Final Design Review

ME 463 | Lab Division 047
April 26th, 2022
DRP Engineering
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1. Executive Summary

Starting with the goal of developing a product that will couple to existing shampoo bowls with minimal plumbing modification and control the temperature of water, DRP Engineering has successfully designed a system that does this and improves the salon experience for stylists and their clientele by reducing the amount of time to get the water to the correct temperature and ensuring comfort by holding the water at that temperature (Figure 1.1).

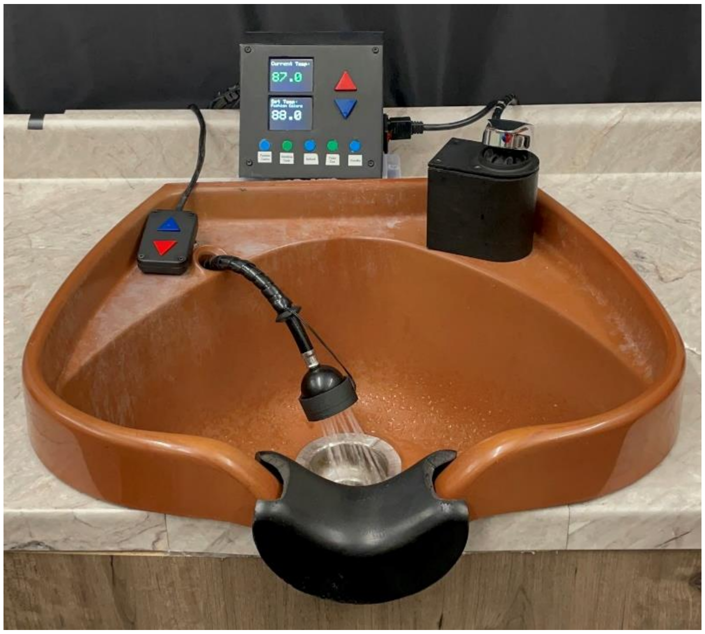

Figure 1.1: Final Assembled Fau-Set

The final design review phase focused on moving the overall design from low fidelity prototypes to high functionality versions that consisted of appropriate fit and finish to resemble the product in actual use-case settings.

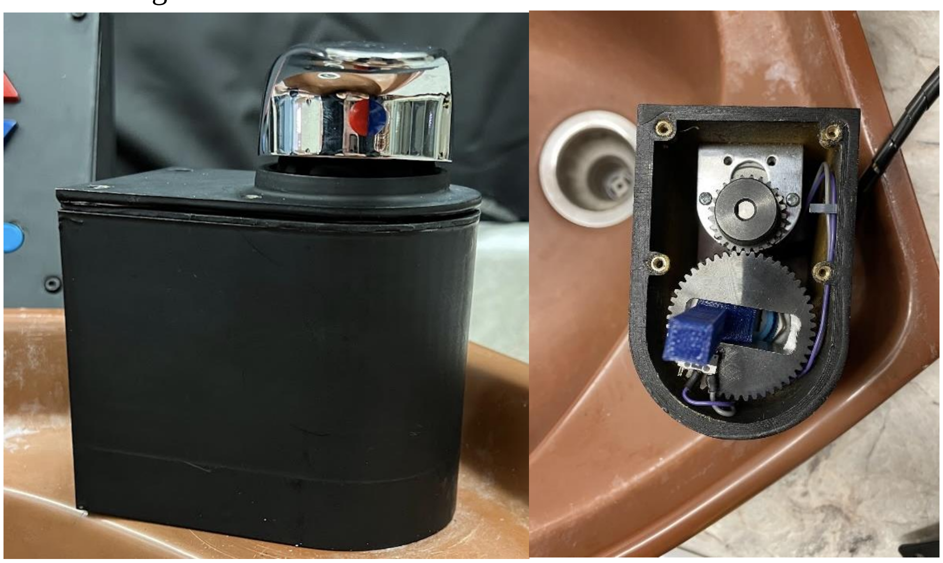

Figure 1.2: Faucet Attachment System Exterior and Interior

Minimal changes were made to the design of the primary faucet assembly as the original design matched very well the functional requirements needed. The final version featured metal gears, a metal bushing, and a metal coupler for the primary functionality of the device (Figure 1.2). The valve lever extender and exterior case remained 3D printed PLA with the outer case being coated in a smoothing resin and painted to more closely resemble injection molded plastic. There was also the inclusion of a rubber gasket between the primary base of the outer case and the upper lid to help with waterproofing the device. Finally, the faucet assembly had the addition of a water-proof and stretchable fabric to cover the hole in the upper casing where the handle and lever moved. This design resembles that of a manual transmission shifter, but prevents any water from entering the internal workings of the faucet assembly.

Figure 1.3: Final 3D Printed Showerhead System with Implanted Thermistor

The shower head was made using 3D printed PLA and painted black with machined holes to mimic the flow of the original shower head (Figure 1.3). The client remote had primarily cosmetic changes, rounding out the edges to more closely resemble a remote that fits nicely in the hand of a user. It was also 3D printed and underwent the same smoothing process as the outer casing of the faucet assembly (Figure 1.4).

Figure 1.4: Final Client Remote with CAD

The final component, the user interface, did see some changes (Figure 1.5). First it was reduced in overall footprint from the CDR phase to take up even less space than earlier. It also had the addition of a seventh button used to put the system in ‘standby’ mode where the motor is completely disengaged and the system operates like a normal faucet. Finally, the inside had the addition of shelves to help organize the electronic components. The product was 3D printed and also made to appear as injection molded.

