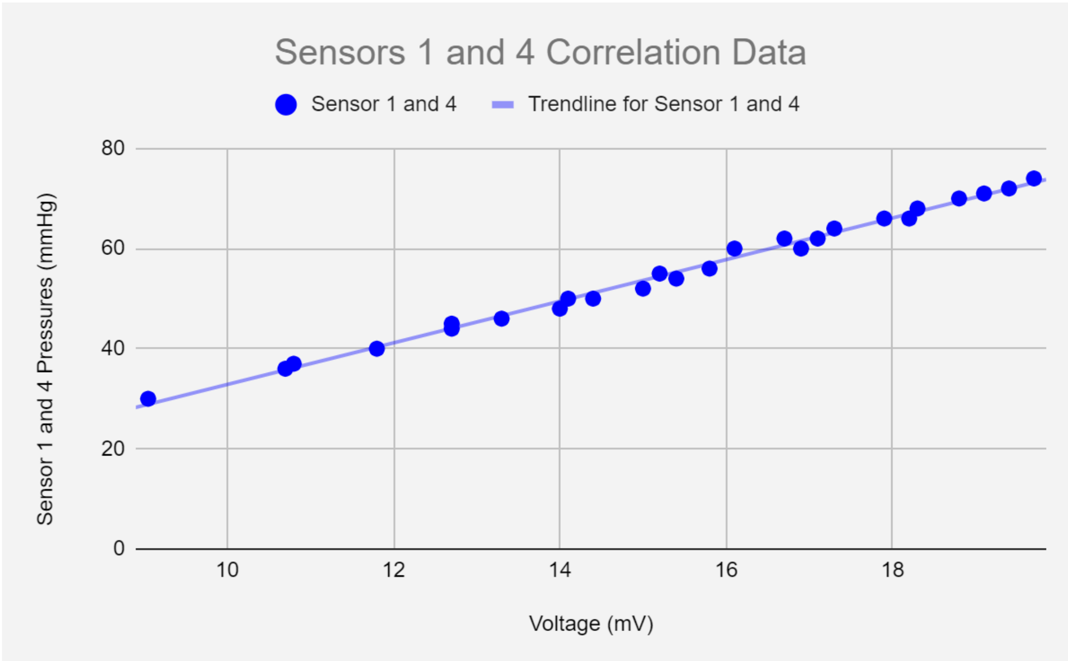


Figure 6.2.4.5: Chart for Linear Correlation Between Sensor 1 and Sensor 4

Now with the graphed data it was possible to calculate a function for each of the individual sensors. As seen in the figure above, a trend line of the data from the sensors is listed as its linear function. With this acquired information it was possible to narrow down which two pressure sensors would be used for the cast. In order to receive the most accurate results from the system, and ease the work needed to be performed by the circuit, the functions with the largest degree of similarity were chosen as the sensors that would be incorporated into the pressure apparatus. The sensors that ended up being chosen based on this criteria were sensors 1 and 4 since they held slopes with a difference of .18 and their y-intercepts differed by less than one. As such the next step was to create a function that combined the data set of both sensors which is shown in figure 6.2.4.5. The formula that came from the correlation was y=4.16x-8.72 where x is the voltage (in millivolts) being read by the multimeter and y is the pressure read by the analog source in mmHg. Furthermore, the calculated R^2 value for the function was .994 which proves that there is a strong linear correlation between the two data sets when compared to voltage and pressure. With the sensor chosen it was possible to move onto the construction of the pressure subsystem itself.

6.2.5 - Construction

Attaching the pressure system to the smart cast itself was a challenge amongst itself due to a multitude of variables that would determine its efficiency, practicality, and aesthetics, with the most blatant point of contention being where to adhere the pressure cuffs. Logically the most sound answer to this predicament was to secure them onto the center cuff of the upper and lower sections of the arm. In this position the cuffs where most comfortable for the person wearing the apparatus, as they did not interfere with any joints at their locations, yet also allowed for the maximum amount of surface area to be covered by the pressure cuffs. In addition, having the cuff on the upper arm located within the center bracket, allowed for most of the tubing to remain away from the circuitry which helped alleviate the congestion of the upper arms system control section. To affix the inflatables to the brackets of the cast, super glue was used as an adhesive rather than hot glue due to its ability to better cope with high stresses from the inflation and deflation process. Due to the cast being no longer able to open and close, the purpose of having the cuffs do the same was deemed unnecessary. Luckily, due to the methods at which the system inflates (as it applies pressure from all sides), it always forms a tight, yet not uncomfortable seal around the user's arm.

Next, came the process of rigging up the tubing system for each of the cuffs not affixed to the smart cast. One end of the tubing would hook up to the motor driven pumps that inflated the apparatus, while the other end would lead to the digital and analog pressure sensors. In order to attach the variable pressure sensors to the tubing, a special CAD rendered junction had to be printed to accommodate for their unwieldy design. With this junction it became possible to show that the pressure being read by the system within the app was the same as the one recorded by the analog pressure reader. Another issue that was resolved using a CAD model was the ability to connect two tubes together with an airtight seal. This was done by creating a connection point that would allow the flexible rubber of the tubing eleasticaly seal itself around the attachment point (Figure 6.2.5.1). If need be an adhesive such as hot glue could be applied to ensure the seal had no means of coming undone do to any outside forces (or internal ones such as pressure). To secure the tubing to the cast itself, electric tape or hot glue was used to hold it to the surface of the cast reducing the chance of it getting caught if someone were to be wearing the device and moving around. In addition, near the center of the upper arm the tubing from two cuffs is wrapped together in order to preserve space as both lead to the pressure sensors located in the same spot within the circuit.

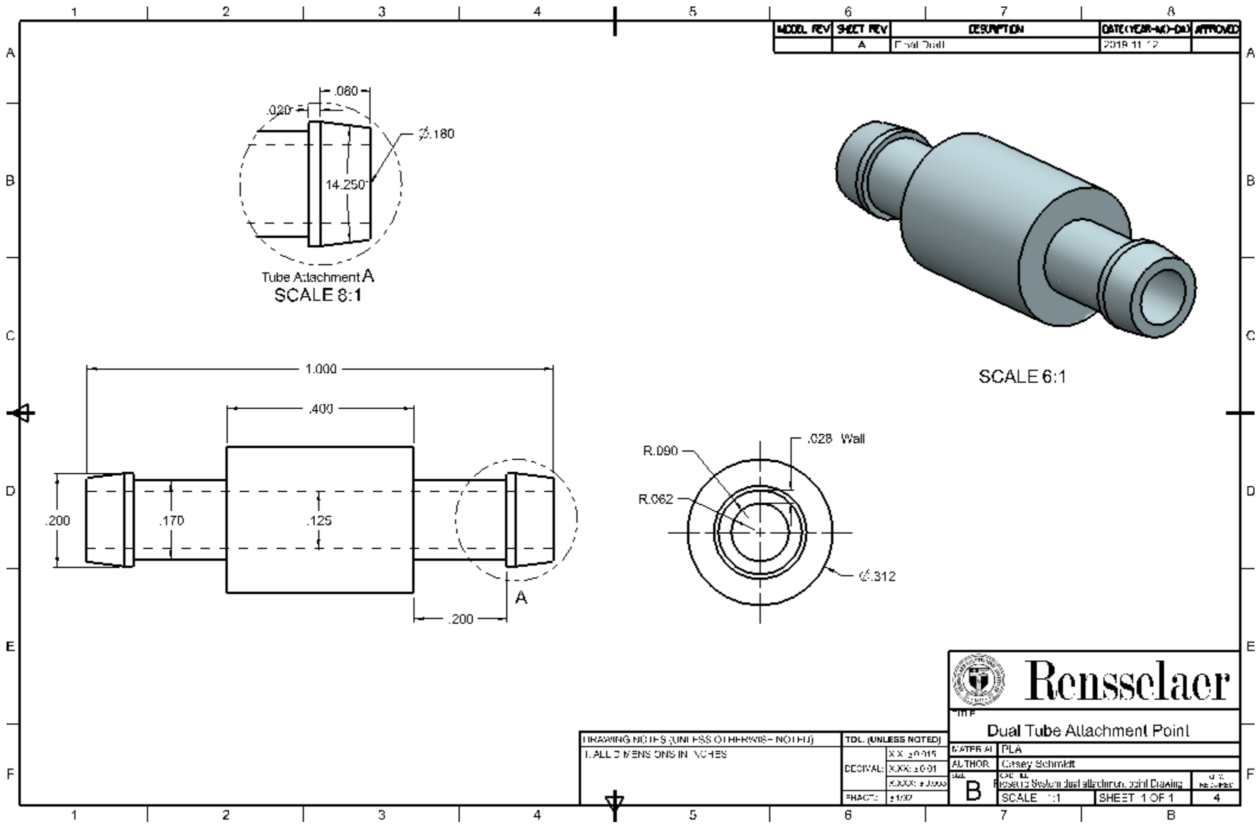


Figure 6.2.5.1: Dual Tube Attachment Point CAD Sketch

In order to prepare the motors for their integration into the motor drivers, they need to have female header pins solder onto them in addition to long wires to ensure they could reach the position of the motor drivers from where they were connected on the smart cast. To house the motorized electric pumps within the cast, a plastic sleeve was created to both hold them in place, as well as to make them appear more aesthetically pleasing. Special care was taken when making the plastic sleeve in order to not hinder the wiring that needed to power the motor, or block the input valve. Furthermore, to ensure no chance of leaking air pressure, the tubing connected to the output valve of the pump was sealed using a layer of hot glue which dries into a hardened airtight polymer skin around the connection region. Also, to ensure that the pressure sensors could be easily plugged into the circuit it was vital to attach long wires with female header pins to the leads located on the sensors themselves. With the pressure system in place, it was possible to then move onto full system testing using the circuit and code to control the pressure.

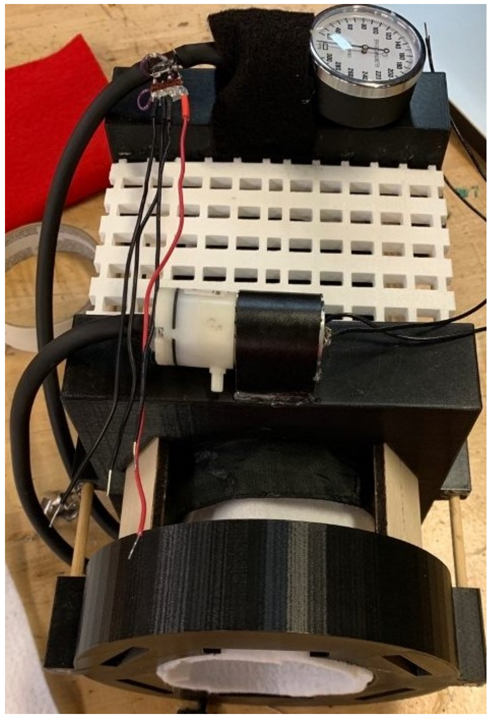


FIgure 6.2.5.2 Pressure Apparatus for Upper Section of Cast

6.2.6 - Problems with the system

A problem that was found during the testing of the inflation system was that the pressure sensors themselves allow a small leakage of air to pass through them. This was purposeful as this was how they measured pressure which was done through reading the differential change as the air from the apparatus escaped. Unfortunately, when ordering the pressure sensors, this fact was not abundantly obvious, and in the future, it would make sense to use sensors that could read pressure without needing to read a differential. Luckily the motors were able to pump air into the system faster than it leaked out of the sensors so the only major downside to this design was that their needed to be a constant power draw in order to keep the cuffs inflated at the correct pressure.

Another issue that was experienced during the prototyping phase of the subsystem assembly was a tolerance issue with one of the prints. The prototype junction for the pressure sensor (Figure 6.2.6.1) was slightly too small for the nozzle to connect to, so when the sensor was connected, it caused the connection point to experience large amounts of strain. When pressure was added to system they would crack due to the addition of air pressure to their walls. This problem was overcome by accounting for 3D printer expansion when reconstructing the CAD file, as well as creating a design that could handle a higher level of strain than the previous design. To accomplish this, the region which held the pressure sensor was given a large shell wall and the infill of the entire print was increased so it could handle larger stresses on its structure during inflation. Figure 6.2.3.2 shows what the final design for the pressure sensor junction that ended up being integrated into the pressure apparatus was.

Figure 6.2.6.1: Prototype Pressure Sensor Junction

One minor issue that the system had was it relied on potentiometers for accurate readings. Due to this, the calibration of the system could sometimes be thrown off if the devices moved. It was easy to recalibrate the system because of the variable nature of potentiometers, however in the future it would make more sense to add specific resistance value resistors into the circuit to ensure that values would not change in the pressure system.

6.3 Heating System

By: Sierra Carr

With the end goal of creating an arm cast which would speed up the bone regeneration process, the group had decided to integrate two variable systems into the design: temperature control and pressure control. The purpose of the temperature system is to vary the temperature at the sight of injury, in an effort to increase blood flow rate to speed up the healing process. Initially, the heating system was intended to be a temperature varying system with heating and cooling capabilities. The final decision was to only use a heating system due to complications with the cooling system, which will be mentioned in this report. With time and cost in mind, the best option to create the temperature system was to use peltier plates to generate the hot and cold environments, and to use temperature sensors as a way to monitor the temperature of the peltier plates.

6.3.1- System Testing

Before any final decision could be made about the temperature system, testing had to be performed to see if the peltier plates could do both heating and cooling, and to see if the temperature sensors were capable of reading both hot and cold temperatures. Using a DC power supply, analog discovery oscilloscope, and excel, testing was performed. A DC power supply was used to supply a DC voltage to one peltier plate, supplying from 0.5 V up to 3.5 V. The analog discovery oscilloscope was used as a power supply for the temperature sensor, which used a +5 V power supply, and as a multimeter reading the output voltage across the temperature sensor. The temperature sensor will output 10 mV/℃, as described in the sensor pinout in figure 6.3.1.1.

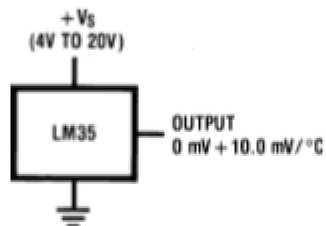


Figure 6.3.1.1: Sensor Pinout

Peltier plates will heat up on one side and cool on the other side when current flows in one direction. When the direction of current is reversed, the hot side and cool side flip. To perform testing, current was passed in one direct through the peltier plate, powered by a DC power source. The sensor was placed in direct contact against the cool side of the peltier plate where a voltage output was observed across the temperature sensor and by the analog discovery, then recorded into an excel sheet. An infrared thermometer gun was used to verify accuracy of the temperature sensors by recording the temperature reading from the cool side in degrees fahrenheit. After recording data for the cool side of the plate, the temperature sensor was then placed in direct contact with the hot side and then a voltage across the sensor was recorded, then the temperature was also verified using the temperature gun. Initial data is shown below in table 6.3.3.1

Table 6.3.1.1: Peltier Plate and Temperature Sensor Data

Voltage of Pelltier plate	Cool Side Voltage Across Sensor (mV)	Calculated Cool Temperature	(F)Temperature Gun Cool Reading	Temp. Gun Deg C	Hot Side Voltage Across Sensor(mV)	Calculated Hot Temperature	Temperature Gun Hot Reading (F)	Temp. Gun Deg. C
0	212.2	21.22	69.8	21	212.2	21.22	69.8	21
0.5	217.6	21.76	72.1	22.27777778	228.7	22.87	73.9	23.27777778
1	216	21.6	73	22.77777778	244	24.4	74.9	23.83333333
1.5	217.8	21.78	75.2	24	268.6	26.86	86	30
2	236.7	23.67	82.7	28.16666667	308.7	30.87	95.1	35.05555556
2.5	239.6	23.96	81.5	27.5	338.8	33.88	104.5	40.27777778
3	249	24.9	84.5	29.16666667	405	40.5	130.2	54.55555556
3.5	286.9	28.69	92.3	33.5	429.4	42.94	139.4	59.66666667

The final data analysis was observed by generating data graphs. The temperature gun readings were converted from fahrenheit to celsius using an equation in excel, and the voltage across the sensor was also converted to degrees Celsius by using the 10mV/℃ conversion from the manufacturer's data sheet in order to be graphed in degrees celsius. Three graph as were generated as seen below: calculated cool vs. calculated hot (figure 6.3.1.2), calculated hot vs. measured hot (figure 6.3.1.3), and calculated cool vs. measured cool (figure 6.3.1.4). All of the data began with an initial room temperature reading from both the temperature sensor and the infrared temperature gun.