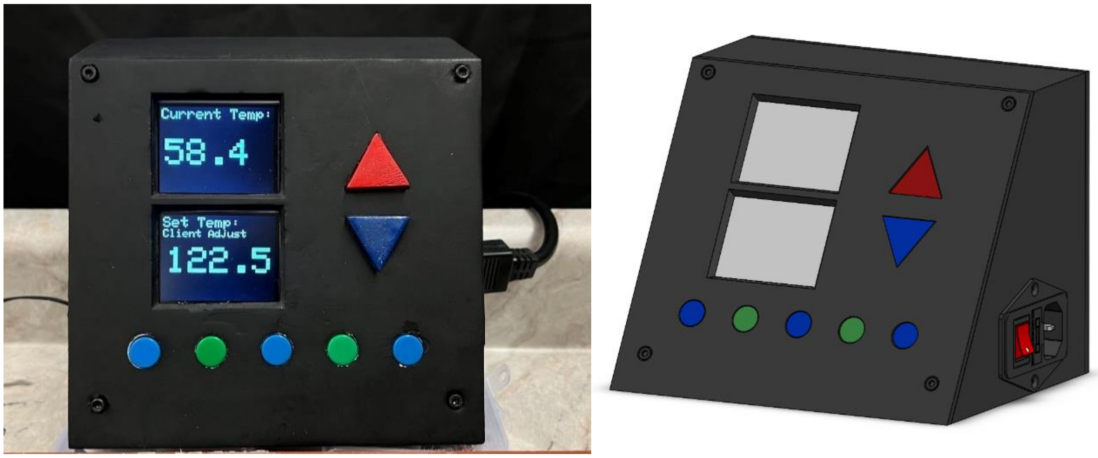

Figure 1.5: Final User Interface with CAD

With this design, the device was tested on a new test bench that embeds the shampoo bowl in the counter similar to an actual salon (Figure 1.6). After several rounds of testing and minor changes, the system performs as well or better than expected, passing every single test and meeting the customer requirements (Table 1.1).

Figure 1.6: Front and Back of Final Test Stand

Table: 1.1: Key Fau-Set Testing Results

Requirement	Minimum Value	Testing Result
Manual Control Rating	7/10 Minimum	7.8
Waterproof	No Water	No Water In System
Ease of Use Rating	4/5 Mimimum	4.14
Temperature Accuracy	±2.5°F	±2.5°F
Settling Time	30s or Less	28.7s Average
Installation Ease	Less than 5 Minutes	4 min 12 sec Average

With a final cost of only $499, the system proposes a solution to water temperature control that can set temperature in less than 30 seconds and is incredibly easy to use. Ending under budget (See Appendix C) and with a product meeting all requirements, DRP Engineering is ready to take the Fau-Set to the next phase and implement small changes for large scale commercialization.

If taken into the commercial market, some small changes need to be made. For example, the faucet attachment system casing is designed and 3D printed to specifically fit the shampoo bowls at Bernadettes. This casing could be redesigned to have a smaller footprint that would allow it to fit on other shampoo bowls and faucets. Additionally, the current power system requires 3 power sources, one for the motor, Arduino, and user interface. This power system should be rectified with one larger power supply before commercialization.

With a final cost of only $499, the system proposes a solution to water temperature control that can set temperature in less than 30 seconds and is incredibly easy to use. The Fau-Set's innovative faucet attachment system can be used far beyond the salon industry for pet grooming, childcare, and for people with disabilities. Ending under budget and with a product meeting all requirements, DRP Engineering is ready to take the Fau-Set to the next phase and implement small changes for large scale commercialization.

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2. Introduction

Hair salons in the US are a nearly $40 billion industry. Shampoo bowls are present in the vast majority of salons but have seen little innovation since they were first patented in 1939. Working with a local hair salon, DRP Engineering has created the Fau-Set, an industry-leading product to enhance client experience by automating the water temperature selection process for shampoo bowls without impacting existing plumbing. Setting the perfect water temperature is a tedious but necessary process to ensure client relaxation and the efficacy of the hair products. In current shampoo bowls, the client and stylist must constantly communicate about the preferred water temperature. The Fau-Set eliminates this feedback loop with a user interface for the stylist to select different temperatures for different products and a remote so the client can make adjustments for their own comfort. In the final design review phase, the team created a final prototype of the Fau-Set to meet the engineering and customer requirements defined in the previous phases. The Fau-Set is the next step in faucet innovation, by saving stylists time and empowering clients to take control of their salon experience. This report details the work of DRP Engineering during the Final Design Review Phase and why the Fau-Set is ready for mass production with some modifications from the final prototype.

3. Background

Working with a local salon – Bernadette's Babeshop – in Lafayette, Indiana, and its co-owner – Katie Perry – DRP Engineering built a system to specifically attach to the eMark Beauty shampoo bowls used there. Current competition on the market is not made for salons and requires extensive plumbing modification (Appendix E). In the critical design review phase, the team prototyped a concept for the Fau-Set comprised of four subsystems: the modified faucet, showerhead, client remote, and user interface (Figure 3.1).

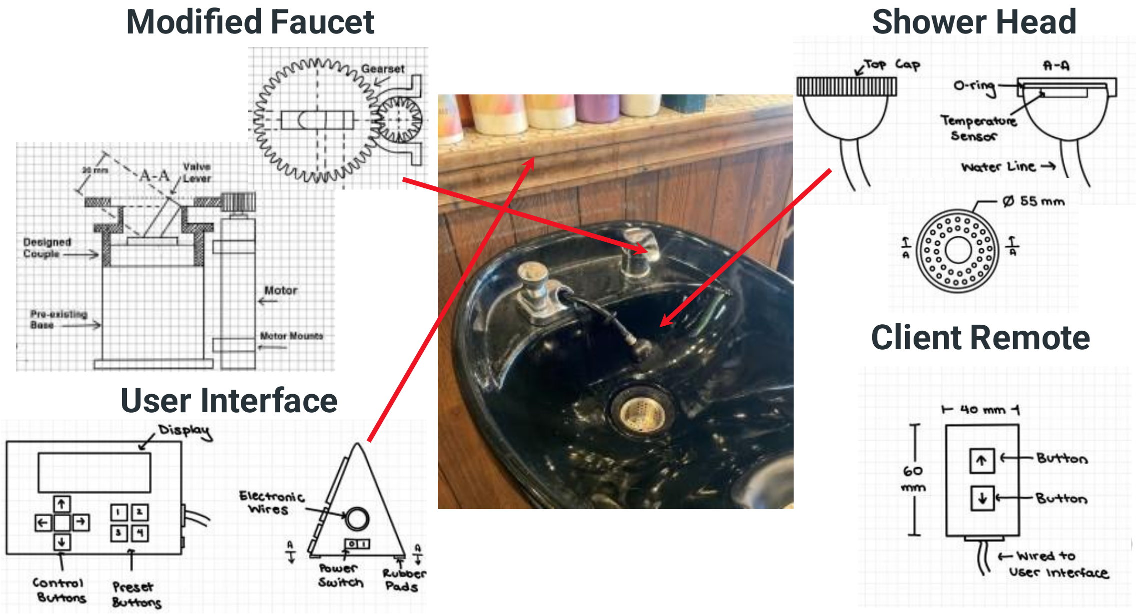


Figure 3.1: Preliminary Design Review Subsystem Sketches

These subsystems were designed using a brainstorming and down selection process detailed in Appendix H. Some key decisions include using buttons instead of dials or a touchscreen for the user interface to make it easier to use with wet hands and using a faucet attachment system that utilizes the original faucet handle to allow for manual control of water flow rate.

In the CDR phase, key milestones included:

1. Finalizing the CAD including sourcing purchased components, designing machined parts, and planning for full system testing and assembly
2. Rapid prototyping key functionalities such as the faucet control mechanism in order to ensure the product would be successful
3. Initial development of a shampoo bowl test bench to allow in-house validation testing at PEARL.

4. Technical Approach

To develop the Fau-Set, DRP Engineering utilized the resources in the PEARL labs to save time and money. Key design features were rapidly prototyped early in the design process in order to ensure all the system requirements could be met. Key components for the prototype were developed based from parts already found in the PEARL lab stockpiles such as the buttons for the user interface. Additionally, the team heavily utilized 3D printing to test parts such as gears before purchasing them. Further hand calculations and FEA was used to iterate through solutions and optimize final components (Appendix I). Finalized CAD drawings and manufacturing drawings were used to machine components, assemble subsystems, and test for fit and function. Each subsystem was tested and iterated before full system assembly occurred. All system requirements were tested through the test plan and were successfully met.

5. Results & Discussion

Faucet Attachment System

The CDR phase saw development of a medium fidelity model of the system, in which every part was 3D printed. For reliability purposes, the high-fidelity prototype would move away from printing and towards machining for components such as the slotted gear and the shaft coupler, as shown in Figure 5.1. The slotted gear was machined using conventional milling as shown in Appendix 3.H to within 0.010” of the desired specification. The final pass was done using climb milling so as to achieve a more polished surface finish. The shaft coupler was manufactured on a lathe, again as shown in Appendix 3.H. However, in order to achieve the desired finish, the automatic feed was disabled and the tool was moved slowly and by hand. The threads on the shaft coupler were successful in mating with the threads on the original faucet base. While the bushing was not intended to be a manufactured part, the fit to the driving gear was too tight and prevented the bushing from freely spinning. Thus, material was removed from the inner diameter 0.001” at a time until the parts fit as intended.

Figure 5.1: Shaft Coupler and Other Machined Parts

3D printed components were further iterated in order to ensure better fit and function with the rest of the components. The height and geometry for the valve lever extender was modified in order to ensure that it could reach its full range of motion without interfering with the shaft coupler and casing. Tolerances for the screw holes and threaded insert holes were adjusted in order easily assemble components. After 3D printing the valve lever extender, top casing, and bottom casing, components were epoxied, spray painted, and sanded in order to have a commercial look similar to that of injection molded components.

To waterproof the modified faucet system, a gasket was manufactured and a waterproof fabric was added to attach between the top casing and valve lever extender. The fabric provided the necessary stretch to allow the valve lever extender to rotate in all directions while ensuring water did not enter from the top of the casing. A limit switch was also attached to the slotted, driven gear so when the valve lever was in the off position, the system would enter standby mode. When in standby mode, the system pauses motor control, allowing for manual control of the faucet position.

The screen also displays “STANDBY” in red print to notify the user of the disruption. The limit switch also indicates to the control system that no water is flowing in standby mode, therefore preventing the system from continuously adjusting the motor to reach the desired temperature. Manufacturing, purchased, and 3D printed parts were then assembled onto the existing faucet base.

Through design iterations, manufacturing, and assembly of components, the modified faucet system was successful in meeting all key requirements, as shown in Figure 5.2. Through the PDR and CDR phase, the modified faucet assembly was designed to control the temperature of the water by rotating the valve lever attached to the existing faucet base. To control the valve lever autonomously, the required torque was calculated and the gearmotor and gear train system was chosen according. After manufacturing and assembling components such as the motor bracket, shaft coupler, and gears to the casing, the system was tested and was successful in rotating the valve lever. Further, components had been chosen to have a minimum end to end gear ratio in order to allow the system to be back drivable and therefore easy for the stylist to override the autonomous system and manually set the temperature if needed. User testing was completed in the FDR phase to ensure that the faucet was easy to rotate when in standby mode and successfully met the criteria.

Another key design innovation was coupling to the existing faucet base while retaining manual control of the flow rate. Through manufacturing a slot in the driven gear and modifying the valve lever geometry, the stylist can easily control the flow rate of the system. The modified faucet casing was also designed to securely fit onto the shampoo bowl within a small profile without clamping down to the edges of the shampoo bowl. In order to do so, the shaft coupler screws onto the existing faucet base and in the process clamps down the bottom casing securely to the shampoo bowl. Through full system assembly and testing, this process for clamping the casing proved successful as the casing would be tightly secured and forces from the motor were transmitted to the casing in order to prevent burnout when stall torque was reached. The final assembly also maintains a small profile, fits within the given space on the shampoo bowl, and retains the original faucet handle and base. Installing the final faucet system also takes less than 5 minutes and is easy for the end user as only a maximum of three tools is needed. Overall, the final faucet assembly was successful in coupling to the existing shampoo bowl, being easily serviceable by the end user, autonomously setting the water temperature, and retaining all features and functionalities of the original faucet.