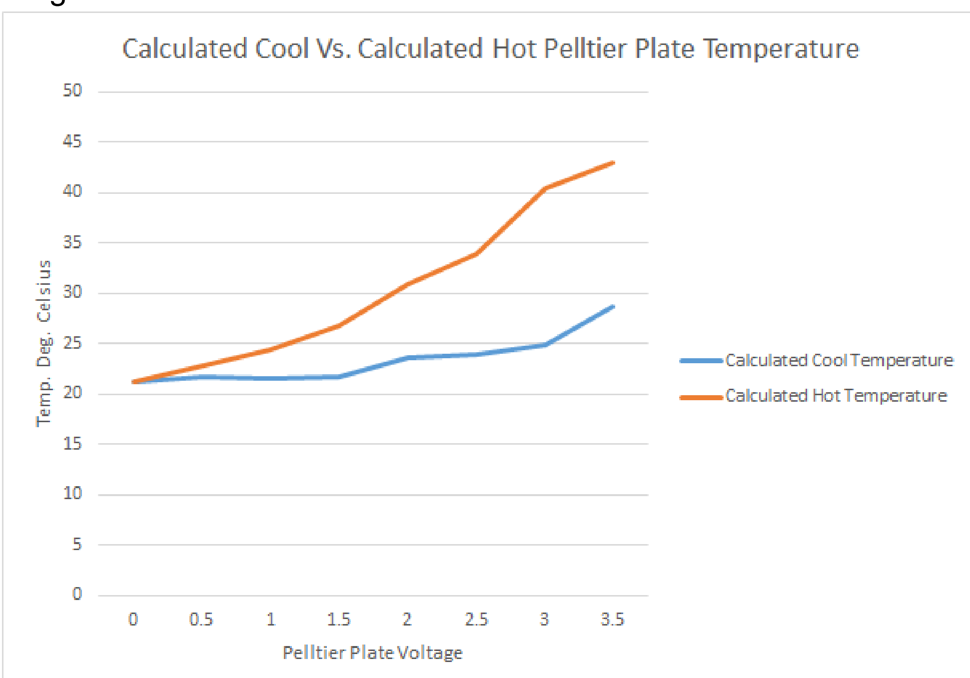


Figure 6.3.1.2:

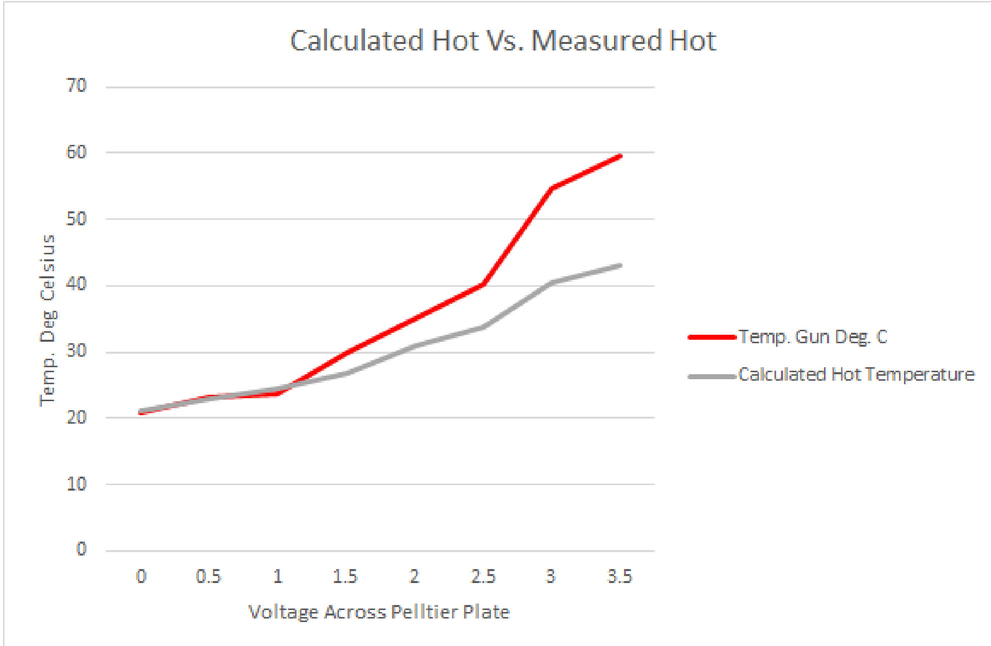


Figure 6.3.1.3

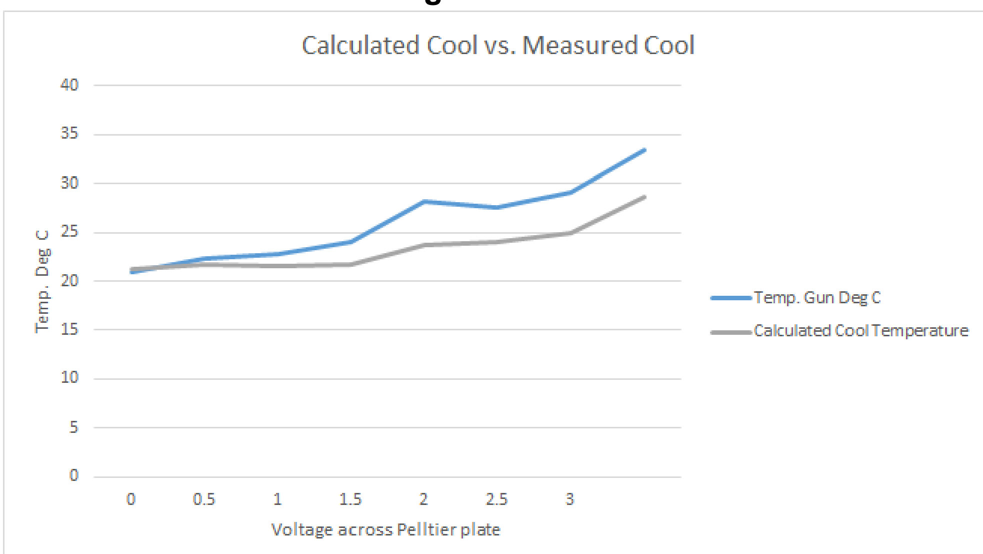


Figure 6.3.1.4

The calculated temperatures are from the temperature sensor output voltage. From the first graph comparing the cool side versus the hot side from the temperature sensor readings, there is a clear difference between the temperatures on the hot side and the cool side. This was the predicted relationship between the hot and cool side of the peltier plates, however there was an issue which can be seen when the peltier plate is being supplied 2 V. The issue recognized is that as the hot side gets hotter and hotter by increasing the voltage across the peltier plate, the cool side will also heat up. While the cool side remains at a lower temperature than the hot side, the heat on the hot side cause the cool side to stop becoming cooler than about 21 °C as seen on figure 6.3.1.2.

The second graph, figure 6.3.1.3, verified that the hot side continues to get hotter as the voltage across the peltier plate increases. The calculated hot temperature and the measured hot temperature show a slight discrepancy, where the temperature gun reads a higher temperature compared to the temperature sensor. This data was not seen as anything alarming, as the infrared sensor is extremely sensitive and will detect any heat dissipation coming off of the peltier plate which the temperature sensor does not pick up on since the temperature sensor is at one specific location on the plate. Since the plates were not the highest quality, they have different temperatures at different points on the plate. The nonuniformity of the peltier plates was not of any concern, as the plate still warms the surrounding environment to the temperature desired.

The third graph, figure 6.3.1.4, verifies the concern from figure 6.3.1.2. The data of the cool side of the plate from the sensors and from the temperature gun show that as the hot side gets hotter, that the cool side also warms up. This raised the question as to whether or not the cast should do both heating in cooling, because in order to cool the plate, the other side of the plate will always get hotter. One more attempt to see if the system could cool effectively was by integrating a thin metallic heatsink and thermal paste onto one side of the peltier plate. The goal is to see if the heatsink and thermal paste will create the cooling effect on one side while creating better heat dissipation so the cool side does not warm up when higher voltages are supplied to the peltier plates.

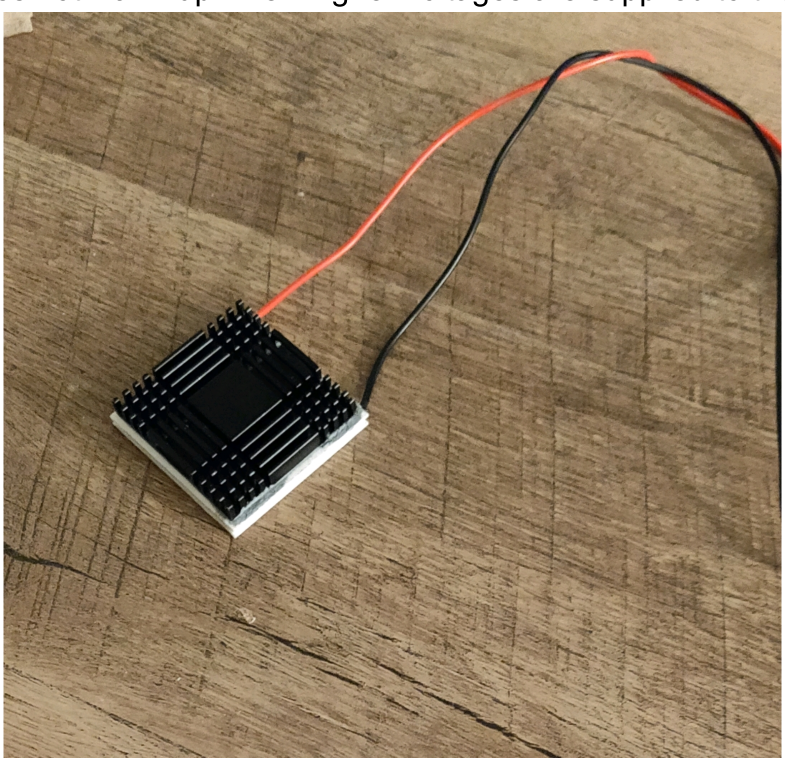


Figure 6.3.1.5: Peltier Plate with Heatsink and Thermal Paste

To test the effect of thermal paste and a heat sink, data was collected while passing current in one direction to cool the plate while increasing the voltage to record the data for cooling. The sensor was placed up against the cool side, which was the side opposite the side that had the heat sink and thermal paste. After collecting all the data for the cool side, the direction of the current was switched and data was collected while increasing the voltage across the peltier plate to observe how the heatsink and thermal paste impact the heating of the peltier plate.

Table 6.3.1.2: Peltier Plate and Sensor Data With Heatsink and Thermal Paste

Voltage of Pelltier plate	Cool Side Voltage Across Sensor (mV)	Calculated Cool Temperature	Temperature Gun Cool Reading (F)	Temp. Gun Deg C	Hot Side Voltage Across Sensor (mV)	Calculated Hot Temperature	Temperature Gun Hot Reading (F)	Temp. Gun Deg C
0	215.7	21.57	68.3	20.16666667	215.7	21.57	68.3	20.16666667
0.5	224.4	22.44	75	23.88888889	224	22.4	76.1	24.5
1	216.3	21.63	70.5	21.38888889	227.9	22.79	75.5	24.16666667
1.5	214.7	21.47	71.4	21.88888889	227.5	22.75	80.9	27.16666667
2	213	21.3	70.7	21.5	245.8	24.58	87.9	31.05555556
2.5	223.8	22.38	77.9	25.5	278	27.8	101.6	38.66666667
3	234.3	23.43	83.4	28.55555556	289.1	28.91	117.3	47.38888889
3.5	245.7	24.57	83.4	28.55555556	309.6	30.96	132.6	55.88888889

Initial data using the heatsink and thermal paste was recorded into table 6.3.1.2, where the data from the sensor was recorded as a voltage and then converted into a temperature, and the data from the infrared gun was recorded in degrees fahrenheit and converted into degrees celsius. The data was then graphed the exact same way is was graphed for the data without a heatsink and thermal paste.

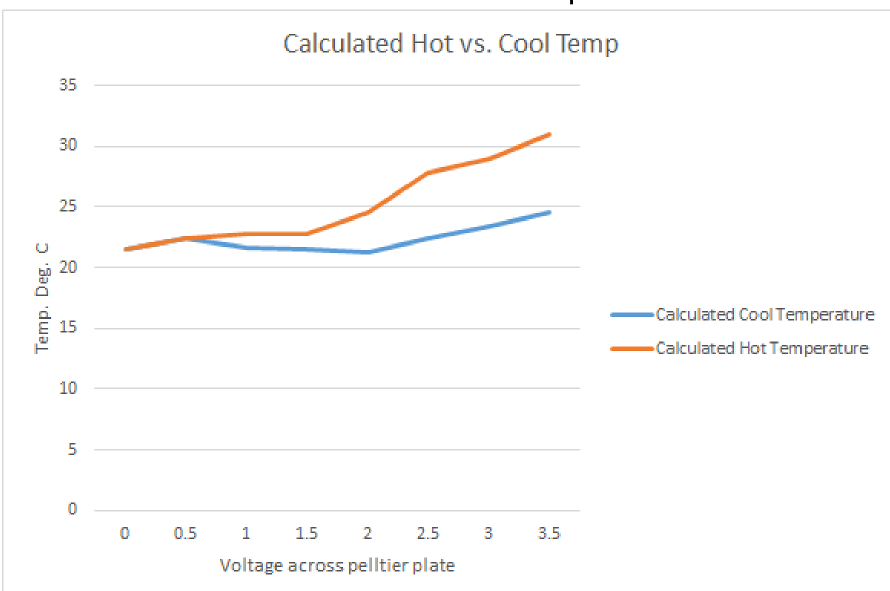


Figure 6.3.1.6

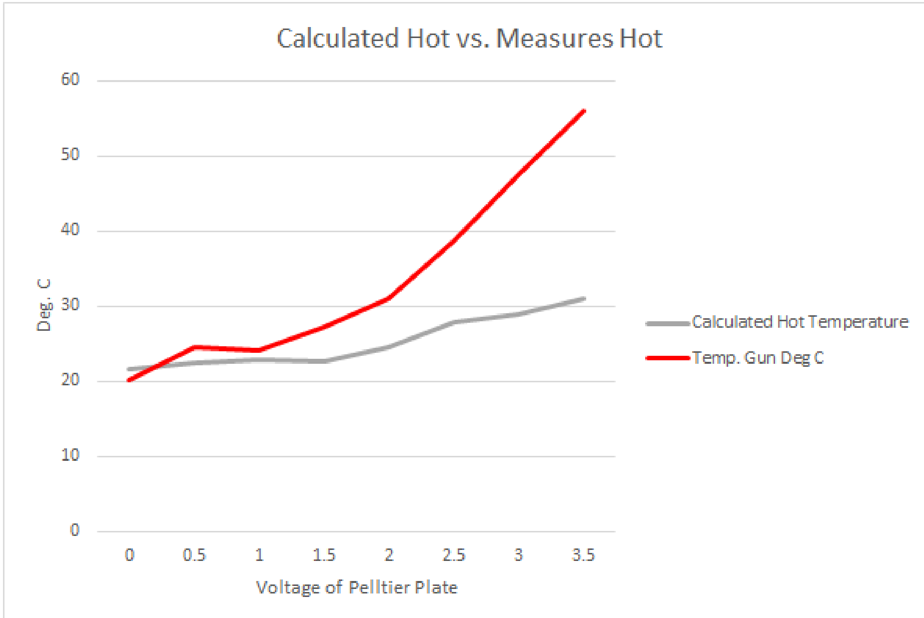


Figure 6.3.1.7

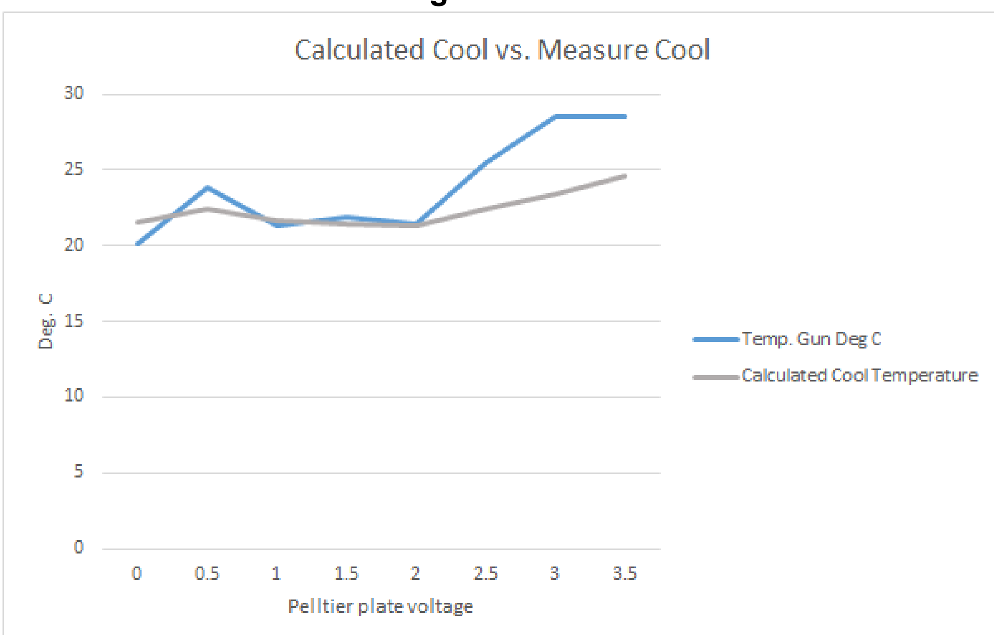


Figure 6.3.1.8

Upon data analysis, the same effect on the cool side was recognized. As seen in figure 6.3.1.6, as the hot side becomes hotter, the cool side also begins to heat up around 2 V across the peltier plate, even with the use of a heatsink and thermal paste. The only thing verified was that the heatsink thermal paste dissipate the heat better, which can be supported with figure 6.3.1.7. The graph shows that the infrared gun has a much higher reading compared to the temperature sensor. This occurs due to the same reason it does in figure 6.3.1.3, however when comparing the two figures, figure 6.3.1.7 shows the heat gun measured a higher temperature, which is due to the fact that the infrared sensor is sensitive enough to measure any heat dissipation. The increased heat dissipation when using the heatsink verifies that the heatsink allows for better heat dissipation. Unfortunately this was not the goal of adding the heatsink and thermal paste, the goal was to increase the cooling effect using the heatsink and thermal paste. Failure to improve the cooling effects of peltier plates resulted in the decision to only use the heating effects of the peltier plates. The cooling effects would not work, because in order to get the peltier plate cool enough to cause a dramatic change in the temperature, the hot side would also be hotter due to a higher voltage across the plate, which would only result in the cool side losing its cooling effect. It is not possible to cool the system, however it is possible and efficient to heat the system.

6.3.2- Peltier Plates

Table 6.3.2.1: Performance Specifications for Peltier Plates

Hot Side Temperature (°C)	25°C	50°C
Qmax (Watts)	50	57
Delta Tmax (°C)	66	75
Imax (Amps)	6.4	6.4
Vmax (Volts)	14.4	16.4
Module Resistance (Ohms)	1.98	2.30

The difficulty of using six peltier plates was finding a power source which would be able to supply enough current and voltage to all six peltier plates. With this challenge, there were a few options tested to power the plates including using one power supply, or using motor drivers. Each peltier plate operates from 0 V to 14.4 V for the desired temperature range set for the SmartCast, as seen in table 6.3.2.1. The final decision was to use three motor drivers to individually power each peltier plate, as seen in figure 6.3.2.1. The motor drivers were used instead of batteries because the motor drivers can vary their voltage output, versus a battery which would output a constant voltage to the peltier plates. The motor driver allowed for varying voltage across the peltier plates, which also allowed for the peltier plates to be set to a variety of different temperatures, since when you increase the voltage across the plate it will heat up, and when the voltage is decreased the plate will decrease temperature.

Figure 6.3.2.1: Motor Drivers for Peltier Plates

The challenge with having six peltier plates is avoiding overcurrent, which if there is not enough current being supplied to the peltier plates, the plates will not heat up. It is necessary for the design that the power supply being used supplies sufficient current to the plates so the plates will heat up to temperatures set by the user interface.

In the final design, the peltier plates were designed to heat up one at a time once a temperature has been set. This not only ensures that there will not be too much current drawn at once, it also ensures that each peltier plate is not going to somehow exceed the set temperature. Six yellow LEDs, as seen in the circuit in figure 6.3.2.2, would light up to indicate when a peltier plate was on, indicating current was successfully passing through that peltier plate. The integration of the LEDs was important, as it allows for troubleshooting the heating system anytime an LED does not light up. If an LED does not light up, this indicates that there is an issue with one of the six total peltier plates.