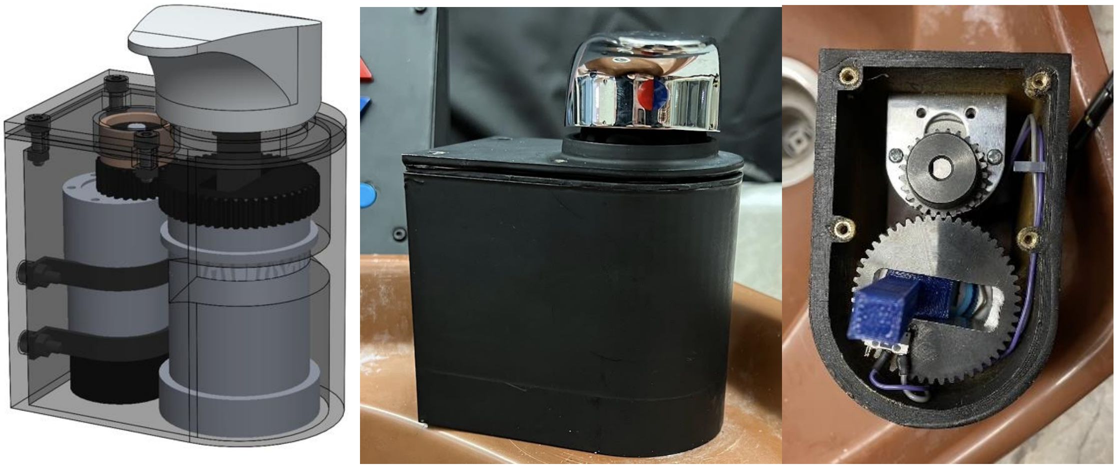


Figure 5.2: Final Faucet Attachment System

Shower Head

From the CDR phase, the design for the shower head was completed, however, small design changes occurred for overall better fit and function. One of the key design requirements was to ensure that the flow rate was enough to wash an individual's hair. Even with the limited water pressure from the aquarium pumps in the test setup, the team was successful in modifying the diameter and number of holes in the custom 3D printed shower head in order to reach this requirement. Another key requirement for the shower head was to ensure that the thermistor would press fit into the inside of the shower head while maintaining a position that allows it to maximize contact with the water flowing out. In order to achieve this, multiple iterations of the shower head were quickly 3D printed and assembled. The original O-ring from the existing shower head was also used for installation and to ensure water did not leak out of the system.

Once the fits and tolerances were determined, the showerhead was spray painted black to match the original look. The thermistor was assembled inside, and putty was used to ensure the hole where the wire was leaving from was sealed. The custom shower head went through extensive testing in order to ensure it functioned as designed and overall was successful in replacing the existing system as shown in Figure 5.3.

Figure 5.3: Final Showerhead System with Implanted Thermistor

User Interface & Client Remote

In the CDR phase, the team discovered that the user interface height could be reduced by 25mm to have a smaller footprint while still accommodating the electronics. Other changes made during the FDR phase was redesigning the front panel to be removal in order to allow easy access to the electronics when prototyping and assembling. The electronics were also placed in various shelves with heavier electronics such as the power supply placed at the bottom in order to increase stability of the user interface. Further dimensions and tolerances were designed and tested in order to ensure space was used efficiently. The layout for the displays and buttons was also finalized and modifications were made to the front panel to allow the screen to be readable and for the buttons to be easily clicked. The overall new design made it easier to manufacture the components, prototype the electronics, and assemble the final system as shown in Figure 5.4.

The screen and button layout were determined through user testing. Five test subjects were asked to rate the readability of the screen and the usability of the buttons on a scale of 1-5. The final design passed with an overall score of 4.14. Further testing details can be found in Appendix L.

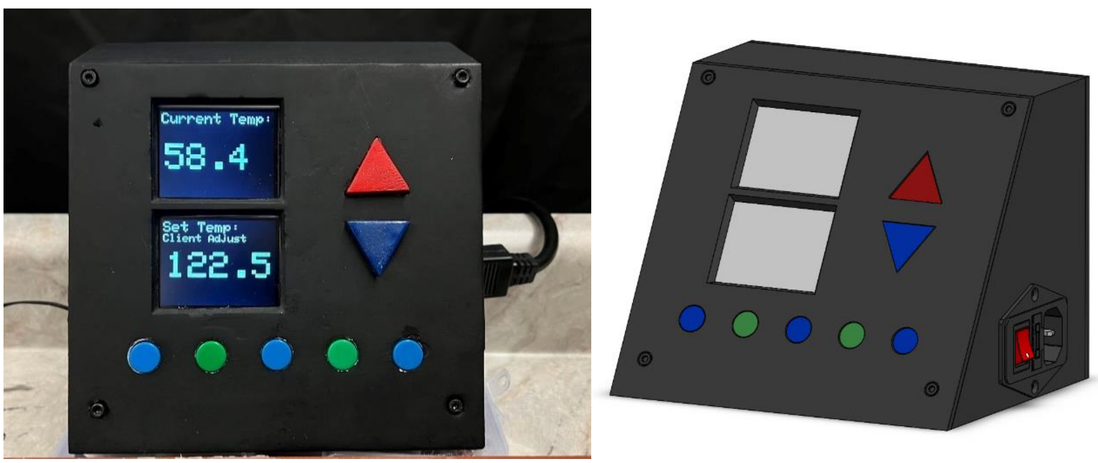


Figure 5.4: Final User Interface with CAD

To begin the FDR phase, the buttons and screens previously tested via breadboard were soldered to a perforated prototype board in the layout determined in the CDR phase. Initially the goal was to have all electronics powered through one port on the side of the user interface. Unfortunately, during testing, noise and current issues between the Arduino, screens, and motor meant the circuits had to be separated to ensure best functionality. The Arduino experienced continual overheating issues from running all of the screens and buttons off of its 5V power supply. Thus, a separate 5V plug was wired to the 5V items, such as the buttons, screens, thermistor, and limit switch. In doing so, the Arduino only provides signal and not power. A separate power adaptor converts 120V AC to 12V DC to run the motors. A shielded cable is used to transfer power to the motor to prevent noise issues with the screen. All circuits are wired together using a common ground.

For the Fau-Set to go into full production, these circuits would need to be rectified using one stronger power supply that can provide enough current and voltage for all components without causing noise issues. DRP Engineering made the decision to continue with validation testing on the Fau-Set instead of spending more time unifying the power system due to time constraints. The updated electronics schematic, as shown in Figure 5.5, minimizes the footprint of the UI, fits all of the electronics and is protected from overheating with the new circuit changes.

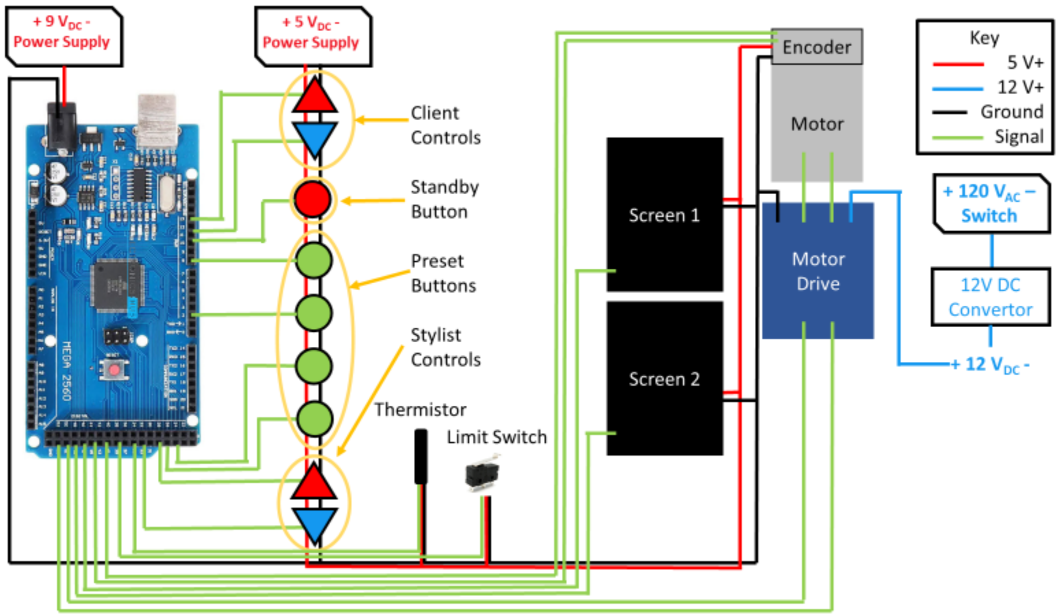


Figure 5.5: Updated Electronics Schematic

Originally the UI had only 4 preset buttons, but after user testing with Bernadette's Babeshop, it was determined that a "standby" button needed to be added in addition to the limit switch in the faucet attachment system. Now stylists can take manual control of the temperature both when the faucet is off or when the standby button is pressed.

The client remote was originally a rectangular prism with two buttons. After 3D printing the casing, it was determined the casing should be slightly reduced in size and have rounded edges to make it fit better in the clients hand as shown in Figure 5.6. The client remote allows the client to adjust the temperature 0.5°F up or down, up to 3°F in either direction. The limit was added as a safety feature to ensure the client wouldn't unintentionally increase the temperature too high and scald themselves. This limit was also chosen to ensure that the initial temperature selected by the stylist was still approximately the temperature used as the stylist will choose the best temperature for the efficacy of the hair products.

Figure 5.6: Final Client Remote with CAD

Although the final prototype is 3D printed, in mass production the user interface and client remote would be injection molded. To match this look, these parts were epoxied, sanded, and spray painted to give it a smooth and even surface. Thermal inserts were assembled onto the 3D printed parts and all components were successfully assembled into the final systems.

Control System

The control system for the Fau-Set was designed with two primary criteria in mind: reduce the overshoot and minimize settling time. These were the primary focus as a small steady state error was acceptable due to the temperature tolerance allowed in the customer requirements. This led to the determination to use a PD controller as it matched the need for reduced time.

To design the controller, the method of direct pole placement was used. This allowed for the choice of the closed loop overshoot and settling time with the knowledge of the plant function which was determined via analysis from a unit step input to the representative system (seen in figure 5.1).

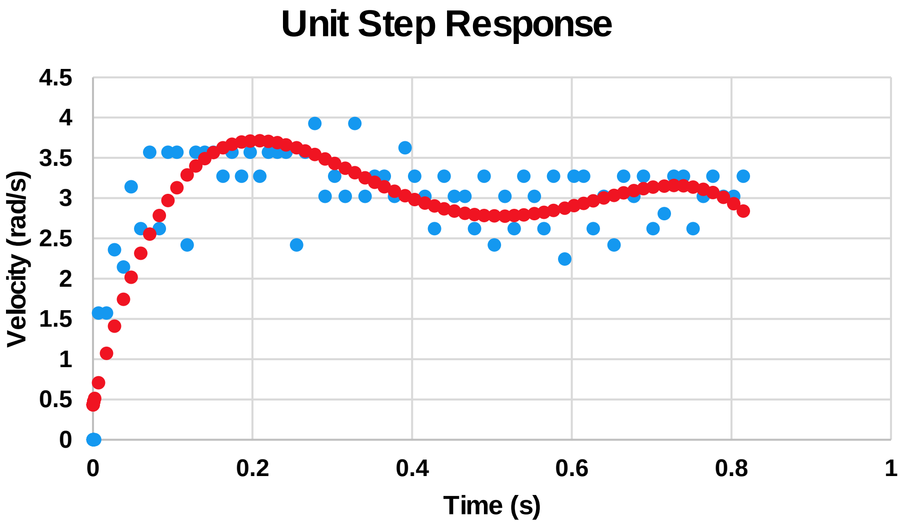


Figure 5.7 Unit Step Response Results

Through the calculations found in Appendix I, the desired closed loop transfer function was found with desired percent overshoot of 10% and settling time of 3 seconds. After direct pole placement analysis, the resulting controller values are a proportional gain of approximately -12 and a derivative gain of approximately -0.5. Through testing, this appeared adequate to meet the system requirements. However, this does not take account for the addition of a set of time delays in the control loops to allow the thermistor to catch up with the sensors and to not create over correction as the thermistor has a noticeable lag.

Appendix I also features a flowchart to better understand the structure of the control loop. In short, the system measures the temperature of the water and compares this to the set temperature. It then determines the direction for the motor purely by the sign of the error and then puts the error through the PD controller. The result of which is then scaled to be between 0 and 1 and then multiplied by 5 to determine the PWM level. The calculated PWM is then added to the dead band region and output to the motor for a period of time determined by the size of the error as well. This is then followed by a delay in the code to allow for the thermistor to detect the change in water temperature and then go through the loop once more.

Product Validation

Throughout the design process, the Fau-Set was put through continuous and rigorous testing to catch issues as the design evolved. This allowed for many early changes such as the addition of a limit switch and better algorithmic structuring. The final prototype of the Fau-Set was then subjected to 20 tests to determine the overall functionality of the device, how well it performs against the customer and engineering requirements, and if the errors determined from the DFMEA were present. The tests were performed on an in house test bench that was built to represent a countertop with the shampoo bowl mounted in it. This test setup gives an accurate depiction of a use case and allows for strong test reliability. The setup can be seen in Figure 5._ below. This stand consists of a laminate countertop and a cabinet that houses the buckets and pumps used to power the shampoo bowl (Figure 5.8). It is 35” tall which is consistent to the height that shampoo bowls are mounted at Bernadettes. Stronger pumps were also added that better mimic the flow rate at Bernadettes.

Figure 5.8: Front and Back of Final Test Stand

A further detail of the tests and the results can be found in Appendix L. Overall, the Fau-Set performed more than adequately. It successfully passed each of the tests performed and met each of the customer requirements. In doing so, it can set the temperature within 30 seconds on average, retains full functionality and the ability to manually control the faucet, and can be easily installed with minimal tools and in minimal time. Table 5.1 highlights some of the key results from testing.