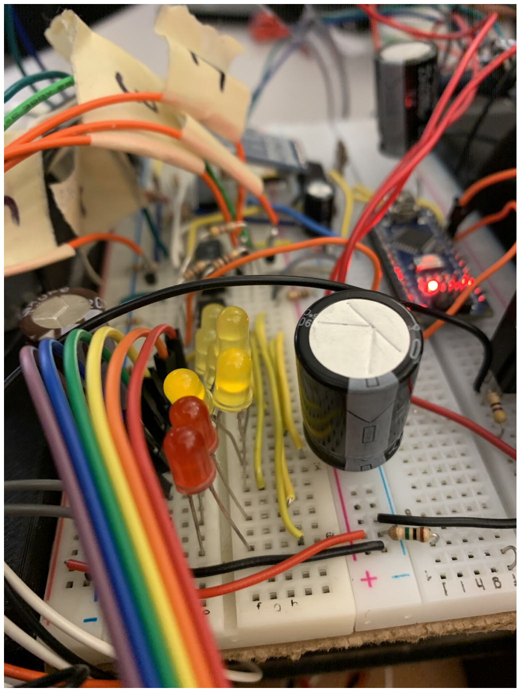


Figure 6.3.2.2: Yellow LEDs For Peltier Plates

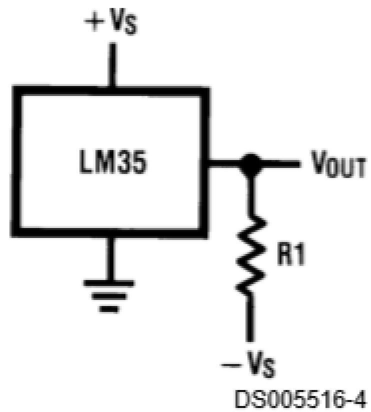
Figure 6.3.2.3: Peltier Plate Wiring and Placement in Exoskeleton

The assembly of the peltier plates into the final design was a design consideration determined by the shape of the exoskeleton. The exoskeleton was designed with slots to slide the peltier plates into place. This design was implemented to save space in the cast, so an arm can fit into the cast. The location of the peltier plates was originally going to be directly against the wearers skin, however with comfort, space, and safety concerns, the decision for the final design was to plate the peltier plates into the exoskeleton as seen in figure 6.3.2.3.

6.3.3- Temperature Sensors

When it came to collecting data about what temperature the peltier plates are, precision centigrade temperature sensor was chosen. Temperature sensors include thermistors, thermocouples, or a semiconductor-based sensor. The decision was to use a semiconductor-based voltage-temperature sensor because these sensors output a voltage which is linear with relation to the temperature. Acquiring linear data makes writing the code to control the peltier plates simpler, since the peltier plates also increase their temperature linearly to their voltage input. The temperature sensors chosen output 10 mV/℃, operate at a voltage from 4 -30 V, and will read temperatures ranging from -55 ℃ - +150 °C (refer to figure 6.3.3.1). For the project, temperatures will not exceed those of which can harm a human. Since the boiling point of water is 100 °C, the decision was to not exceed 40 °C to eliminate the potential risk for injury of a user to occur.

Another decision to make was whether or not to use only one temperature sensor or to use six. If one temperature sensor were to collect data from one peltier plate, it was appropriate to assume that all of the peltier plates were outputting the same temperature as the one peltier plate being monitored by the sensor. During testing, we tried using one sensor one one peltier plate, while powering all six peltier plates. What happens when one sensor is being used on one plate, the arduino will adjust the voltage going to all of the peltier plates to match the temperature which it was set to, and the sensor monitors that the set temperature was the temperature being outputted. By using one sensor with the six peltier plates, an infrared temperature gun was used to see what the other five peltier plates without sensors temperatures were. We discovered that when one single plate was being monitored by the sensor, the other five peltier plates also had the same temperature, meaning the arduino was properly adjusting the voltage across the six peltier plates and outputting the same temperature for all six peltier plates by using just one sensor.



Choose $R_1 = -V_S/50\ \mu A$

$V_{OUT} = +1{,}500$ mV at +150°C

$= +250$ mV at +25°C

$= -550$ mV at −55°C

Figure 6.3.3.1 : Full-Range Centigrade Temperature Sensor

Testing was also performed using six individual temperature sensors and six peltier plates, each having one temperature sensor. The results of this test were nearly identical to testing with one sensor, as we found that each plate was the proper temperature which it had been set at. The final decision was to use the six sensors to monitor each plate individually. This decision was made in order to completely verify that each plate was the proper temperature for safety purposes, because if one plate were to somehow exceed 40 °C , then the safety system would actively shut off the cast to ensure no potential injury or harm. Since each peltier plate heats up individually to prevent current overdraw, this also allows for monitoring of each individual plate as they heat up one at a time. Each sensor reads a slightly different temperature until the system has reached equilibrium. This poses a slight challenge when it comes to showing the user what the temperature of the cast is, so the arduino takes an average of all six temperature sensors and displays the average temperature on the user interface. This means that one pate may have heated up to the set temperature while the other plates have not reached the set temperature yet, so the user interface displays the average temperature and once all six plates reach the set temperature, the user interface will display the final set temperature.

6.4 Electronic Hardware

By: Wei Chen

6.4.1- Initial Circuit

Prototyping the first iteration of the circuit began with finalizing the components the system needed to function. They were six peltier plates, six temperature sensors, two motor pumps, and two pressure sensors. To control these components and place them in an appropriate feedback loop, the easiest solution was using an Arduino Nano to serve as a microcontroller. The six peltier plates and two motor pumps were connected to digital pins of the Arduino and the sensors were connected to the analog pins. Communication between the Arduino and the UI required an HC-05 bluetooth module, which were connected to the RX and TX pins.

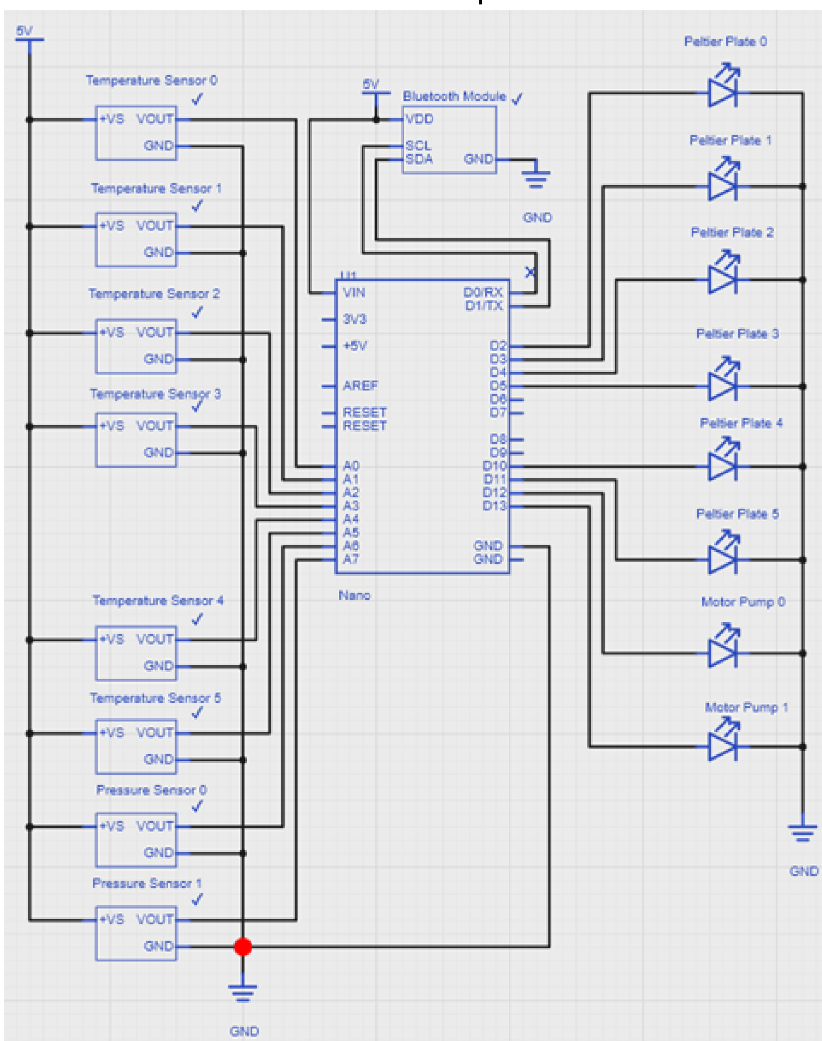


Figure 6.4.1.1: Circuit Diagram Sketch

6.4.2- Motor Drivers

This was a naïve approach as there were many factors left unconsidered. The first was the amperage requirements to run the peltier plates. When plugged into a DC power supply, each plate drew about 0.6A when running at 9V. The Arduino could only output a maximum of 40mA. So, motor drivers were placed in between the Arduino and the peltier plates/motor pumps. Each motor driver took four inputs to drive four outputs with each pair of inputs and outputs controlling forward or negative current flow for a single device. Because there were a total of eight output devices, four motor drivers were used. Three motor drivers controlled six peltier plates and the last controlled the two motor pumps. Each motor driver was powered by the same 9V source. An alternative design considered was using only one motor driver. The peltier plates would've been connected in parallel to one motor driver output, and the pumps in a similar function to the other output. That idea was discarded as it would not allow for individual devices to be on or off. Rather, it would mean either everything would be on or off at the same time. In the healing process heating and applying pressure in targeted areas is important, and only a modular circuit design allows for that.

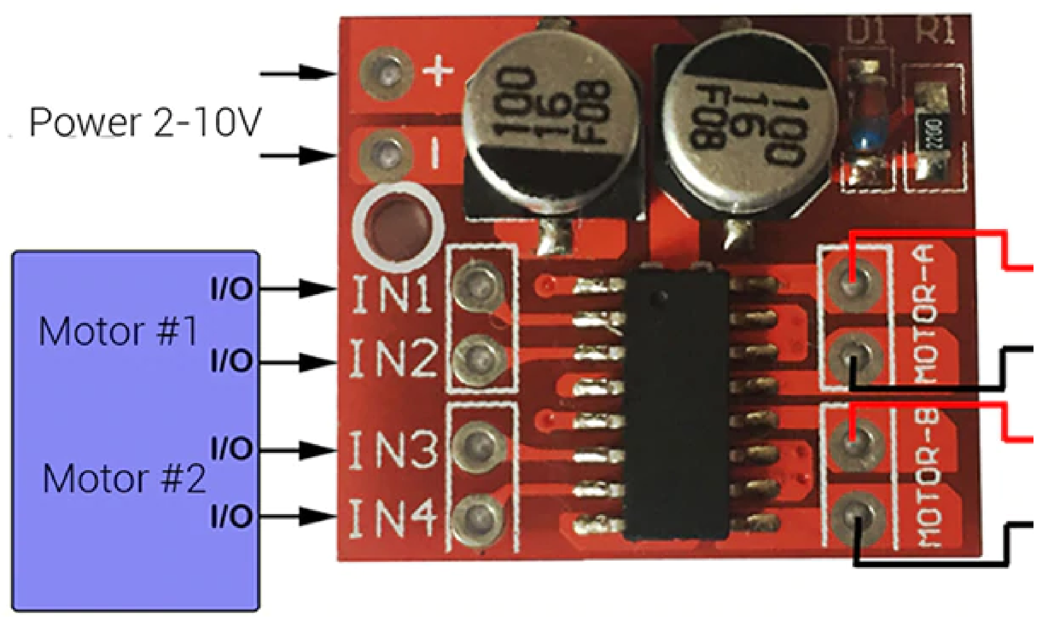
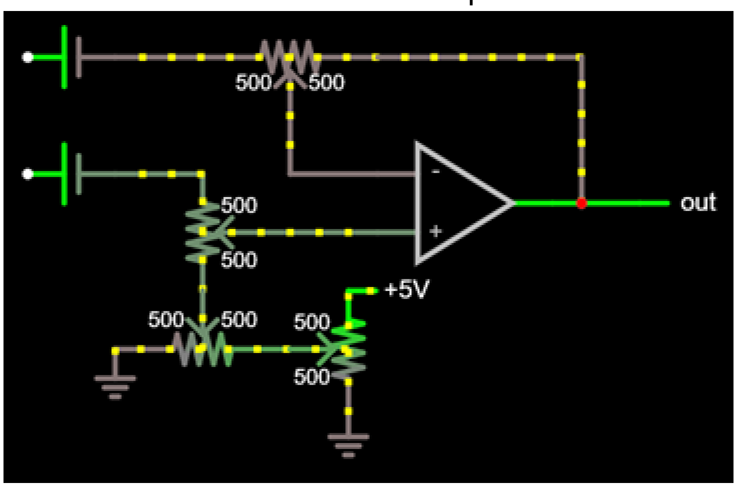


Figure 6.4.2.1: Motor Driver Pin Assignment

6.4.3.- Reading Sensors

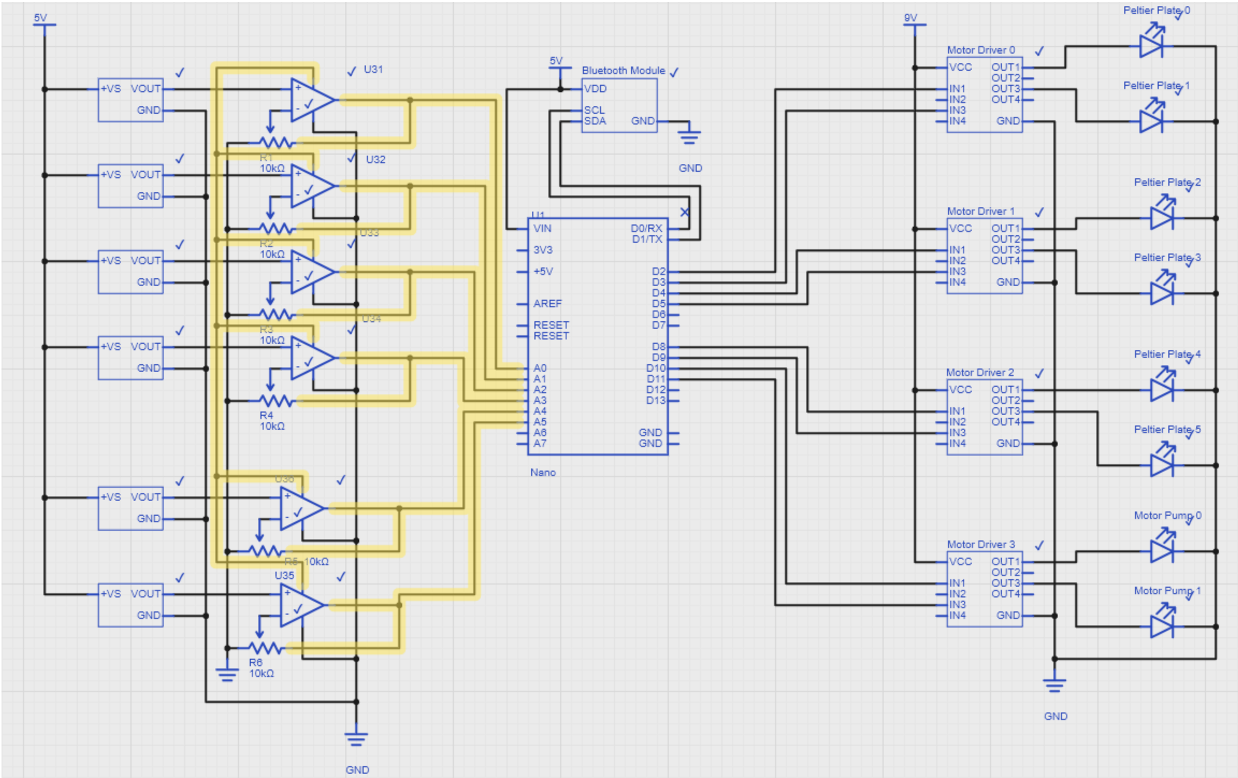
The next area of consideration was what outputs the sensors gave. The original assumption was the sensors would output a higher or lower voltage depending on if the temperature and pressure were higher or lower respectively. This was true for the temperature sensors but not for the pressure sensors. The pressure sensors outputted two voltages, and the difference between the two was the reading relevant to the feedback loop. A modified differential op-amp circuit was used to find the difference. Instead of using four resistors like in a normal differential op-amp configuration, two potentiometers were used instead. Additionally, a third potentiometer was connected in between the non-inverting input and its corresponding potentiometer. And a fourth potentiometer connected to that one. The first two potentiometers control the gain using the relationship $Vout = R3/R1(V2 - V1)$, where V2 and V1 are the two input voltages, R1 = R2, R3 = R4, R1 and R3 being the resistance values from the non-inverting side potentiometer, and R2 and R4 being the resistance values of the inverting side potentiometer. The two other potentiometers control an offset voltage. With the combination of the four potentiometers, it became possible to tune the resistance values until a voltage level the Arduino could read was outputted.



6.4.3.1: Differential Amplifier With Offset Adjustment Circuit

The ideal maximum voltage sent to the Arduino was 3.3V which would correspond to 2psi, a value 0.5psi above the safe pressure limit. After the potentiometer values were calibrated to achieve that value, their respective resistance values were recorded. Each potentiometer was then swapped out for resistors closest in value to the recorded ones.

To achieve a similar resolution to the pressure sensors, the output voltages from the temperature sensors had to be passed through a non-inverting op-amp circuit. Without a gain, the sensors output 10mV per degree Celsius. Using a voltage source of 5V to power the sensor, the maximum temperature reading would be 500 °C. Because a temperature of 40 °C was the maximum safety limit, a maximum possible temperature reading of 50 °C was set, as it would allow for room to maneuver in when testing the safety shutdown subsystem. Therefore, to go from a maximum temperature reading of 500 to 50, the gain of the op-amp circuit was set to 10.



6.4.3.2: Circuit Diagram with Temperature Sensor Gain and Motor Drivers

6.4.4- Shift Register and Multiplexer

After the first prototype for the safety shutoff subsystem finished, the Arduino no longer had enough analog and digital pins to accommodate all the inputs and outputs. To get around this, a shift register was implemented to send signals to all outputs to the motor driver, and an 8-1 multiplexer was implemented to read sensor data. This reduced the pins used on the Arduino to one-half of what was being used. More pins were saved when the second and third selector bits to the multiplexer were also used for the SER and CLK pins on the shift register. Depending on what type of sensor needed to be read, the multiplexer passed its output to two different places. If it was a pressure sensor being read, the output went directly to an analog pin on the Arduino as that output was already passed through an amplifier and its data already readable to the Arduino. If it was a temperature sensor, it was sent to a non-inverting amplifier and then passed to an analog pin on the Arduino. The shift register served as a demultiplexer and was functionally equivalent to having more digital pins on the Arduino. Another component added was a circuit designed to output a negative voltage to be used by the op-amps. Readings from the sensors were expected to go below 0V and pulled down further into negative voltage regions. To prevent losing information, a negative voltage source was required. A 555 timer was used to create a positive clock pulse voltage. It fed into two npn BJTs and then into two opposite facing diodes connected in parallel. This configuration produced a -4V DC output when given a +5V DC input.

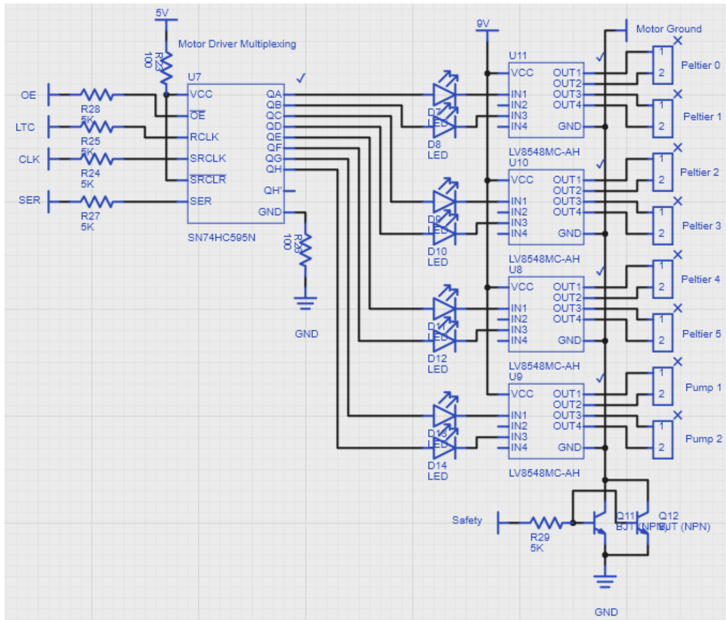


Figure 6.4.4.1: Shift Register Circuit

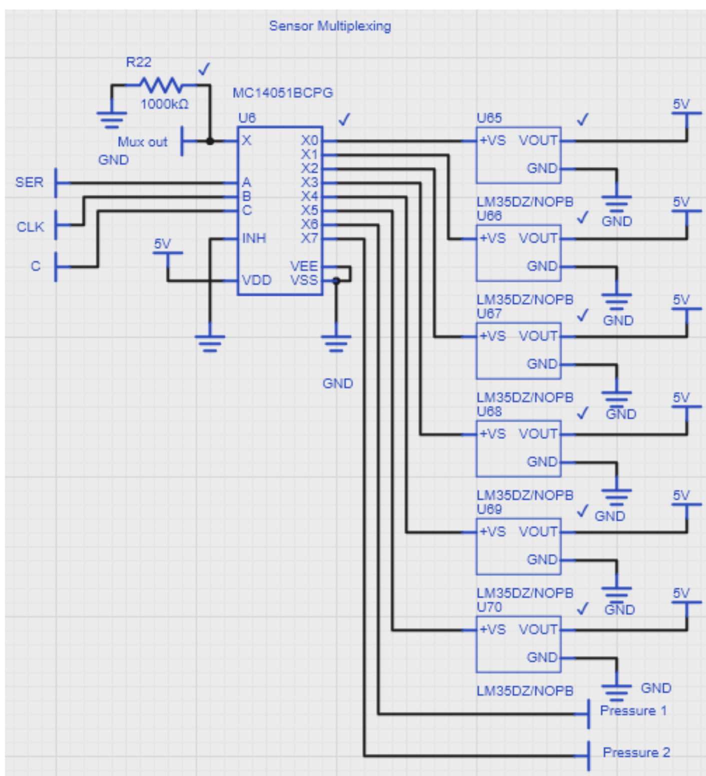


Figure 6.4.4.2: Multiplexer Circuit

With those changes, the circuit was complete in design and physical assembly began. The goal was to build it on a breadboard, debug, get the circuit functional then move the circuit to a perfboard.

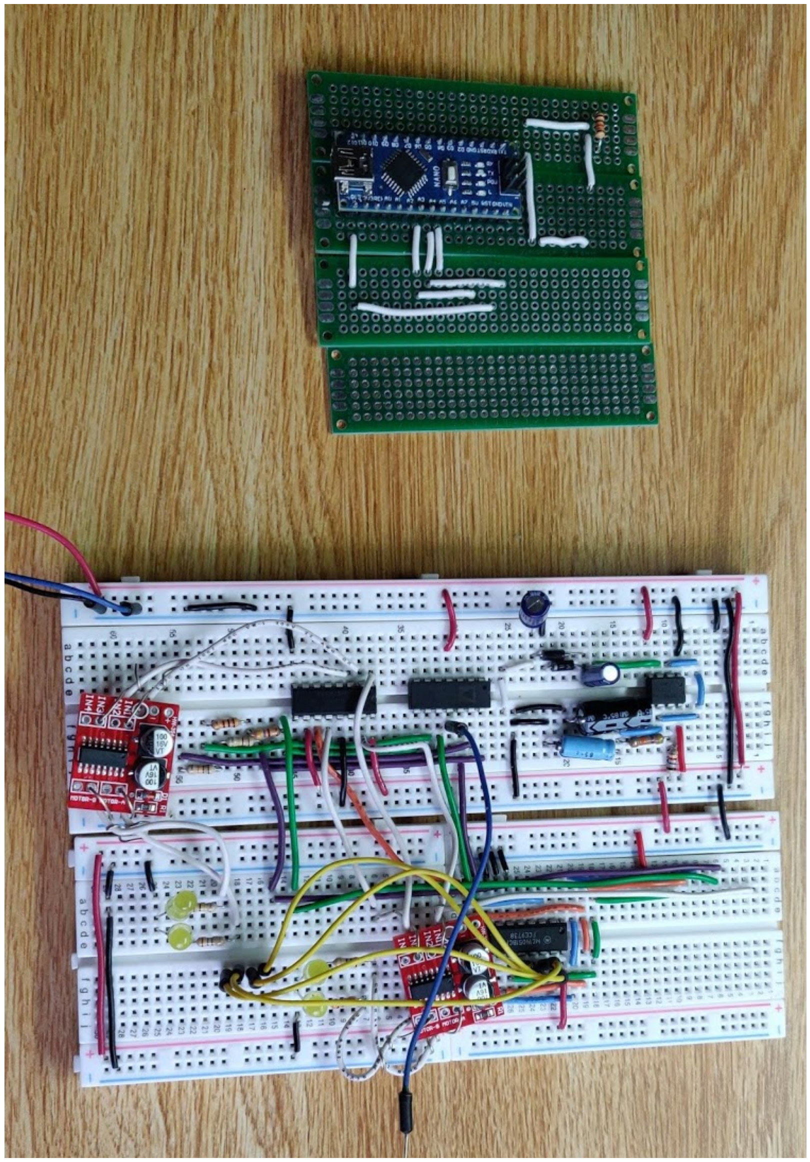


Figure 6.4.4.3: Breadboard Circuit and Perfboard Circuit

6.4.5- Physical Circuit Debugging

However, due to difficulty in debugging and of time constraints, the circuit stayed on a breadboard in the final version. The most glaring issue in the physical construction of the circuit was the amount of noise present in various places on the circuit. Decoupling capacitors quickly took care of that. But, there were still issues with improper circuit behavior even after the capacitors were placed in. Fluctuations in the amplified temperature sensor output that was assumed to be noise turned out to be a superimposed small signal sinusoidal wave generated by the IED shop's oscilloscope. A connection between the oscilloscope's ground with the rest of the circuit's ground mitigated some of the signal, but a small amount was still present. Scope measurements were moved to an Analog Discovery board to completely eliminate the problem. The next problem arose when the negative voltage generator was connected to the op-amp chip. Once connected, the negative DC voltage became a positive pulse voltage. That part of the circuit was scrapped and a 9V battery was used instead to generate the negative voltage. The last major setback was the poor quality of the motor drivers. Unused input pins were not completely isolated. Thus, current was able to flow through the motor drivers even when there should not have been. This caused damage to some of the ICs used because the unexpected current flowing through them was well past the threshold the chips were designed to handle. No changes had to be made to the circuit design because of this problem. However, all unused input pins on the motor drivers had to be grounded, and several components had to be replaced with new ones. After a few more small adjustments to the circuit, the debugging process was finished and full system test runs started. On demo day, the automatic temperature and pressure system performed almost identically to the test runs. There was a small hitch with one potentiometer that needed calibrating, but otherwise the circuit was fully functional.

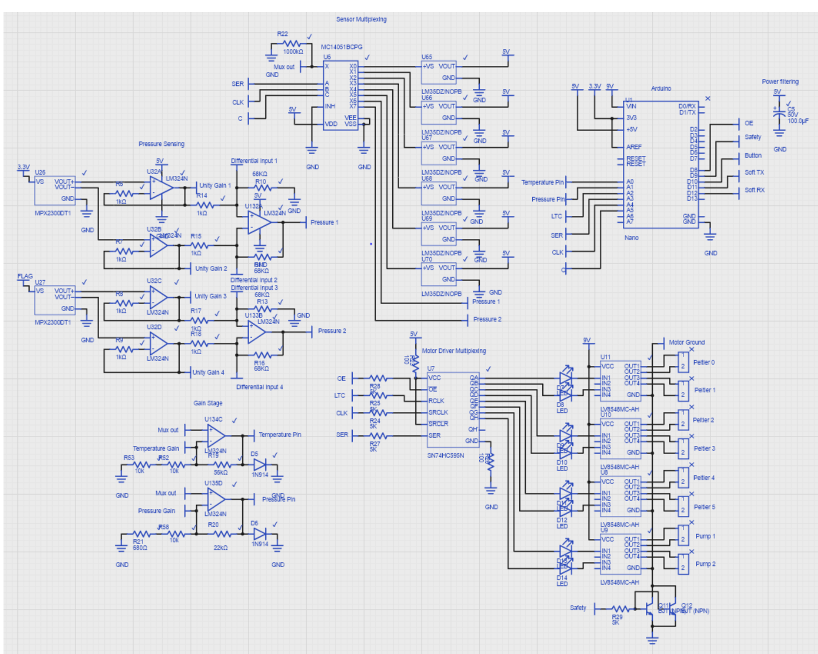


Figure 6.4.5.1: Finalized Circuit Diagram

6.5 Safety Shutoff

By: Thomas Ranney

6.5.1 Overview

As the whole goal of this project is to expedite the healing process, it would not be beneficial to have the user further injure themselves while using it. To ensure this, the temperature and pressure subsystems would have to have a cap on the maximum values that they could output to protect the customer. This would be accomplished by reading the data from each temperature and pressure sensor and outputting voltage accordingly. In addition to this, there would be 3 seperate layers of security around the safety shutoff to ensure that it would not fail, one coded into the arduino, a button on the circuit itself so that the user could manually shut off the power, and one on the user interface. To achieve this, a N-channel MOFSET would be placed between the motor drivers and ground, with the input that switches it on and off.

6.5.2 Initial Design

For the initial design, a MOSFET would be used as a switch to supply power to the motor drivers.Many different switched were considered but the IRF510 MOSFET would be chosen. Its pin out and datasheet is displayed below.

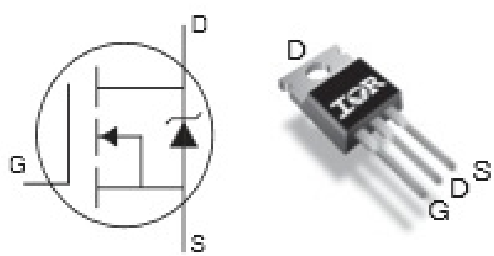


Figure 6.5.2.1 IRF510 Schematic

ORDERING INFORMATION INFORMATION	
Package	TO-220AB
Lead (Pb)-free	IRF510PbF
	SiHF510-E3
SnPb	IRF510
	SiHF510

ABSOLUTE MAXIMUM RATINGS (T_C = 25 °C, unless otherwise noted)

PARAMETER			SYMBOL	LIMIT	UNIT
Drain-Source Voltage			V_{DS}	100	V
Gate-Source Voltage			V_{GS}	± 20	
Continuous Drain Current	V_{GS} at 10 V	T_C = 25 °C	I_D	5.6	A
		T_C = 100 °C		4.0	
Pulsed Drain Current [a]			I_{DM}	20	
Linear Derating Factor				0.29	W/°C
Single Pulse Avalanche Energy [b]			E_{AS}	75	mJ
Repetitive Avalanche Current [a]			I_{AR}	5.6	A
Repetitive Avalanche Energy [a]			E_{AR}	4.3	mJ
Maximum Power Dissipation	T_C = 25 °C		P_D	43	W
Peak Diode Recovery dV/dt [c]			dV/dt	5.5	V/ns
Operating Junction and Storage Temperature Range			T_J, T_{stg}	-55 to +175	°C
Soldering Recommendations (Peak temperature) [d]	for 10 s			300	
Mounting Torque	6-32 or M3 screw			10	lbf · in
				1.1	N · m

Figure 6.5.2.2 IRF510 Datasheet

The IRF510 could handle the large amount of amperage that would be passed into it by the motor drivers, thus why it was chosen. To set up a N-channel MOSFET as a switch, the drain pin, D, needs to be set up to the negative 12 volts that power the motor drivers, the source pin, S, is connected to ground and the gain pin, G, is connected to the arduino. A simulation showing this layout is shown in figure 6.52.3 below. The arduino either outputs 0 volts if either the pressure or temperature exceeds the target values of 40*C or 1.5 psi, or the button on the user interface or circuit is pressed. If none of these occur, it outputs 5 volts. Figure 6.52.4 shows the output of the arduino below. When the arduino outputs a low voltage, 0 volts, the connection to ground is interrupted and the motor drivers can not supply voltage to the peltier plates and air pumps.

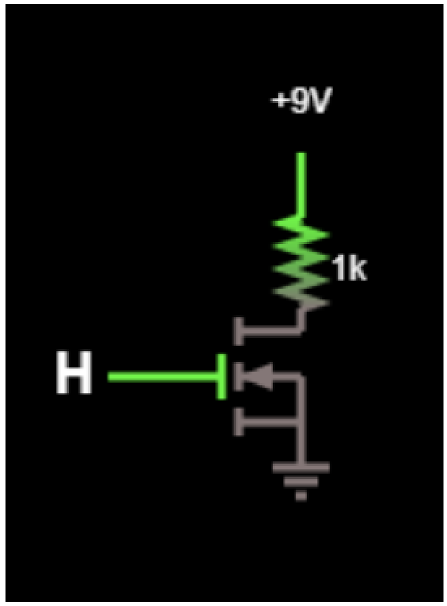


Figure 6.5.2.3 Simulation

Table 6.5.2.4 : Output from Arduino

Condition	**Output From Arduino**
Temperature < 40*C	5V
Temperature >= 40*C	0V
Pressure < 1.5 psi	5V
Pressure >= 1.5 psi	0V
Button Depressed	0V
Button Raised	5V

To test this layout , circuit similar to the one in the simulation was used, but an LED was used in place of the motor drivers. The test circuit was tweaked depending on whether the LED turned on or not, until the desired result was obtained.

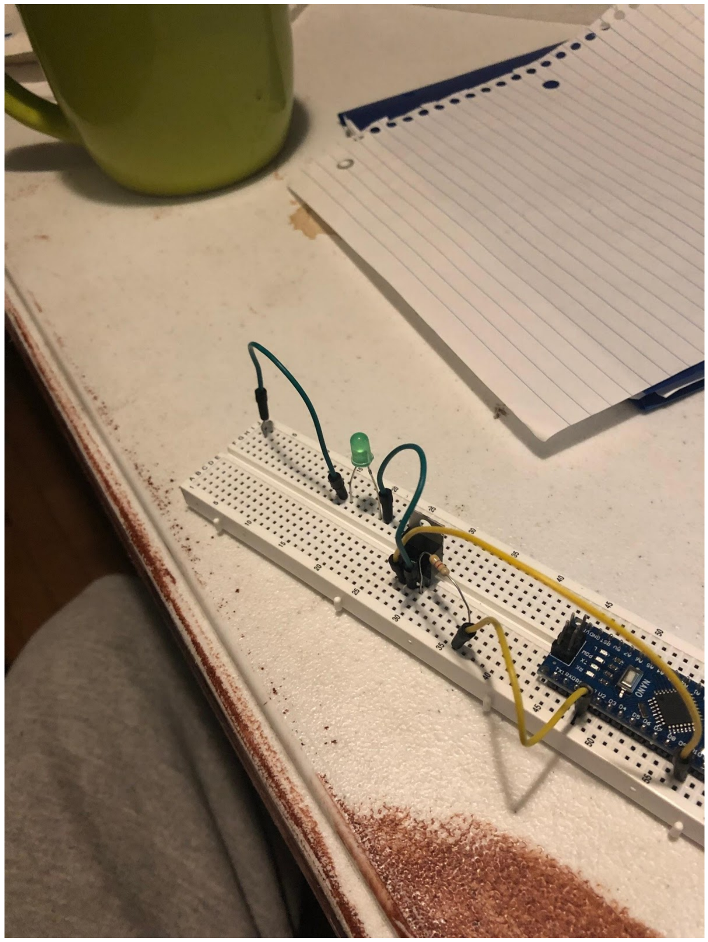


Figure 6.5.2.5 Test Circuit

6.5.3 Emergency Button

In case of the automatic shutoff with the arduino not working, a failsafe emergency button was implemented. It was important to have this hardwired into the circuit in case anything failed with the arduino. To achieve this, a button was soldered with 2 wires and inserted into the circuit board. Along with this code had to be written to correspond with the output as described in figure 6.52.4 above. If the button is pressed, the arduino would output 0 volts and stop the motor driver from powering the peltier plates and air pumps. The button and the code are shown below in figures 6.53.1 and 6.53.2 respectfully.

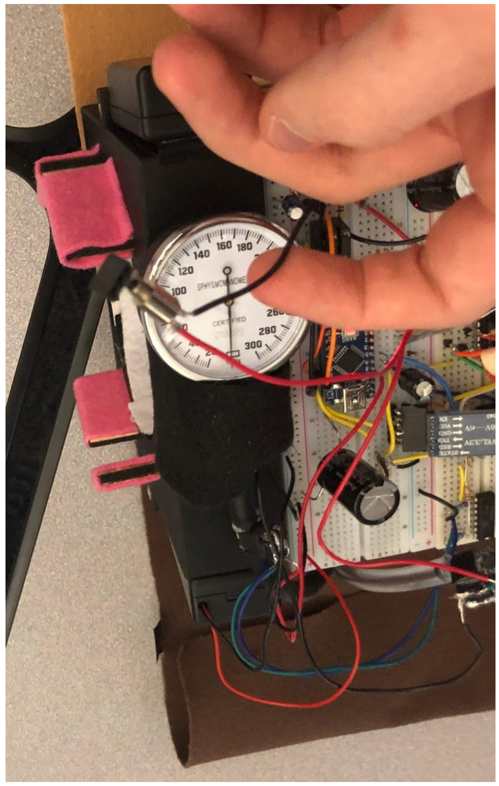


Figure 6.5.3.1 Button

```
    }
  }
  pinMode(11,INPUT);//input pin for the button
  val = digitalRead(11);
  if(val == LOW)//button is pressed
  {
    digitalWrite(12,LOW);//open switch
  }

}
```

Figure 6.53.2 Button Code

6.54 Challenges and Redesign

The main challenge with implementing the safety subsystem came with testing the circuit in the complete project. When the original IRF510 MOSFET was placed into the circuit, it originally worked as planned. When the temperature sensors read a value out of the given range from 0 - 40 degrees celsius, the arduino output 0 volts and interrupted the connection to ground. An unforeseen challenge however was the fact of the reverse polarity that occurs when the motor driver's connection to ground is interrupted. There was a large amount of current that went back into the transistor and motor driver, but power was killed before any electronics were damaged. To combat this, the MOSFET that was used and the layout of the circuit were both changed. Firstly, the IRF510 was replaced with the d1266 N-channel MOSFET. The pinouts for both were the same, but the d1266 could handle more current than the IRF510. Furthermore the layout was switched from 1 MOSFET to 2 in parallel with each other. The idea behind this was to reverse the reverse polarity caused by interrupting the connection to ground. After this change was implemented the subsystem worked exactly as specified.