Table: 5.1: Key Fau-Set Testing Results

Requirement	Minimum Value	Testing Result
Manual Control Rating	7/10 Minimum	7.8
Waterproof	No Water	No Water In System
Ease of Use Rating	4/5 Mimimum	4.14
Temperature Accuracy	±2.5°F	±2.5°F
Settling Time	30s or Less	28.7s Average
Installation Ease	Less than 5 Minutes	4 min 12 sec Average

Next Steps

In order to move into mass production, DRP Engineering recommends the following changes to the current prototype:

1. Add a wireless client remote and thermistor to prohibit wires from getting in the way of the stylist and client.
2. Include the ability to customize the four pre-determined presets so stylists can choose the perfect preset temperatures for their products.
3. Injection mold all 3D printed parts for a more professional, robust system

These changes would allow the mass production version of the Fau-Set to be more successful in the consumer market. If a second-generation prototype of the Fau-Set were to be created, DRP Engineering would recommend the following improvements:

1. Rectify the power system to have all components run off one power supply instead

2. Add electrical connectors between all subsystems to make it easier for the end user to set up and dissemble the electronics
3. Adjust the faucet attachment casing to make it fit on other types of shampoo bowls, not just the ones at Bernadette's.
4. Find a more responsive waterproof thermistor to implant in the showerhead to allow the control system to speed up.

With these adjustments, opportunities for the Fau-Set are endless. This proof of concept could be widely expanded to fit other shampoo bowls and styles of faucets. Outside of the salon, the Fau-Set could be used in pet grooming, childcare, and for people with disabilities to ensure accurate temperature adjustment without invasive plumbing modifications.

6. Conclusion

In the past eight weeks, DRP Engineering has produced a final prototype that fulfills the engineering and customer requirements for a shampoo bowl temperature control device. The team finished the project on time and having spent only $541.92 of the $1,000 budget (Appendix A). With the changes detailed in the section above, DRP Engineering asks for the Fau-Set to move into mass production to allow salons across the country to have accurate temperature control at of their shampoo bowls.

7. References

1. “48% Sale Alea Digital Display Kitchen Sink Faucet at Fontanashowers.com || Alea Kitchen.” *FontanaShowers 800-684-4489*, https://www.fontanashowers.com/Alea-Digital-Display-Kitchen-Sink-Faucet-p/bs112tkf.htm.
2. ANSI Standard Limits and Fits (ANSI B4.1-1967,R1974). Coban Engineering. (n.d.). Retrieved March 2, 2022, from https://www.cobanengineering.com/Tolerances/ANSILimitsAndFits.asp
3. “Barbershops IBIS.” *IBIS World*, https://my.ibisworld.com/us/en/industry-specialized/od5806/industry-at-a-glance.

4. Darlington, Hank. “Understanding Gross Profit Margin.” *Supply House Times RSS*, Supply House Times, 28 Dec. 2012, https://www.supplyht.com/articles/95996-understanding-gross-profit-margin.

~~4.~~5. *Drybarshops.com*, https://www.drybarshops.com/service/blow-services/.

~~5.~~6. Free CAD designs, Files & 3D models: The grabcad community library. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (2017, January 19). Retrieved March 2, 2022, from https://grabcad.com/library/carte-de-prototypage-7x5cm-1

~~6.~~7. Free CAD designs, Files & 3D models: The grabcad community library. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (2016, January 24). Retrieved March 2, 2022, from https://grabcad.com/library/iec320-c14-inlet-module-plug-fuse-switch-male-power-socket-10a-250v-1

~~7.~~8. Free CAD designs, Files & 3D models: The grabcad community library. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (2012, November 17). Retrieved March 2, 2022, from https://grabcad.com/library/arduino-mega-2560--1

~~8.~~9. Increment and decrement value using push button. (2017, February 06). Retrieved March 02, 2022, from https://forum.arduino.cc/t/increment-and-decrement-value-using-push-button/435266/6

~~9.~~10. Pololu high-power motor driver 36V9. Pololu Robotics & Electronics. (n.d.). Retrieved March 2, 2022, from https://www.pololu.com/product/756/resources

~~10.~~11. “Salon IBIS.” *IBIS World*, https://my.ibisworld.com/us/en/industry-specialized/od4410/industry-at-a-glance.

~~11.~~12. Thermistor interfacing with Arduino Uno. (2021). Retrieved March 01, 2022, from https://www.electronicwings.com/arduino/thermistor-interfacing-with-arduino-uno

~~12.~~13. “US6913203B2 - Self Powered Electronically Controlled Mixing Valve.” *Google Patents*, Google, https://patents.google.com/patent/US6913203B2/en?q=~patent%2FUS5148824A.

~~13.~~14. Woodward, B. (2022, February 3). 5 easy tips for picking an ADA compliant faucet. Ferguson. Retrieved March 1, 2022, from https://www.ferguson.com/content/trade-talk/tricks-of-the-trade/ada-compliant-faucet-tips#:~:text=If%20so%2C%20you're%20in,twisting%20or%20straining%20your%20wrist

Appendix 1: Project Management

This appendix contains the key project management documentation used by DRP Engineering including the team charter, schedule, budget, and risk register. The charter has not changed since the last report. The team followed the schedule throughout the project. The budget and risk register have been updated to include the new risks and team spending in the FDR phase. The team finished the FDR phase both on time and under budget.

A. Charter

The Team

DRP Engineering consists of five members each with specific roles on the team. Chris Fadel as manufacturing manager; Jennifer Ascher as project manager; Trevor Ladner as validation and engineering lead; Eugenio Frias-Miranda as analysis lead and buyer; and Nitya Agrawal as CAD lead.

Project Scope, Assumptions, and Resources

Working out of the Purdue Mechanical Engineering PEARL labs, DRP Engineering will complete a final prototype by April 21st using a budget of $1000. The Fau-Set will be made to interface only with the shampoo bowls found at Bernadette's Babeshop and minimally alter existing plumbing. Additionally, the team will only pursue solutions that do not require heating or cooling to control temperature and will instead focus on a control system for the existing faucet as specified by the customer. The Fau-Set will also be specifically calibrated with the Bernadette's Babeshop shampoo bowls and may require further calibration or mechanism redesign if used at a different location. For more information about the team's charter, see the attached excel Charter file and a photo of the charter in Figure A.1.

PURDUE UNIVERSITY Mechanical Engineering

ME 463 Senior Design

Project Title: Fau-Set

Team Name: DRP Engineering

Team Members: Jennifer Ascher, Chris Fadel, Eugenio Frias-Miranda, Trevor Ladner, Nitya Agrawal

Vision Statement: We aim to improve the salon experience for stylists and customers by inspiring innovation one faucet at a time.

Problem Statement (Current State)

Current hair salon shampoo bowls do not give stylists specific control of the water temperature making it difficult for them to reliably select the most comfortable water temperature for their clients.

Key Stakeholders (Role, Influence, Interest)

1. Katie Perry, owner of Bernadettes Barbeshop in Lafayette, IN
She will be the end user of the system and the main source of knowledge regarding costmotology
2. eMark Beauty, shampoo bowl maker out of Argyle, TX
The system will be retrofitted onto a shampoo bowl made by eMark Beauty

Business / Society Benefit (Future State)

Develop a temperature control system for salon shampoo bowls to accurately and efficiently adjust the water to a specific temperature specified by the hair stylist to improve the customer experience and save hair stylists time.

Project Scope

IN Scope	OUT of Scope
Developing a system that attaches to the eMark Beauty TLC-B07-W Shampoo bowls at Bernadette's Barbershop.	Adjusting the system to meet other types of faucets or shampoo bowls. Adjusting anything to do with the plumbing attached to the shampoo bowl. Developing a heating/cooling element to control water temperature.

Key Milestones

In the preliminary design review phase, the team will establish the vision, mission, have an initial customer meeting, perform a market analysis, and generate and select a final concept, and create a preliminary budget. In the critical design review, the CAD model and preliminary prototype will be completed. In the final design review a final prototype will be constructed and tested and final modifications to the budget will be performed.

Key Assumptions & Risks

The system will be calibrated and designed to the Bernadette's Barbershop shampoo bowls and may require further calibration or mechanism redesign if used at another location or with another faucet/shampoo bowl.

Team Members & Roles

Chris Fadel - Manufacturing Manager
Jennifer Ascher - Project Manager & Customer Eyes
Trevor Ladner - Validation Lead & Electronics Lead
Eugenio Frias-Miranda - Analysis Lead & Buyer
Nitya Agrawal - CAD Lead

Key Resources Required

Access to water faucet with discrete hot and cold controls while in lab.
Ability to hook up purchased shampoo bowl faucet system to hot and cold water lines in lab for testing
ME machine shop and 3D print lab
Access to Bernadette's Barbershop for final system testing and integration
For our budget we will not exceed $1000

Version: 1

Last Updated: 1/30/22

Figure A.1. Team Charter

B. Schedule

Using Microsoft Project, the team has developed a schedule for the 16-week Fau-Set development. In the preliminary design phase, DRP Engineering created the vision and mission, performed a market analysis, defined system requirements, and went through concept generation and downs election. In the critical design review phase, the team built a preliminary prototype and finalized the CAD model. A testing rig was developed for testing to occur in PEARL Labs. In the Final Design Review Phase, the final prototype was created and validated using the DVP and DFMEA. The project finished on time on April 21st at the final prototype demonstration. For more information about the team's schedule, see the Microsoft Project Plan file submitted with this report.

C. Budget

The final budget of DRP Engineering is shown in Figure C.1. The team mainly used resources available in the PEARL labs to limit spending. Because of this the final expenditures totaled $541.92 of the $1,000 budget. Since the CDR phase, some key purchases include parts to build the new shampoo bowl test stand and waterproof material for the user interface. For a more extensive look at the budget, see the attached excel file.

PURDUE UNIVERSITY Mechanical Engineering

ME 463 Senior Design

Team Name: DRP Engineering **Date:** 21-Apr-2022

PENDING ORDERS

Item Description	How will the item be used for the project?	Vendor	Item Cost	Shipping Cost	Estimated	Quantity
		TOTAL	**$ -**	**$ -**	**$ -**	

COMPLETED ORDERS

Item Description	How will the item be used for the project?	Vendor	Item Cost	Shipping Cost	Purchase date	Quantity
eMark Shampoo Bowl	Testing: Used for modeling and testing the faucet and shower head	Amazon	$ 39.98	$ -	25-Jan-2022	1
Temperature Sensor 1	Showerhead Subassembly: Measures the temperature of water.	Digikey	$ 9.90	$ 6.99	12-Feb-2022	5
Temperature Sensor 2	Showerhead Subassembly: Measures the temperature of water.	Digikey	$ 16.62	$ 6.99	12-Feb-2022	5
Screen	User/Client Interface: Displays the temperature and settings. 2.2" 18-	Adafruit	$ 24.95	$ 12.88	13-Feb-2022	1
Gearmotor	Faucet Subassembly: Powers the motor/gear system	Digi-Key	$ 39.95	$ 6.99	22-Feb-2022	1
Buttons	User/Client Interface: Used to take user input (12 buttons)	Digi-Key	$ 5.85	$ -	22-Feb-2022	1
50 tooth gear	Faucet Subassembly: Gearing up the motor	McMaster	$ 30.03	$ 8.16	22-Feb-2022	2
25 tooth gear	Faucet Subassembly: Gearing up the motor	McMaster	$ 16.64	$ -	22-Feb-2022	2
Bearing	Faucet Subassembly: Transferring loads from the motor shaft	McMaster	$ 5.48	$ -	22-Feb-2022	1
2nd Bearing	Faucet Subassembly: Transferring loads from the motor shaft	McMaster	$ 5.46	$ -	22-Feb-2022	1
Screen second screen	User/Client Interface: Displays the temperature and settings. 2.2" 18-	Adafruit	$ 24.95	$ 12.88	22-Feb-2022	1
2 pack of 32 GB microSD cards	User/Client Interface: Stores data in the user interface screens	Amazon	$ 14.99	-	24-Feb-2022	1
M2 M3 M4 Screws Assortment Set	Nuts and Bolts to hold together faucet assembly and user interface	Amazon	$24.99	-	9-Mar-2022	1
Hilitchi 250-Pcs M2 / M3 /M4 Female	Thermal inserts to hold together user interface	Amazon	$14.84	-	9-Mar-2022	1
MATNIKS Rubber Sheets, Black, 6x6-Inch	Gasket to waterproof faucet assembly	Amazon	$9.42	-	9-Mar-2022	1
Pololu Stamped Aluminum L-Bracket Pair	Brackets to mount gearmotor in faucet assembly	Pololu	$7.95	$4.95	9-Mar-2022	1
Slipstick GorillaPads CB147 Non Slip	Gripper feet for bottom of UI to stop it from sliding	Amazon	$6.99	-	9-Mar-2022	1
THERMISTOR NTC 10KOHM 3435K BEAD.	Showerhead Subassembly: Measures the temperature of water.	Digikey	$ 9.90	$ 6.99	10-Mar-2022	5
Black Delrin® Acetal Resin Rod	Wear-Resistant, Easy-to-Machine, 2-1/2" Diameter, 8576K32, 1 ft,	McMaster	$36.77	-	10-Mar-2022	1
Black Delrin® Acetal Resin Sheet	1/8" Thick, 12" Wide x 24" Length, 8575K213, Extra plastic material	McMaster	$36.98	$8.26	10-Mar-2022	2
Cylewet 25Pcs AC 1A 125V 3Pin SPDT	Limit Switches, tell the system when the Fau-Set is off	Amazon	$6.99	-	10-Mar-2022	1
ELENKER DS18B20 Temperature Sensor	Additional thermistor options in case the ones we chose aren't	Amazon	$12.99	-	10-Mar-2022	
2 x 3 x 8' Stud or Better	Framing for the test bench cabinet	Menards	$ 3.99	-	31-Mar-2022	6
CustomCraft Countertops® 4' Silver	Countertop for test bench cabinet	Menards	$ 31.99	-	31-Mar-2022	1
1/4 x 4 x 4 Oak Plywood Handi-Panel	Walls for test bench cabinet	Menards	$ 28.23	-	31-Mar-2022	4
		TOTAL	**$ 466.83**	**$ 75.09**	**$ 541.92**	