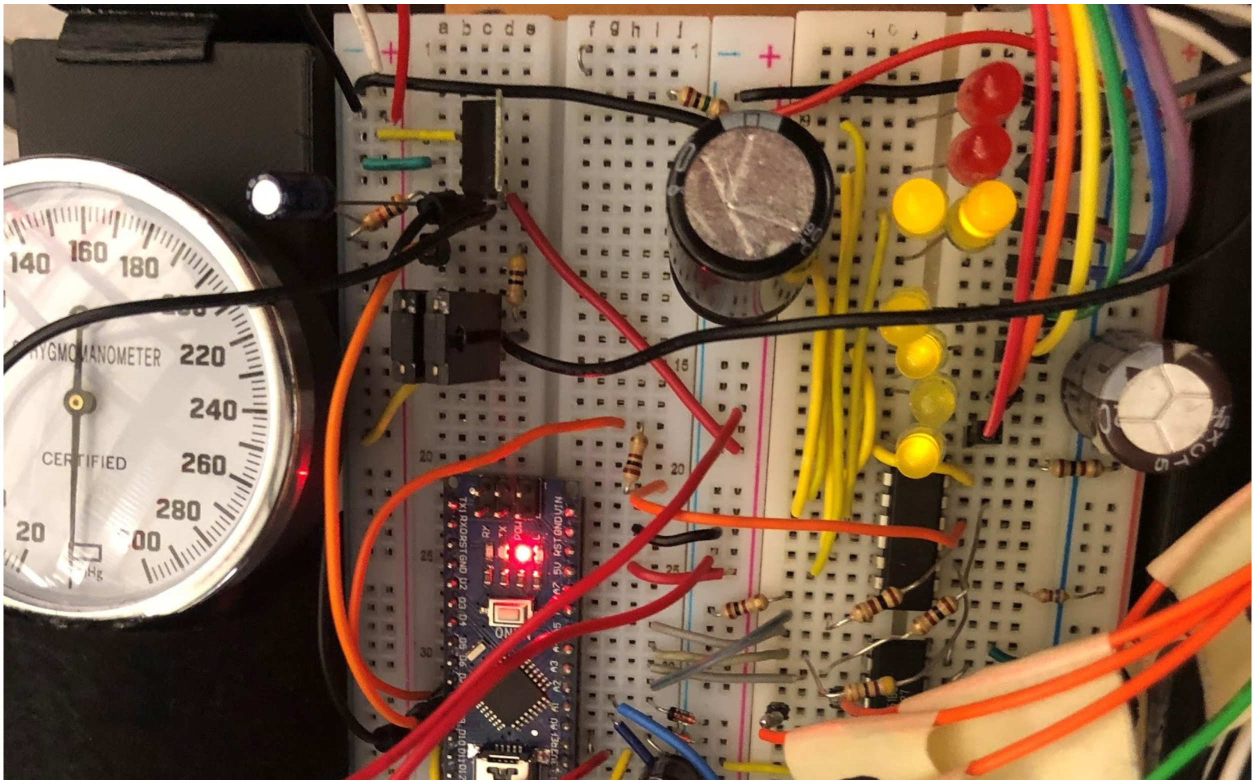


Figure 6.54.1: Updated switch

6.6 Software

By: (Charles Pike)

The software running on the microcontroller is the brain of the device. The software, running on an ATMega328p microcontroller, is written in Arduino, a variant of C++ optimized for use on CPUs with limited speed and memory. It coordinates inputs and outputs, necessary for all other subsystems that rely on electronics. Just as the device can be divided up into subsystems, software itself can be divided up into several algorithms. User input and output, as well was input and output to the rest of the electronic hardware, have algorithms for control.

6.6.1 Command Line Interface

One of the most important forms of input to the system is human input. Since a hardware-based user interface consisting of, for example, an LCD and button array, would be beyond the scope of this project, serial communication was used as the medium for communicating between the microcontroller and other computational devices. Arduino-compatible microcontrollers typically communicate using UART, including both hardware serial ports useful for communication with a USB controller, as well as software-defined serial ports, allowing communication with as many other devices as the pin count allows, such as, in this case, a bluetooth module, and there are similar libraries to manage either.

Figure 6.6.1.1: Flowchart of algorithm for commands

The command line algorithm stores the command in a string, one for each serial connection. The string can be dynamically concatenated and erased as new data comes in. A “start of command” character erases the command and starts new, an “end of command” character sends the command to the parser, and all other characters are concatenated to the command, though anything besides capital letters and numbers are invalid. The inclusion of start and end characters vastly simplifies the computational overhead of interpreting commands, as well as compensating for erroneous characters.

The parser works by simply checking the characters in a command one by one and evaluating which function it corresponds to. The parser then uses this to either change the state of the system, or return a string that will be sent by the serial back to the connected device that the command came from. This allows a human user typing into a terminal or a serial-connected device to both request data about the state of the system, as well as to request changes to state of the system. This framework lays the foundation for the user interface, as well as making virtually any debugging possible.

Table 6.6.1.2: Set of valid commands

Command	Usage
PING	MCU replies PONG to affirm connection
GT	MCU replies with average temperature
GP	MCU replies with average pressure
CT	MCU replies with temperature setting
CP	MCU replies with pressure setting
STij	MCU changes temperature setting to ij^{0}C
SPij	MCU changes pressure setting to i.j PSI
OFF	MCU shuts off all actuators
ON	MCU turns allows actuators to turn on
M	MCU prints readings from individual sensors

6.6.2 Data Acquisition

The ability of the microcontroller to regulate the temperature and pressure is heavily dependent on the ability to make accurate measurements from those systems. The external circuitry does most of the heavy lifting, scaling and offsetting raw readings from the sensors so that the data is more readable to the microcontroller. An analog to digital converter is used to interface the external circuitry with the code, and a simple subroutine is used throughout the code to take readings from all 8 sensors.

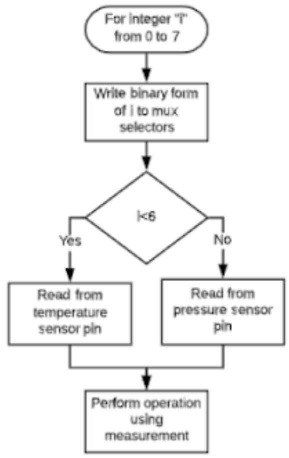


Figure 6.6.2.1: Flowchart of archetypical analog input

6.6.3 Peripheral Control

With only inputs and UART outputs, the software would be capable of little more than a data logger or compound sensor. A rigorous system to control the outputs to heating and temperature is paramount to the functionality of the software. The primary method of control is by using a synchronous serial data stream to a shift register, turning 4 pins on the microcontroller into 8.

This is one of many instances in the code that makes use of the measurement subroutine, using measurements from the sensors to adjust the output. The method for regulating the peltier plates and pumps, the "actuators", can be thought of similar to how one might play the now-classic video game "Flappy Bird". There is a narrow target range that must be achieved: active pulses increase the level, and the level passively decreases. Thus, by turning an actuator on when the respective sensor is too low and turning it off when to high, an adequate response time guarantees that the value will be well-regulated.

Because of the innate limits of a real rather than ideal DC power source, the amount of power required to turn all actuators on simultaneously is too high to be supplied by a battery or even some DC power supplies. However, once the desired values are reached, the power consumption decreases considerably. Therefore, an algorithm was implemented to stagger the most power-consuming actuators, keeping the current draw while the values of pressure and temperature climb to desired levels.

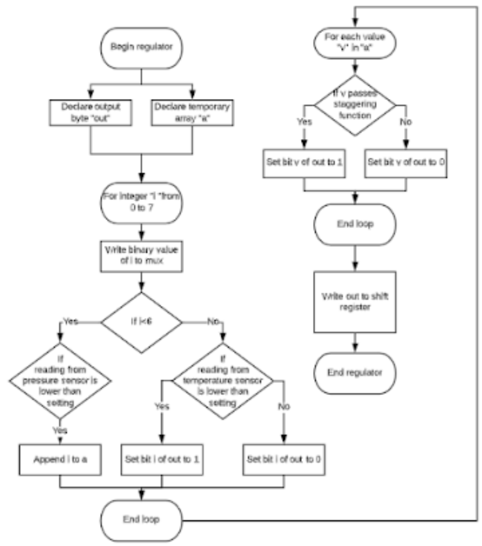


Figure 6.6.3.1: Flowchart of algorithm used to control peltier plates/ pumps

6.6.4 Testing

It is nearly impossible to characterize the effectiveness of software in a vacuum. Doing so is akin to evaluating the mental faculties of someone who is blind, deaf, and paralyzed, but nonetheless conscious. Just as the appendages of eyes, ears, mouth, and hands are necessary for the full range of communication with a person, the software can only be judged by the result produced on its output peripherals as a function of data from its input peripherals. Therefore, the technical specifications and testing of the software are measured as the outputs on other subsystems.

Because the inputs and outputs of the software are so heavily integrated with other subsystems, the only effective way to gauge the effectiveness of the software is to measure its effects on the other subsystems. The software needs hardware to work, and the hardware needs software to work. For preliminary, pre-assembly testing, a simplified circuit can be constructed as a crude proxy. However, any comprehensive test of the software is also a test of each electrically connected hardware system.

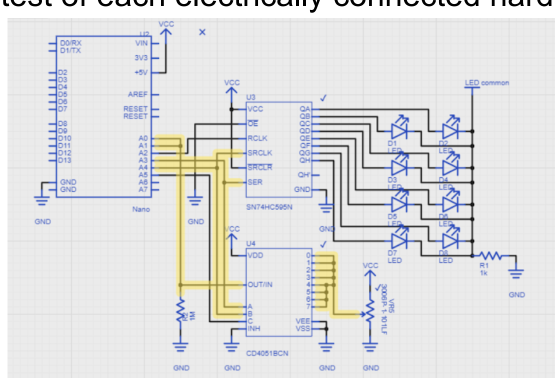


Figure 6.6.1: Example of a circuit used for testing

6.7 User Interface

By: Cynthia

6.7.1 Overview

The user interface for this smart cast system is a phone application on an Android device. The purpose of this subsystem is to make the users feel convenient under a controlled healing environment. The data displayed in this subsystem heavily relied on the electronic hardware and the software. If these two systems failed, this subsystem would not work properly at all. The online platform used for developing this phone application is called the MIT App Inventor. The other platforms which have been considered are Adobe XD and App Builder. Eventually the MIT App Inventor platform was selected because it is the fastest and most convenient platform to create an app for Android and it works with the Arduino of the software subsystem very well. The design for the user interface is mostly based on making it convenient for the users with clear instructions.

There are two screens for the user interface. The background for the screens is chosen to make users more comfortable and have a good mood when using the user interface. The purple city and moon theme gives people a little comfort when looking at it. The first screen is the main screen which users are able to read data of the cast, shut off the cast, and gets redirected to the help and support webpage. The top of this screen includes two important instructions for the users bolded in red. In this main screen, the most important function is reading the temperature in either degrees Celsius or Fahrenheit and pressure in psi. This function will work only if the users connect their phone to bluetooth. Other than that, the emergency shut off button can be used if the user wants to shut off the device at any time. When the shut off button is clicked, the Arduino will shut off the heating and the pressure systems immediately. If the users have any questions or concern about this device, they can click on the help and support button at the bottom of the screen to get to the website to obtain more information. The figure below is the layout of the main screen:

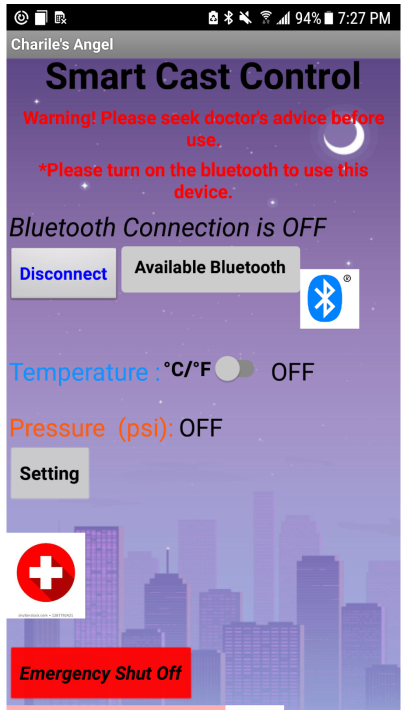


Figure 6.7.1.2: Main Screen of the User Interface

The second screen is the setting of the smart cast system. The users are able to set whatever temperature and pressure they want to. However, there is a range for both the temperature and pressure. The range for temperature is 21 to 40 degrees Celsius. The range for pressure is 0 to 1.5 psi. These ranges are displayed on this screen to remind the users to set within range. In addition, the users are able to switch the temperature mode between Celsiuis and Farenheit. If the temperature and pressure are over the threshold, 40 degrees Celsius and 1.5 psi, the safety system will be triggered and the screen will display “Error” in the readings. The figure below is the layout of the setting screen:

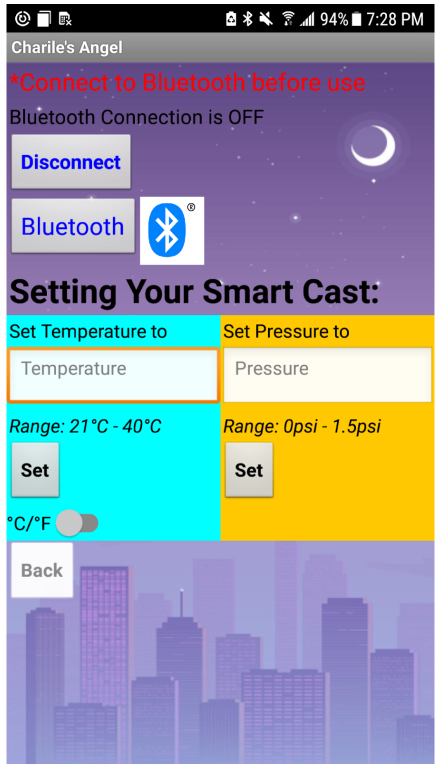


Figure 6.7.1.2: Setting screen of the User Interface

6.7.2 Technical Specifications:

The most significant technical challenge in this subsystem is the communication between the HC05 bluetooth module and the phone application. Both the phone application and the bluetooth module are sending bytes of text with an opening and closing brackets to each other for communication. The following table shows the commands signaling what kinds of action from the phone to the bluetooth module and from the bluetooth module to the phone:

Table 6.7.2.1: The Commands for Communication Between the Bluetooth and the Phone Application

Commands	***Meanings***
[GP] (phone to bluetooth)	a command sent by the phone to tell the Arduino to send pressure data
[GT] (phone to bluetooth)	a command sent by the phone to tell the Arduino to send temperature data
[TX1X2] (bluetooth to phone)	a command sent by the Bluetooth to tell temperature. X1,X2 are the two digits of the temperature data
[PX1X2] (bluetooth to phone)	a command sent by the Bluetooth to tell pressure. X1,X2 are the two digits of the pressure data multiply by 10
[CTX1X2] (bluetooth to phone)	a command sent by the Bluetooth to the phone to confirm temperature set by the user. X1 and X2 are the 2 digits of the temperature value
[CPX1X2] (bluetooth to phone)	a command sent by the Bluetooth to the phone to confirm pressure set by the user. X1 and X2 are the 2 digits of the pressure value
[OFF] (phone to Bluetooth)	a command sent by the phone to the Bluetooth to tell the Arduino that an emergency shut off is activated
[EX] (Bluetooth to phone)	a command sent by the Bluetooth to the phone to tell the phone that there is an error and the heating and pressure systems are being turned off

This leads to another technical challenge is the coding part of the user interface. The user interface has to interpret the commands sent by the Bluetooth and respond in the correct way. The coding of the user interface is done by using the style of block programming. The data is being read one byte by one byte. The opening bracket indicates the start of the text and the closing bracket indicates the end of the test.

6.7.3 Testing:

For an initial testing on the Bluetooth programming, a prototype app is created. This prototype is used to test sending and receiving data from either end of the phone and the Bluetooth. This prototype can send the text written by the user on a textbox to the Bluetooth and display sent data from the Bluetooth. The screen for this prototype is on the figure below:

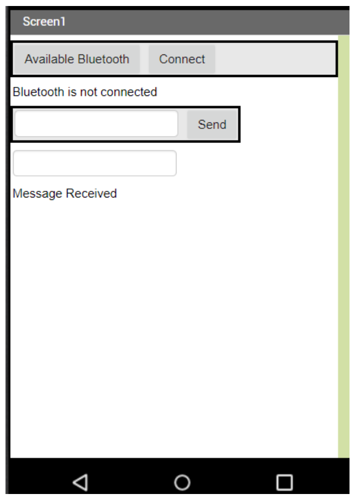


Figure 6.7.3.1: Screenshot of the testing app.

A very simple program was written on the Arduino to test the communication. The Arduino will receive data from the Arduino and print out the data on the computer terminal and it will send data to the Bluetooth so that the phone is able to receive that data. After it is being integrated into the system, it will display temperature and pressure data from the Arduino and send data to the Arduino to set the heating and pressure systems. A prototype circuit is built to test the user interface with the hardware and software system.

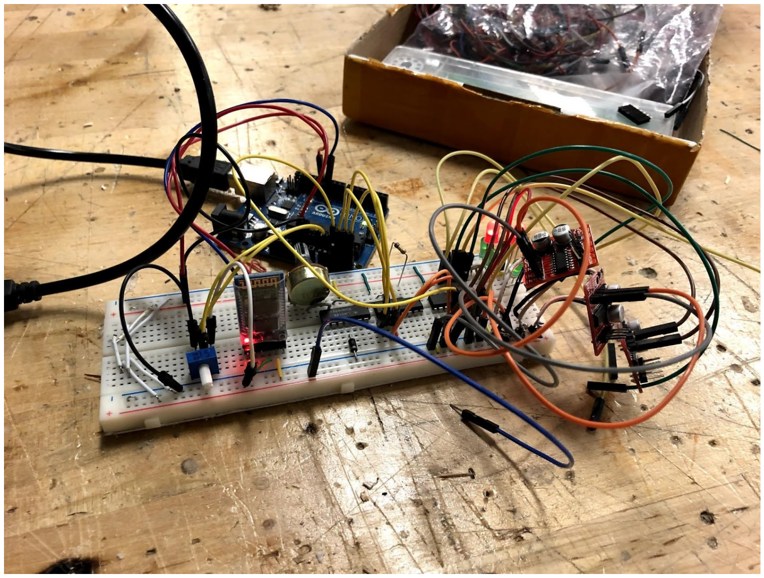


Figure 6.7.3.2: The prototype circuit which simulates the whole system

7 Results and Discussion

By: Cynthia Li

7.1 *Results*

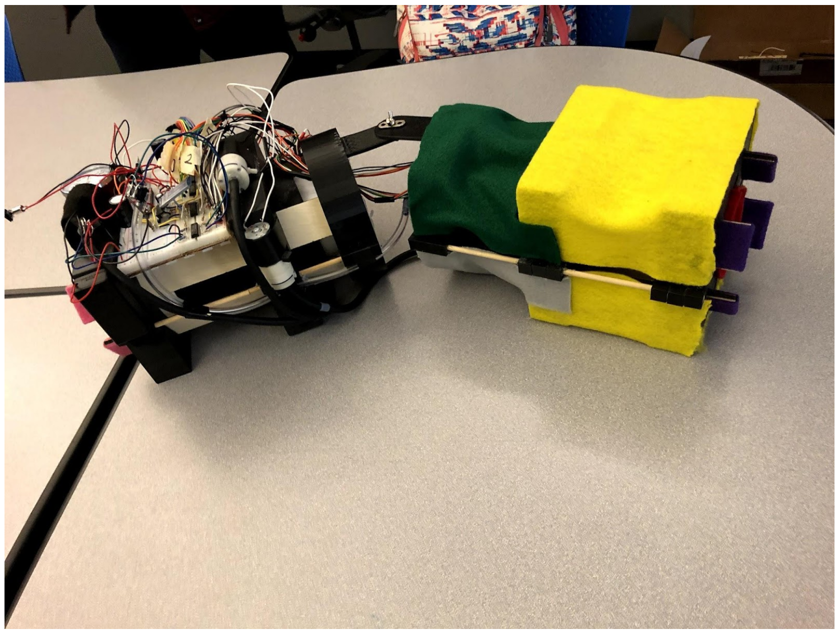


Figure 7.1: The final design

The results of the final design align with the specifications that the team had set. The prototype is working according to the expectations of the team.

7.1.1 Testing

Testing is being discussed thoroughly in the section of the subsystems. Because of this, this section will give a summary on testing and the results. Even though the team had done many testings, not all of the result data were documented. For testing the hardware, the team used the DC power supply and Analog Discovery. A serial connection is used to print out the values read by the sensors on the computer. Since the heating and pressure systems needed and performed a significant amount of testing, the following part will cover briefly on the testing being done on these two systems.

The first test is being done on the heating system to see if heating and cooling can be done at the same time efficiently. This test is written in more detail in Section 6.3. The team member used the 5V DC power generator of the Analog Discovery. In the range from 0 - 5 V, the voltage is increased by 0.5 V each time. The Peltier plates are being heated up as the voltage increased. The Analog Discovery showed the voltage received from the temperature sensors, which was the accurate temperature. Next, the heating system is being tested with the Arduino to display data on the computer screen. The table below shows the testing data of the heating system with the Arduino.

Table 7.1.1.1: Test Data of Heating Subsystem using Arduino and Code

Heat Gun	Arduino	Analog Discover (V)	Analog Discovery Temperature
23.7°C	23°C	2.401	24.01°C
20°C	20°C	2.107	21.07°C
24°C	25°C	2.527	25.27°C
28.8°C	29°C	2.863	28.63°C
31.2°C	31°C	3.342	33.42°C
37°C	35°C	3.515	35.15°C

The result of the testing was that the cool side was reading inaccurate temperature but the hot side had accurate temperature data. The decision was made to get rid of cooling from the heating system. Therefore, the range of the temperature value is from room temperature to 40°C. The heating system is being fully tested before it was being integrated into the whole system.

For the pressure system, there were two choices for the pumps: the vacuum pump and the diaphragm pump. Both of the pumps are being tested to see which one has more efficiency. As a result, the vacuum pump is chosen because it has a significantly faster flow rate (4.5L/min) than the diaphragm pump (0.8 L/min). Even though the vacuum pump had air leakage during testing, this problem was addressed by calibration on the software code and the hardware circuitry. The testing for pressure sensors was also a crucial part for the pressure system. The team chose two of the pressure sensors which performed the best on testing, which they read in accurate pressure values. The average of the values read by these two pressure sensors was an accurate reading displayed on the user interface. The following data shows the testing results for one of the pressure sensors.

Table 7.1.1.2: Test Data for the pressure sensor used

voltage (mV)	analog reading (mmHg)	duty cycle (%)
9.05	30	20
10.7	36	25
11.8	40	30
12.7	44	35
13.3	46	40
14	48	45
14.4	50	50
15	52	55
15.4	54	60
15.8	56	65
16.9	60	70
17.1	62	75
18.2	66	80

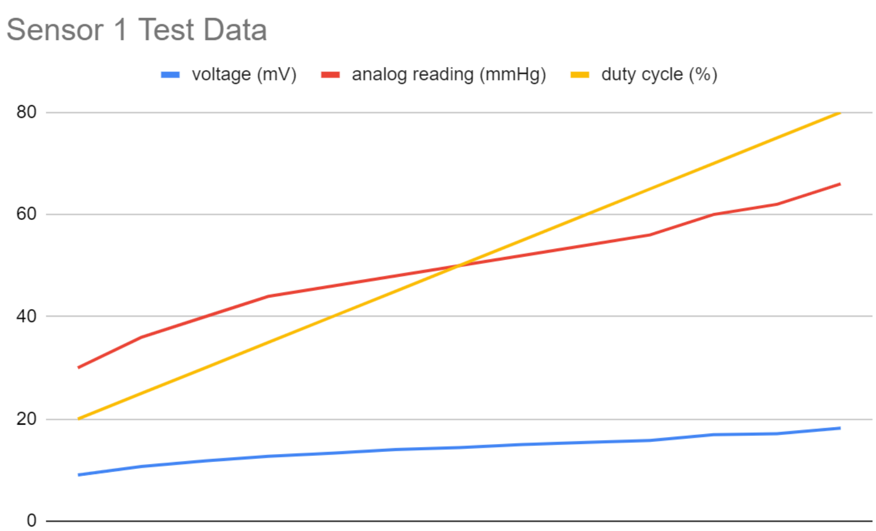


Figure 7.1.1.1: Graph of the Test Data

For the whole system, the Arduino was connected to the computer to display values. Because the Arduino was powered by the computer during testing, the team was getting accurate readings and results. During testing, the terminal on the computer was printing out values read by every sensor in the system. In this way, the team was able to know that everything was working fine for the system. The figure below shows the readings for all the 4 temperature sensors and 2 pressure sensors when the temperature was set to 30°C and pressure was set to 1 psi. (Note: the pressure values were showing 10 because they were multiplied by 10.)

```
COM10

[CT30]
[CP10]
[T 30 30 30 30 32 30 P 10 10]
[T 30 30 30 31 32 31 P 10 10]
[T 30 30 30 30 34 31 P 10 10]
[T 30 30 30 30 32 31 P 10 10]
[T 30 30 30 30 32 31 P 10 10]
[T 30 31 30 30 32 31 P 09 09]
[T 30 30 30 30 31 30 P 10 10]
[T 30 30 30 30 35 31 P 10 10]
[T 30 30 29 30 32 30 P 10 10]
[T 30 30 30 30 32 31 P 10 10]
[T 30 30 30 30 32 31 P 10 10]
[T 30 30 29 30 32 31 P 10 10]
[T 30 30 30 29 33 31 P 10 10]
[T 30 30 30 30 29 31 P 10 10]
[T 30 30 30 30 32 31 P 10 10]
[T 30 31 30 30 34 32 P 10 10]
[T 30 30 30 30 32 31 P 10 10]
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[T 30 30 30 30 33 31 P 10 10]
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[T 30 30 29 30 31 31 P 10 10]
[T 30 30 30 30 32 31 P 10 10]
[T 30 30 30 30 33 31 P 10 10]
[T 30 30 30 30 34 32 P 10 09]
[T 30 31 30 30 32 31 P 10 09]
[T 30 30 30 30 29 31 P 10 09]
[T 30 30 30 30 33 31 P 10 10]
[T 30 31 29 30 31 31 P 10 10]
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[T 30 30 30 30 33 31 P 10 10]
[T 30 31 30 30 31 31 P 10 10]
[T 30 30 30 30 33 31 P 10 10]
[T 30 30 30 30 32 32 P 10 10]
[T 30 31 30 30 31 31 P 10 10]
[T 30 30 30 30 31 31 P 10 10]
[T 30 30 30 30 33 31 P 10 10]
[T 30 30 30 30 29 31 P 10 09]
[T 29 29 30 30 33 31 P 10 10]
```

Figure7.1.1.3: Screenshot of sensor data on the computer screen

As we can see, the temperature and pressure values were accurate and precise. However, things worked differently when the USB cable was unplugged between the Arduino and the computer and two 9V portable batteries were being used to power the circuit. It messed up the readings for temperature and pressure. After testing around with the circuit, the team noticed that the voltage being supplied to the Arduino because the 555 timer in the circuit. Thus, a fix was done to the circuit and the 555 timer was being taken off. Because of this fix, the readings for temperature and pressure were back to normal. Debugging the hardware and the software was a painful process to the team. the However, the team overcame this challenge with perseverance and an ambition for success. Overall, these testings mentioned above led to a functional prototype for the day before demo and the team had put in a tremendous amount of effort into testing the prototype.

7.1.2 Demo Day Results:

During demo day, there was an error on the temperature and pressure readings because the potentiometer on the circuit was not adjusted/calibrated correctly. However, one of the team members fixed it at the end and the readings were accurate again. Other than the potentiometer, everything worked according to plan. This proved that this product does not only worked only for one time. It works as long as the batteries last.

In the future, we should:

- make sure every subsystem works properly and test each thoroughly before assembly
- give more time for testing and corrections
- make sure the circuit works with the Arduino disconnecting from the computer

7.2 Significant Technical Accomplishments

The team has learned many different skill sets from this project. The design process is new and useful to The most significant technical accomplishment is the electronic hardware and the software system. The circuitry for the hardware system is very complicated since it used parts like multiplexer and operational amplifier. It required a significant amount of time for testing and adjustments. Additionally, we resolved the problem of drawing a lot of current to power the Peltier plates with two 9 volts batteries. Even though it takes time for the Peltier plates to heat up, the system still works eventually. In the future, the team may consider different electronic components rather than using the Peltier plates for the heating system. Acquiring accurate data from the sensors is also a great accomplishment for the team. The team members used their knowledge of electronic substantially.

A technical accomplishment that the group held in high regard, was the ability to control both the pressure and the temperature from a smartphone using a combination of the circuits, arduino code, and the code in the app. Having all of those subsystems works in tandem was a testament to the work and effort that went into constructing the smart cast. It was the first time that the group members working on the subsystem had created such an advanced system that was to be controlled remotely.

This project gives the opportunity for all the students in the team to know more about electrical circuits and 3D printing. For some team members it was their first time working with electronics. Additionally, CAD drawing is one of the important skills applied to this project as it allowed for the ability to 3D print custom made parts which for many of our group members it was their first time seeing the process in action. Furthermore, the cast's structure itself implemented wooded braces that were cut to precision using a laser cutter which was the first time any of our team members had used a laser cutter to manufacture parts of a team project. The team members acknowledge the importance of CAD drawings in the design process. Despite the difficulty of this project, the team strived with perseverance and assembled this working system.

8 Conclusions

By: Thomas Ranney

The goal of the SmartCast is to expedite the healing process by applying heat and pressure in a more effective way than anything else on the market. To do this, peltier plates and air pumps are mounted on a lightweight 3D printed cast. The peltier plates and air pumps are then controlled by a user interface on the customer's phone, the customer being able to adjust either to their hearts delight.

This product has met the needs of its targeted customers, primarily medical professionals and centers such as orthopedics, physical therapists, athletic trainers, hospitals, pharmacies, or urgent cares, who would need to get this product to their patients. Secondary customers include individuals have broken a bone and can not afford to wait the typical timeframe for it to heal.

To create this product, the team stuck to a strict design process which included selection matrices, brainstorming, and concept combinations were employed. The solution is composed of a 3D printed exoskeleton with wooden support pieces in slots in a circular layout, joined together in the middle by a joint. In addition to this there is a 3D printed mesh to harbor the circuit on top of the exoskeleton. The peltier plates are laid out on the inside of the cast, and are connected to the motor drivers on the circuit board. The air pumps were stationed on the outside of the exoskeleton, on both halves of the cast. Along with each Peltier plate and air pump, there is a corresponding pressure and temperature sensor. These read back to the arduino which is mounted on top of the exoskeleton on the circuit board.

When choosing the materials to construct these subsystems, many different factors were taken into consideration. These included strength, weight, and cost were among the most important ones. Many of these parts were ordered online, so many different vendors were perused. While each team member was working on their subsystem, several challenges were faced by the whole team. Some of these included damaged parts, and miscalculations. These were resolved by the team coming together and combining their opinions to solve them.

The final prototype had seven fully functional subsystems. All of the required specifications were met but there were still some small problems. One of these was that the peltier plates took very long to heat up, and is not feasible to be a substitute for existing models, also the air pumps were slightly inaccurate due to the small values that the system was dealing with. Furthermore the cast itself was too large to be practically used on a human arm. Due to all of these shortcomings, the team decided that the product is not ready to be shipped to market.

Many improvements would need to be made before this project is ready for production. As stated above, the heating and pressure systems would need to be slightly reworked to make them more efficient. The pressure system would need to be more accurate in its readings and adjustments, and the temperature system would need to heat up quicker. In addition to this, the circuit board would need to be converted from the breadboard that is currently used to a smaller more compact PCB board. Finally the size of the exoskeleton would need to be reduced to fit an actual human arm. After all these changes are implemented the team could start the process of getting a patent. After a patent is obtained, the product could be streamlined for production.

The team has completed this project by a process that is defined by the group, and subgroups, held to deadlines set by the gantt chart and team contract. By utilizing the strengths of all of the group members, constant communication, and outside information the team was able to accomplish success.

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10 Appendix A: Selection of Team Project

By: Sierra Carr

The goal for our team project was to create something which could make someone's life better or easier. Initially, the team generated multiple ideas to help humans with troubled mobility and impairments of various types; ranging from medical difficulties such as old age, debilitating diseases, and physical injuries on people of all ages. The goal of our project was to come up with something which could help someone with a medical issue. Below, figure 10.1 contains potential ideas for solving a medical challenge. The highlighted box at the end was the engineered solution for the medical challenges which were brainstormed. In the end, the decision was to go with the solution for broken bones with the cast which controls and speeds-up bone healing. In the section below the decision process will be highlighted as to why this decision was made.

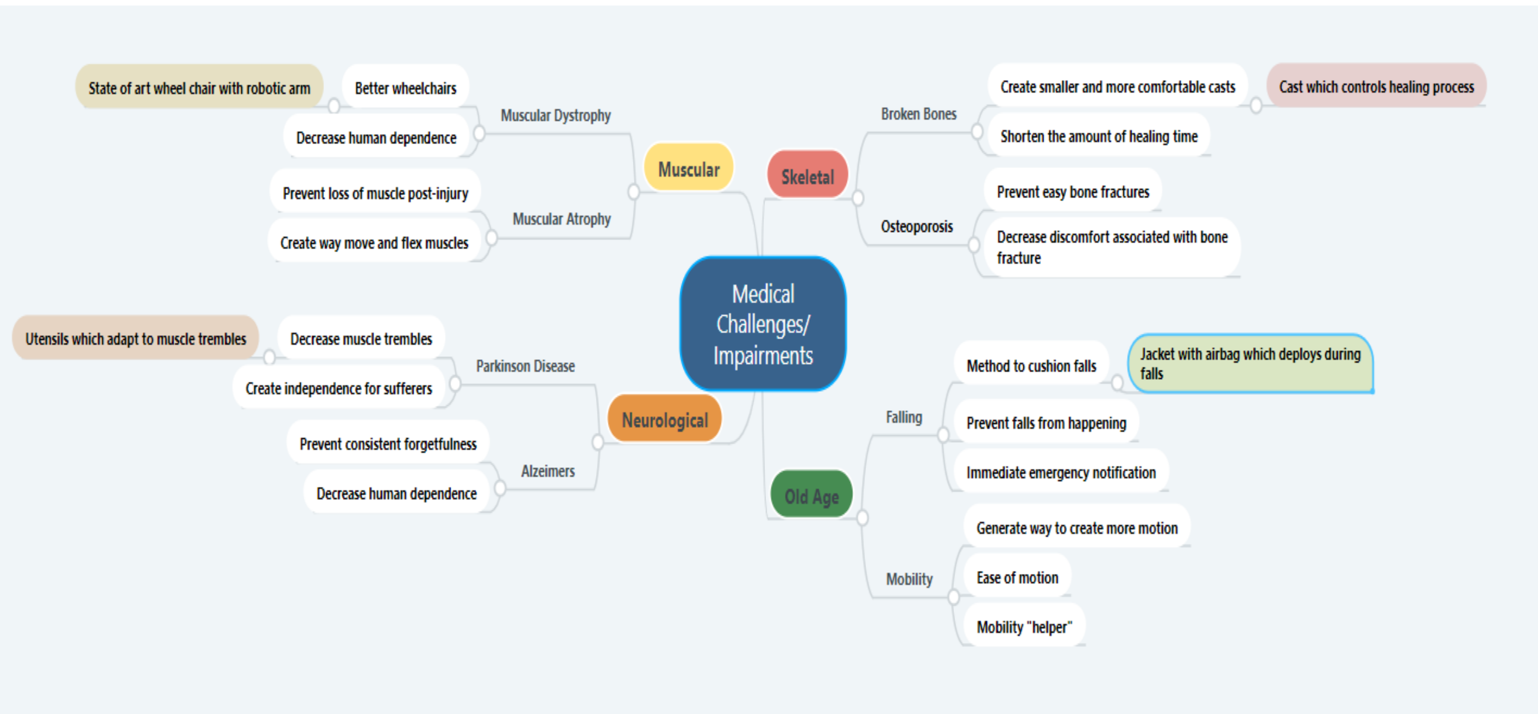

Figure 10.1: Problem Mind-Map

Table 10.1: Concept Selection Matrix

	Concepts			
Selection Criteria	Robotic Arm Wheel Chair	Utensils for Parkinson disease	Airbag Jacket	Cast with controlled healing
Cost	-1	0	-1	0
Complexity	-1	1	-1	-1
Build Time	-1	1	1	1
Practicality	1	1	-1	1
Weight/portability	1	1	1	1
Durability	1	0	-1	1
Modeling complexity	-1	1	-1	-1
Market	1	1	-1	1
User Base	1	-1	-1	1
Existing Availibility	1	-1	1	1
Division of Subsystems	1	-1	1	1
Net Score	3	3	-3	6
Rank	2	Reject	3	1
Continue? (Y/N)	Y	N	N	Y

Using concepts from the mind map in figure 10.1, a concept selection matrix was generated in table 10.1. Based off of the concept matrix, the concept of making a utensil which people with trembles could use was eliminated due to the lack of subsystems for the project. The good news about eliminating such a necessary tool for people with Parkinson disease is that a team of engineers has already generated a prototype of utensils for people with bad muscle trembles. The top ranked concept was the cast with controlled healing, the second best was the wheelchair with a robotic arm, and ranking last in third place was the idea of the airbag jacket. Despite ranking third, the airbag jacket has a negative netscore with a score of -3. Due to the negative netscore, the group had decided not to pursue this project. The airbag jacket posed several potential difficulties, including finding a safe way to get the airbag to inflate within seconds of a fall occuring and inflating before the person hits the ground. The potential difficulties with this project were just too great for this to be feasible project to finish within a ten week period.

<u>Concept 1:</u> State of the art wheelchair with robotic arm for people with muscular dystrophy

Table 10.2 : Concept Selection Matrix for Robotic Arm Wheelchair Design Considerations

Concept	Chair		Robotic Arm				Wheels	
Selection Criteria	Purchase Electric Wheelchair and modify it	Purchase regular wheelchair and make it electric	Joystick controlled mechanical arm	User Interface controlled mechanical arm	Human Hand (5 finger design)	Clamp Hand (2 finger design)	Four wheel	Drive belt for traction
Weight	-1	1	0	0	-1	1	0	0
Energy Efficiency	1	0	0	0	0	0	1	-1
Durability	1	1	0	1	0	0	1	1
Size	-1	1	-1	1	-1	1	1	1
Safety	1	-1	0	0	1	1	0	0
Materials	0	0	-1	1	-1	1	-1	1
Cost	-1	1	-1	1	-1	1	1	1
Time	1	-1	1	1	-1	1	-1	-1
Difficulty	1	1	1	1	-1	-1	1	1
Net Score	2	3	-1	6	-5	5	3	3
Rank	2	1	2	1	2	1	tie	tie
Continue (Y/N)?	N	Y	N	Y	N	Y	N	Y

For the wheelchair with a robotic arm, a concept selection matrix was generated, as seen in table 10.2 above. The green highlights the ideas which the group decided would best fit the concept. The idea behind the wheelchair was to give current wheelchairs an upgrade and to add an electric mechanical arm which would be able to grab objects for the person in the wheelchair. This concept was brainstormed with the thought of giving people who have limited to no use of their arms due to musculoskeletal diseases an arm which could make their life easier. In figure 10.2, the mechanical arm is shown attached to one of the arm rests on the wheelchair. The concept selection matrix led us to want to take a regular wheelchair and make it electric in order to power the arm as well as to allow for the wheelchair to be controlled by a joystick so man labor to push the wheelchair is not necessary.

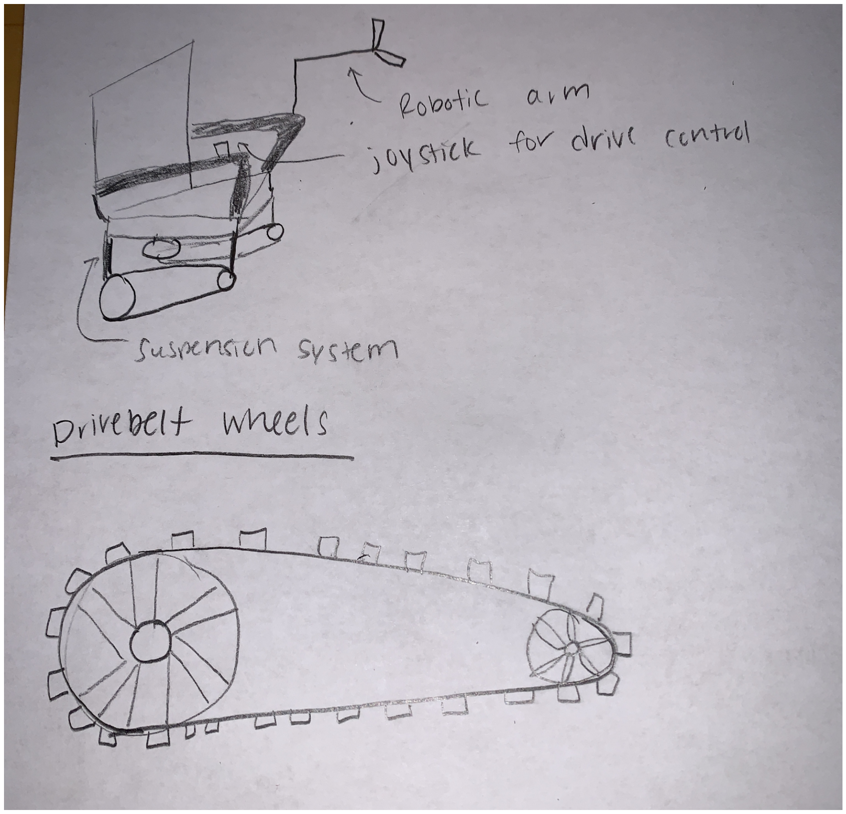

Figure 10.2: Sketch of wheelchair with robotic arm

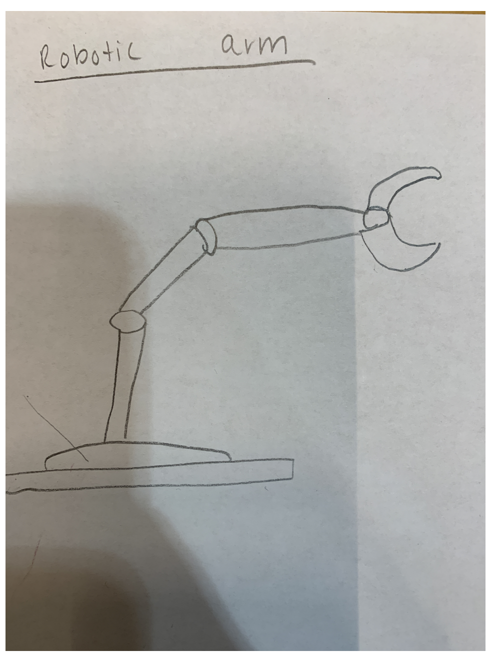

Figure 10.3: Robotic arm

Another concept which was thought of was replacing the typical four wheel system of an electric wheelchair with a drive belt system. The idea is to increase the terrains which the wheelchair can operate in, so a suspension system would also be integrated into the drive belt wheels. Two rotating motors would be attached to the larger rear wheels of the chair to rotate the belt and the front wheels. In figure 10.3, the mechanical arm concept is shown, where the arm has three separate joints which allow for versatile motion and varying direction of the mechanical arm.

Concept 2: Cast which controls the healing process of broken bones

Table 10.3 : Concept Selection Matrix for Cast Design Considerations

Concept	Cast Structure		Power Supplies		Heating System		Pressure System	
Selection Criteria	3D print Exoskeleton	Machnice Wooden Exoskeleton	Batteries	External DC Power supplies	Water pump temperature control system	Peltier Plates	Rubber Bladders	Blood Pressure Cuffs
Weight	1	1	1	-1	-1	1	1	1
Energy Efficiency	0	0	-1	1	0	-1	0	0
Durability	1	-1	0	0	0	0	0	1
Size	1	1	1	-1	-1	1	-1	-1
Safety	1	-1	1	-1	0	0	0	1
Materials	1	1	0	0	-1	1	-1	-1
Cost	-1	0	1	0	-1	-1	1	1
Time	-1	-1	0	0	-1	1	-1	1
Difficulty	-1	1	-1	1	-1	-1	0	1
Net Score	2	1	2	-1	-6	1	-1	4
Rank	1	2	1	2	2	1	2	1
Continue (Y/N)?	Y	N	Y	N	N	Y	N	Y

For the cast which controls healing for broken bones, a concept matrix was generated in table 10.3. The green highlights are used to show the ideas which the group decided would be best for this concept. The idea of the cast is to create a controlled healing environment to speed up the rate at which a bone regenerates, therefore shortening the amount of time a patient needs to wear a cast.

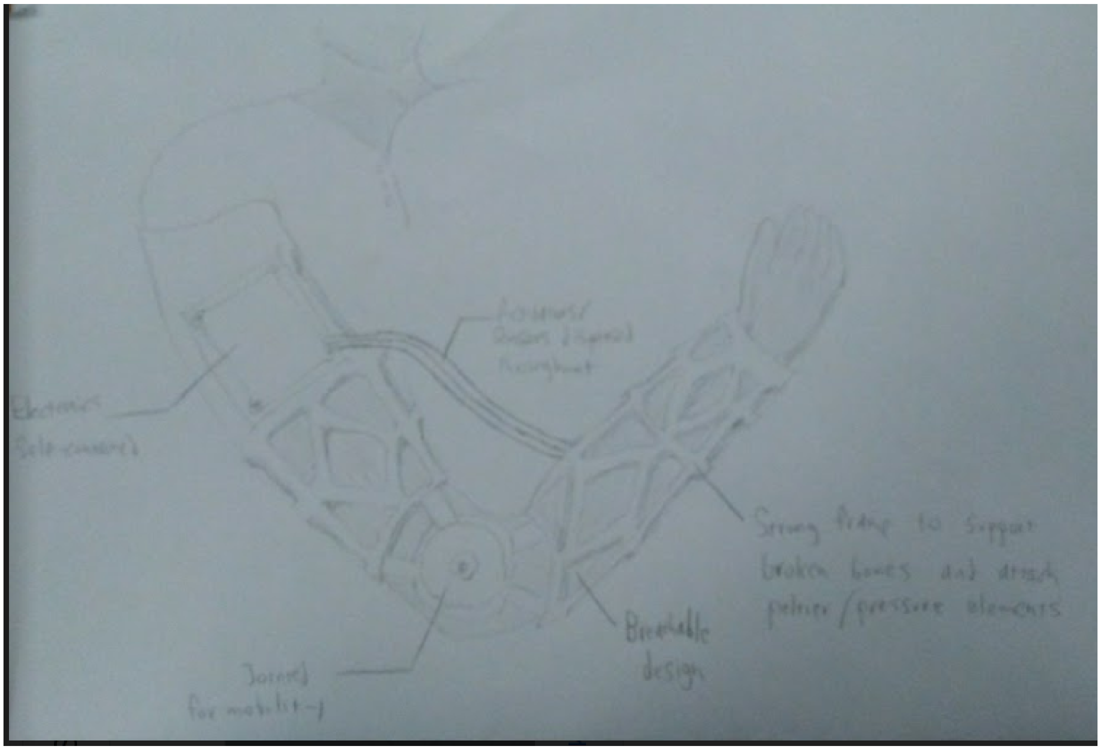

Figure 10.4: Initial Sketch of 3D printed exoskeleton cast

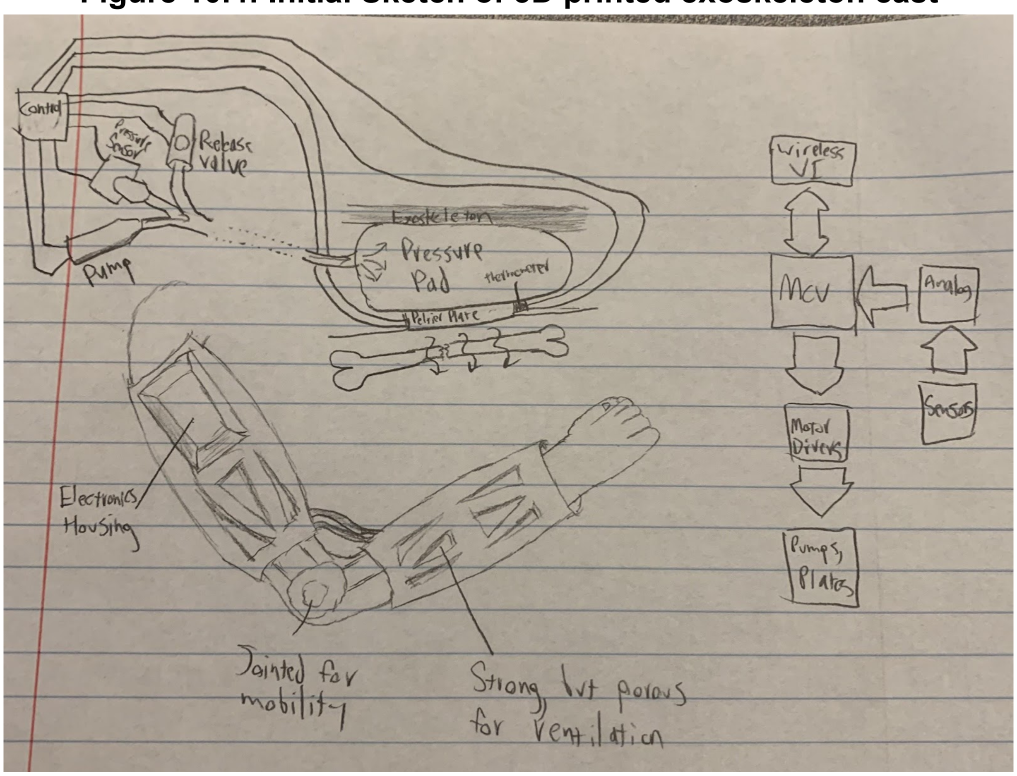

Figure 10.5: Side view sketch showing pressure and heating system, and description of electronic system

In figures 10.4 and 10.5, the original concept for a 3D printed arm cast with a heating and pressure system are shown. The idea of the cast is to create a healing environment including heat and pressure to create blood flow variations around the region of injury. Figure 10.5 shows the positioning of the peltier plates below the pressure system in relation to their positioning on a broken bone. In this figure, there is a block diagram on the right. The block diagram describes the electronic system and embedded control, and how the plan is to use and analog device and motor drivers to power the pressure pumps and the peltier plates.

Final Decision

Table 10.4 : Concept Selection Matrix Comparing the Projects

	Concept							
Selection Criteria	3D print Exoskeleton	Batteries	Peltier Plates	Blood Pressure Cuffs	Purchase regular wheelchair and make it electric	User Interface controlled mechanical arm	Clamp Hand (2 finger design)	Drive belt for traction
Weight	1	1	1	1	-1	0	1	0
Energy Efficiency	0	1	1	0	1	1	-1	-1
Durability	1	0	1	1	1	0	1	1
Size	1	1	1	-1	-1	0	1	-1
Safety	1	1	0	0	1	0	0	1
Materials	1	0	0	0	0	1	-1	-1
Cost	-1	1	1	1	1	0	1	-1
Time	-1	0	0	0	0	-1	-1	-1
Difficulty	1	1	-1	1	1	-1	-1	-1
Net Score	4	6	4	3	3	0	0	-4
	Sum for Cast	17			Sum for Wheelchair	-1		

When it came time to make the final decision on what project we would pursue, we constructed table 10.4, a concept selection matrix where we compared concept one to concept two. The final decision came down to choosing concept 2, the cast. It was chosen since it scored higher in the concept matrix, and because the group felt as though the wheelchair concept would take longer than ten weeks to finish. In terms of difficulty, time, and cost the cast was the best choice in comparison to the wheelchair.

Table 10.5: Concept Selection Matrix for SmartCast final design selection

Selection Criteria	Plaster	Fiber Glass	3D Printed PLA	Aluminum	Batteries	Rechargable System	External Power Supply	Water Heating and Cooling	Peltier Plates	Rubber Bladder	Pressure Cuffs	DC Motor Pumps	Mehcanical Pumps
Weight	-1	1	1	-1	-1	1	1	-1	1	1	1	1	-1
Energy Efficientcy	1	1	-1	-1	-1	1	1	1	1	1	1	-1	1
Durability	1	1	0	1	1	1	-1	1	-1	1	1	1	1
Size	-1	-1	1	1	0	1	-1	-1	1	-1	1	1	-1
Safety	1	0	1	0	1	0	1	1	1	1	1	1	-1
Reusability	-1	-1	-1	1	0	1	1	1	1	1	1	1	1
Cost	1	1	-1	1	-1	1	1	-1	1	1	1	1	1
Difficultly of Implementaion	1	1	1	0	1	-1	0	-1	1	1	1	-1	1
Hygeine	-1	-1	1	1	0	0	0	1	1	1	-1	0	0
Sum of +1's	5	5	5	5	3	6	4	5	8	8	8	6	5
Sum of 0's	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum of -1's	4	3	3	2	3	1	2	4	1	1	1	2	3
Net Score	1	2	2	3	0	5	3	1	7	7	7	4	2
Rank	4	3	2	1	3	1	2	2	1	1	2	1	2

Table 10.6: Concept Combination Table for SmartCast

Object to Modify	Method to Modify Object	Use to...
Hardshell Cast	3D print- hard exoskeleton formed by a system of brackets and cuffs	Brace and hold a broken bone in place to prevent bone from being more damaged
Heating Pads	Peltier Plates	Heat and cool the region of injury by varying current direction
Pressure Pumps	DC motor	Pump air in and out of inflatable pads made out of rubber bladders
Control Circuit	Microprocessor	Automatically adjusts the temperature and pressure
Sensor System	Pressure and Temperature	Monitors and controls the healing process

For final design selection for the SmartCast, table 10.5 was used to make design decisions prior to actually building the cast. A concept combination table for the cast was made to explain the major electrical and mechanical components and functions for the project. The concept combination table served as a guide to backup and support design decisions which were made in table 10.6 prior to attempting to make the prototype for the cast.

11 Appendix B: Customer Requirements and Technical Specifications

By Thomas Ranney

Table 11B.1 Complete Requirements

Customer Requirement	**Importance**	**Technical Requirement**	**Milestone 1 Targets**	**Revised Targets**
Lightweight	5	Total Weight	< 4 lbs	< 3lbs
Can adjust Temperature	5	Temperature	0 - 70°C	20° - 40°
Can adjust pressure	5	Pressure	.5 psi - 3 psi	0 psi - 1.5 psi
Is safe to use	5	Voltage	< 15V	< 9V
		Current	< 10 mA	< 2 A
		Shutoff Temperature	Not Considered	50 degrees celsius
		Shutoff Pressure	Not Considered	2 psi
Won't impede everyday functions	5	Number of joints	1	1
Not bulky	4	Dimensions	24in x 6in x 6in	24in x 6in x 6in
Sturdy	4	Minimum force withstood	130-200 lbs	20 lbs
Affordable	3	Maximum Total Cost	$150	$250
Doesn't itch	4	Coefficient of friction of material to skin	< 0.2	< 0.2
Doesn't smell	4	Airflow Rate	> 0.3 liters/second	> 0.3 liters/second

Don’t have to charge it often	3	Power	4W	< 4W(quiescent) < 18W (transient)

For the initial prototype, table 11B.1 was instrumental in the design of it . The given customer needs were taken into consideration before anything was built. The customer needs were considered when designing the individual subsystems. For example the exoskeleton’s design was heavily influenced by the customer needs of a lightweight, sturdy, sleek product. As the product progressed, some of the initial target values were toned back to be more realistic.

12 Appendix C: Gantt Chart

This Gantt chart was extremely useful to create a systematic way to follow subsystem progress and individual achievement. This was helpful to keep expectations of each member realistic and allow each subassembly to flow more evenly. This chart helped to keep the delays from outside sources to be the only major delays that our project endured and that it was not hindered by a lack of communication between team members. With a thorough understanding of the standing of each subsystem the team was able to follow the progress of each individual creating a free flowing exchange of information and aid that led to an exponentially faster production and testing process.

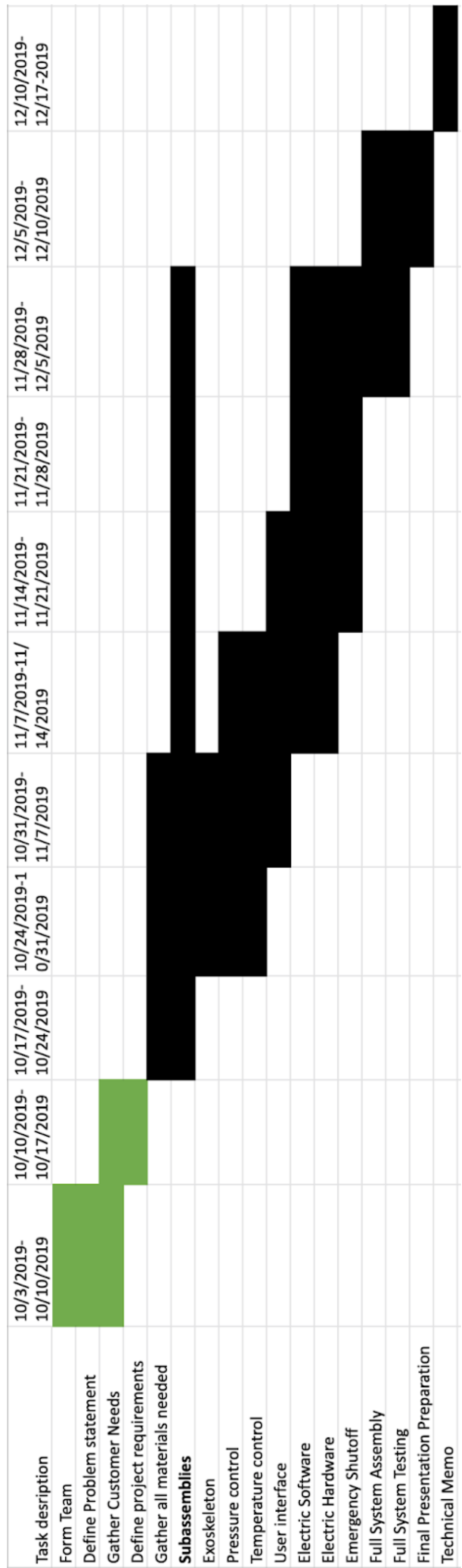

Figure 12.1: Team Charlie's Angels Gantt Chart

13 Appendix D: Expense Report

Table 5 - Project Expenses

Purpose	Item	Pieces	Amount	Price	Total (+ship.)	Vendor	Init.
Circuit Building	Prototyping board	34	1	$6.10	$11.11	AliExpress	CP
	Header pin pack	20	1	$1.88	$2.03		
Current limiting	PTC thermistor	50	1	$13.00	$14.04		
Embedded control	Arduino Nano	1	4	$1.96	$11.09		
Bluetooth module	HC-05	1	2	$2.36	$5.61		
Motor driver	L298N	1	10	$0.97	$13.17		
Temperature sensor	LM35DZ	10	3	$6.05	$19.61		
Temperature control	Peltier Plate	1	10	$1.30	$20.44		
Pressure sensor	MPS20N0040D	1	10	$0.55	$9.67		
Pressure control	Air pumps	6			$19	America Surplus	CS
	Inflatable pads	2			$15.98	Amazon	CS
	Tubing	2			$7.98	Home Depot	CS
Physical construction	3D Printing				$61	Forge	CS CP
Power	Batteries	4			$20		
	Total purchase cost				$230.73		

The project could have thrived if given a better focus on purchasing only a necessary amount of materials, and using an improved quality for the vendor in order to receive better individual parts without using the bloated costs on irrelevant and excess material. This is particularly true for the prototyping board in which the team was carried away in the excitement of the project and did not in fact need 34 boards.

14 Appendix E: Team Members and Their Contributions

14.1 Team Member 1 -Casey

"For this project I was responsible for the pressure control and application subsystem. In order to create an efficient system, I was to resource the most ideal electric pumps, inflatables, and pressure sensors for the system our team was creating. During testing I was able to create a simple prototype of the system that could pump air into the system at variable speeds to test the power of the separate motors. Once I had done that I had to run tests on the pressure sensors in order to find the correlation between their outputted voltage and the pressure that was being applied to them. This was critical as the linear correlation provided could be converted into digital information by the circuitry using the found function. Due to how integrated my subsystem was with the circuitry and code, I worked closely with Wei and Charles throughout the project in order to ensure my system's compatibility with theirs. Furthermore in order to construct the apparatus that would connect the pumps, inflatable cuffs, and pressure sensors I had to work with Michael to ensure their would be room to accommodate both the tubing network and the inflatables. To connect the tubing to other parts of the apparatus, I had to use CAD to model junctions which could subsequently be 3D printed and then attached to the system where they were needed. Lastly, I help solder some of the wiring associated with my subsystem in order to attach head pins to the motors to make them easier to integrate into the circuit. For the final report I wrote the System Concept and Development as well as my own subsystem. In addition I also helped write the Technical Accomplishments and Lessons Learned"

14.2 Team Member 2 - Charles

"My primary responsibility has been to develop the embedded control software for the electronic function of this project. This puts me in a tight position: in order for the software to work, all other subsystems must work, and conversely, in order for other subsystems to work, the software must work. This has demanded that I work closely with each and every member in the group. With Michael, I ensured that the physical aspects of the cast would be accommodating to electrical hardwareWith Cynthia, we developed a protocol for communication between the microcontroller and a phone via bluetooth. With Casey and Sierra, I have worked to characterize their subsystems and how to get readings from them, deepening my understanding so that I can put that understanding to use in my code. With Thomas, I offered my own experience with electrical hardware and helped incorporate his code with the rest of the software.

My greatest contributions have been made with the help of Wei. The two of us put an uncountable number of hours toward the functionality of the circuitry. Code had to constantly be adjusted as flaws were continuously uncovered and patched in the electrical hardware. Without his help, all of my efforts would have been for naught."

14.3 Team Member 3- Cynthia

"For this project, my responsibility is the user interface subsystem. For the user interface, I have been working by myself most of the time. First, I researched on creating an app for the system. I learned that the best platform to make the app is MIT App Inventor. I self-learned on how to use this platform and its block programming syntax. Next, I designed the user interface. There are two screens to this user interface: main screen and setting screen. For earlier time in this project, I have been testing the Bluetooth communication between the phone and the Bluetooth. Later, I worked on refining and debugging the code and the design of the user interface. I worked with Charles's software system a lot in this project. He created a prototype circuit and a testing code for me to test my user interface. I have done a lot of testing for the user interface alone. During the assembly period, I have helped on testing the whole subsystem and help other members to put their subsystems together. I also developed a web page for help and support. The url link to this webpage is lic20.github.io. For this final report, I took part in writing the Results section, my own subsystem section, and the user manual."

*14.4 Team Member 4 -*Michael

"For this project my responsibility was to create the structure and body of the cast that would make up the physical creation. I worked closely with almost every other subsystem in order to create the space that they needed on the physical cast while still maintaining a form that was true to the team's vision and did not sacrifice structural support. Most of my design work was done on my own with input from Wei, Charles, Sierra, and Casey about necessary dimensions. I designed each of the cuffs and their connecting pieces through the use of CAD and printed these drawings with the help of Casey and Charles. Additionally I chose the materials that would be used in the construction of the assembly and where each part would be attached. I used a laser cutter with Charles's help to cut out each of the wooden plates and created the grips that would allow them to be used. I planned out where each of the subsystems would fit into the casts ecosystem and how to incorporate the heating for it to be felt while mounted in the cast. Additionally, I was responsible for covering the cast to hide any possibly dangerous exposed wires. Lastly, I glued and combined each of the individual pieces to create the final assembly. For the final report I wrote the expense report, the benchmarking section, the GANTT chart and made a contribution to the lessons learned section."

14.5 Team Member 5- Sierra Carr

"For this project, I contributed to the testing and circuit integration of the heating system. The heating system involved six peltier plates and six voltage temperature sensors, as well as three motor drivers to power the peltier plates and an op-amp to read the output of the six temperature sensors. By performing tests, I helped calibrate the analog system to read the correct voltage-temperature output by varying the temperature of the peltier plate and recording the voltage output of the temperature sensor. I also soldered numerous cables to extend the length of the cables connecting to the peltier plates and of the temperature sensors to make sure the lengths would fit down the arm cast. After the exoskeleton was assembled, I also mounted the peltier plates to the exoskeleton and organized the wiring going from the bottom of the cast up to the circuit mesh at the top of the cast. I ensured safety by shrink tubing any exposed wire and using electrical tape to mount the peltier plates to the exoskeleton. I also helped write some of the website information, including the section on the bone regeneration process as well as writing commonly asked questions. I also contributed to the technical report by writing multiple sections, including the executive summary, introduction, mission statement, subsystem analysis and design of the heating system, and appendix A- selection of team project. I also made an individual contribution to the lessons learned section."

14.6 Team Member 6 -Thomas

"For this project, I was responsible for the safety subsystem. More specifically of the design and implementation of this subsystem. As this subsystem consists of a switch, I researched and tested many different methods of achieving this. Some of the alternative solutions I came across were optocoupler, P-channel MOFSETs, and op-amps, but after testing none were suited for our product. Finally deciding on the d1266 N-channel MOSFET. Also I wrote and tested the code for both the automatic shutoff, and the manual shutoff with the button. Furthermore I wired both the MOFSET switch and the button into the circuitry. As this subsystem is very electrically focused, I worked closely with Charles and Wei to complete it. For milestone I I was responsible for the customer needs and technical requirements sections of the presentation, for milestone III presentation I was again accountable for the customer needs and technical requirements along with the summary and conclusion on top of the slides about the safety subsystem. For the final write up, I was responsible for the customer and technical requirements, the safety subsystem and the conclusion."

14.7 Team Member 7- Wei

"For this project, my task was the electronic hardware subsystem. I designed the circuit to place the other components in the project into a feedback loop that was controlled with an Arduino. Through reading through the datasheets of all the integrated circuit chips, peltier plates, and motor pumps I decided on the best way to connect them together. For the sensors, I used an 8-1 multiplexer with selector bits from the Arduino to obtain readings. All sensor outputs were put through amplifier circuits to boost their voltage levels to a readable level. I worked closely alongside Charles to calibrate resistance values in the amplifier circuit so that his code would receive relevant data. I also connected the peltier plates and motor pumps to motor drivers. I worked with Sierra and Casey to see what voltage and current levels their parts would need to power them efficiently. The safety subsystem that Thomas was responsible for had circuitry involved, thus I also worked closely with him to find the most effective spot on the circuit where his subsystem could be placed. In the presentation, I spoke about my subsystem, the

GANTT chart, and lessons learned. In the final memo, I wrote the professional and societal considerations, the electrical hardware subsystem, and statement of work."

15 Appendix F: Statement of Work

Prepared by: Wei Chen

Team: Charlie's Angels
Members: Casey Schmidt, Charles Pike, Cynthia Li, Michael Sweitzer, Sierra Carr, Thomas Ranney, Wei Chen

Semester Objectives:

1. Develop a unique design that combines individual subsystems into a coherent and functional finished product
2. Use proper engineering procedure to model a project prior to physical assembly to gain a better grasp on underlying fundamentals of the system
3. Test and debug system step by step to ensure final version is error-free
4. Collect and analyze data to demonstrate correct operation
5. Organize all information to give an articulate presentation and a systematic technical memo that details the intricacies of the project

Approach:

A Smart Cast that sets internal temperature and pressure to a user specified level will be built by separating the design into separate subsystems before merging them all together. Group members with interconnected subsystems will work together to ensure designs are compatible with each other. Whole group meetings will be called to update each member on current status of subsystems and assign tasks to corresponding people. The end goal is a completely new product robust in design and capable of rivalling traditional cast technologies

Deliverables and Dates:

- Obtain complete list of customer requirements (10/3)
- Translate customer requirements into technical specifications (10/4)
- Milestone one presentation and memo (10/10)
- Begin preliminary designs on subsystems (10/17)
- Present current progress of subsystems (11/4)
- Finalize subsystem designs (11/27)
- Combine all subsystems for full system testing (11/28)
- Complete debugging for full system (12/2)
- Milestone two: Demonstration (12/5)
- Milestone three: Presentation (12/9)
- Technical memo (12/9)

16 Appendix G: Professional Development - Lessons Learned

By Charles

<u>Problem: Following the Gantt Chart</u>

A big issue for the group was getting parts of the project done by the time we needed them to be done. The project was finished a week later than intended, and there was a big time crunch when it came to full system testing. If the group had actually followed the gantt chart, we would have been able to finish the project sooner. This taught us the importance of actually following a set schedule to guarantee success in a project. Following the gantt chart would have also allowed for the group to finish the tasks which take a longer amount of time to do versus trying to finish the less time consuming parts first. Finishing the more time consuming tasks first ensures that there will be plenty of time to finish the project come the deadline.

<u>Problem: Using the wrong infill for Prints and not accounting for expansion</u>

An issue that occured when 3D printing parts for the various subsystems was not using the correct infill. This happened more with the smaller delicate prints for the pressure subsystem as well as the elbow shackle. In the case of the prototype pressure junctions, the results were catastrophic as the fragile prints cracked under the strain of the pressure experienced by the sensors. Another complication we had with the 3D printed parts was not accounting for the expansion of the material due to the heat of the printer's extruder. This led to the opening and closing ability of the cast brackets being near impossible to implement as the friction between the two piece was too large to easily overcome once they were positioned together.

<u>Try: Using a multi-part hinge to connect each cuff together</u>

One of the problems that were faced while constructing the cast was keeping each cuff in place while attempting to have a removable hinge for the cuffs to open about. If instead the team used a secondary metal clasp to keep each of the cuffs closed that was held in place using the same structural beams which could have been machined to open and close each of the cuffs without much danger to the circuitry or the structural stability. An additional solution could be the use of multiple permanent rigid plates that hold each of the cuffs in the correct position along the arm that would not put the circuit or the structure in danger.

<u>Try: Using a Different Pressure Sensor</u>

The pressure sensor used for the smart cast read differential pressure so it required a constant leak to create accurate reading for the circuit. Due to this factor the motors had to be on nearly constantly to ensure they could maintain a consistent pressure. A drawback of this is that they drain power quickly due to the large currents needed to sustain them, in addition to the noise they create which might be a complaint that the patient would have. In order to resolve this in a future design it would require a pressure sensor that does not take differential pressure, but rather off of the force applied by the pressure itself.

Problem: Pressure Sensor Readings

The pressure sensor had high-impedance, low-voltage, differential outputs. An arduino is only particularly well suited for reading analog voltage in the range of 0-5V, with, at best, a 3mV resolution when the reference voltage at 3.3V. This was unsuitable for reading from the pressure sensor. To overcome this, a complicated circuit was constructed, consisting of 6 Op amps, to transform the raw output of the temperature sensor into something that was actually usable.

Problem: Op-Amp Power

The op-amp we were initially using, the LM348, is ill suited for outputting voltages lower than 2V above its negative power supply. Thus, a subcircuit for generating a negative voltage was designed, allowing readings to be comfortably taken close to 0V. The subcircuit was quite elegant, incorporating a 555 timer square wave generator and an inverting BJT amplifier to create substantial negative voltages through capacitive coupling and rectification. However, the subcircuit anomalously stopped functioning on battery power, working perfectly fine on any DC power supply. The solution that ultimately saved the project was simply using a different op-amp, the LM324, which was capable of getting only millivolts above ground with no need to generate a negative voltage.

Problem: Motor Driver Shutoff

It was initially decided that the best way to cut power to the motor drivers was to interrupt their connection to ground, effectively shutting them off. However, on the first attempt of this, it was discovered that the inputs were of exceptionally low impedance, allowing several amperes of current to be diverted from the ground terminal to flow out through the inputs. This not only fried the shift register, but caused three of the motor drivers to violently combust. It can be agreed that this is the exact opposite of the desired outcome for a safety shutoff circuit. It was thus decided that safety needed to account for more than just a simple shutoff, and multiple points of failure that had been previously overlooked were immediately addressed. Diodes were placed on the inputs to the motor driver to prevent current from flowing out, all connections between the shift register and other parts of the circuit, including power and ground, were given current-limiting resistors.

Problem: Analog Circuit Potentiometers

At first, it was presumed that using potentiometers instead of resistors on the analog circuitry would allow for a great degree of convenience in calibration. Instead, it was found that that made the circuit unbelievably touchy and nearly impossible to calibrate. Drawing the circuits, clearly defining the behavior, and solving gain equations for exact resistor values was found to be far more reliable than leaving the circuit adjustable.

Problem: Low Quality Hardware

For the purposes of reducing cost, integrated circuits were purchased from a somewhat unreputable vendor. Of those circuits, every single one proved to be defective. New ones needed to be ordered from a more expensive, but more trustable vendor.

Problem: Soldering a Finalized Circuit

Though a schematic of the circuit was completed early, it was subject to extensive change. Not only that, soldering can be very time consuming. Therefore, soldering the final circuit ceased to be a viable solution, and the final circuit remained on a breadboard.

Problem: Transistor Current Limitations

The transistor chosen for the safety shutoff switch was found to be too resistive: when turned on, it did not allow sufficient current to operate the peltier plates. In order to ensure functionality, a different transistor needed to be chosen. It was found that the necessary amount of current could be supplied by putting two D1266 power transistors in parallel.

Keep: Team work Dynamic

Throughout the whole project, the team handled any conflict by using collaborative efforts. The team handled any miscommunications well and resolved any disagreements immediately. For the most part, the team had equal efforts throughout the whole project and everyone helped someone else in one way or another.

17 Appendix H: User Manual

By Cynthia

Congratulations on your purchase of this smart cast system!

This device is made for you to increase your experience in your bone healing process. Please follow the instructions below. If you have any more questions, please go to our customer support webpage. The url link to the webpage is lic20.github.io.

Instructions:

There are two parts to this smart cast system: the smart cast itself and the phone application. There are many features in the app which are able to control the smart cast. Only Android system is able to use our app. We are very sorry for those users that have an iphone. Please download the software by scanning the QR code below, the software will start downloading once the QR code is opened.

Note: There is a safety shut off system in this device which will protect you from having overheating and too much pressure.

Important Safety Precautions:

In case of severe pain in your arm or malfunctioning of the smart cast, click on the emergency shut off button on the app or the button on the smart cast itself. *Call 911 immediately to get medical treatment for the pain.*

Set Up

Step 1:

Put the smart cast around your broken arm carefully. Make sure your arm feels normal and comfortable in the smart cast.

Step 2:

Open the app you already downloaded to your phone. Make sure the bluetooth connection is available on your phone. Pair the bluetooth named “HC05” and the passcode to connect is 1234.

Step 3:

In the main screen, click on the button “Available Bluetooth”. Select the “HC05”. After it is being selected, the Bluetooth connection is being made. Temperature and pressure will be displayed on this screen.

<u>Setting:</u>

If you want to set the temperature and pressure to a certain value, click on the “Setting” button on the main screen. On the setting screen, you have to connect to Bluetooth again. After the connection has been made, you can start setting the cast. Keep in mind that the range for temperature is between 20°C and 40°C and the range for pressure is between 0 to 1.5 psi. If you will set values out of range, it will trigger an automatic shut off safety system to shut off the heating and pressure system.