GRAND TOTAL	**$ 466.83**	**$ 75.09**	**$ 541.92**

Figure C.1. Final Budget

D. Risk Register

To ensure on-time and under budget completion of key deliverables, DRP Engineering created a risk register to identify and mitigate key project risks. As shown in Figure D.1, risks were added at each phase. In the FDR phase, most risks revolved around parts failing as the team got closer to the final prototype demonstration. For most items the team purchased duplicates to ensure minimal delays if a part were to break. There were multiple instances of hardware failure, for instance, the test stand's water pumps no longer working and having 3D printed parts breaking such as the valve lever extender. Additionally, the team dealt with multiple electrical component failures, like frying wires or burning the Arduino which resulted in the addition of capacitors and individual powering of all the electrical components. For more examples of key risks mitigated by the team, see the attached Risk Register excel file.

1. IDENTIFICATION						2. CURRENT ASSESSMENT			3. TREATMENT		4. RESIDUAL ASSESSMENT			5. REVIEW, CONTROL, COMMUNICATE	
ID	RAISED BY	DATE RAISED	CAUSE (IF…)	EFFECT (THEN…)	RISK OWNER	P	I	Current Risk Score	STRATEGY	TREATMENT DESCRIPTION	P	I	Residual Risk Score	Commentary	Last Updated
	The originator of the risk	*When the risk was first identified*	*If **uncertain event** occurs due to (or because of) specified **root cause(s).** Tip: ask "why, why, why…" to drill down to root*	*then the **ultimate impact** to our objectives are. Tip: ask "so what, so what, …"*	*Single named owner*	*Probability of the event*	*'Worst' impact*	*Calculated risk score*	*Select overall approach to treatment (Mitigate or Accept)*	*Summary of the treatment responses (actions, controls, fallbacks) that treat the risk.*	*Probability of the*	*'Worst' impact*	*Calculated risk score*	*Any additional notes, comments or actions*	*Enter the last review or update date for the risk*
1	Jennifer	26-Jan-22	Team member gets covid	May be unable to come to class or entire team might become quarantined	Jennifer	M	M	10	Accept	Already have zoom link set up and have online file sharing so team members can participate virtually if necessary. Only meet with masks on to prevent entire team getting covid at once.	M	L	5	Eugenio, Trevor, and Chris have all have Covid at this point so it's less of a risk	1-Mar-22
2	Jennifer	20-Jan-22	eMark beauty faucets go out of stock	the team would be unable to have a device to test with or experiment on	Jennifer	H	H	20	Mitigate	Team ordered the in stock faucet early in the semester and decided to not use the entire shower bowl setup because that was fully out of stock and wouldn't be in stock until May	M	L	5	Faucet arrived and is in use	1-Mar-22
3	Eugenio	18-Jan-22	Raspberry pi's continue to be out of stock around the globe	We will be unable to have a main control system for the design	Nitya	H	H	20	Mitigate	Team will talk with e-shop to determine if there are any available for use. If not, Nitya may have one available for use if her parents are able to ship her one. Could also switch to arduino if necessary	H	L	9	Team switched to arduino and has an Arduino Mega from the E-Shop	1-Mar-22
4	Nitya	27-Jan-22	Covid causes shipping delays	Failure to meet key deliverables	Nitya	H	M	14	Mitigate	Adjust design to utilize items that are already in stock in the PEARL lab. Also will order items as early as possible.	M	L	5	Talked with e-shop and Mike Sherwood about parts available to us. Also have many parts that can be 3D printed instead of being ordered.	30-Jan-22
5	Trevor	19-Jan-22	Covid continues to get worse in the US/Lafayette area and we can no longer test at Bernadettes	Failure to meet key deliverables	Trevor	L	M	6	Mitigate	Develop an in lab testing apparatus using a gravity feed system	L	L	1	Team working with Mike Sherwood to develop gravity feed system. Will have more information once team has access to lab room.	30-Jan-22
6	Nitya	26-Jan-22	Available thermocouples do not have resolution that is fine enough for our specifications	Control system won't be accurate enough to do fine temperature adjustment	Nitya	M	M	10	Mitigate	Test devices early on and prepare for redundant temperature sensors if necessary	M	L	5	Trevor has robust testing method set in DVP for temperature resolution	30-Jan-22
7	Nitya	20-Jan-22	Shampoo bowl at Bernadettes is no longer functional	No testing can occur at the customer's location	Nitya	L	M	6	Mitigate	Use lab testing apparatus with gravity feed system, also reach out to other local hair salons and see if they have availability for us to work with them	L	L	1	Team built in house test rig using aquarium pumps, a donated shampoo bowl, and five gallon buckets.	1-Mar-22
8	Chris	24-Jan-22	Purchased parts/stock break during mnfg/modification	Parts are unusable and covid makes it difficult to get things shipped on time	Chris	M	M	10	Mitigate	Purchase redundant stock if cost effective or use cheaper and more available stock to practice the manufacturing on before using the actual stock. Also expensive components can be 3D printed to practice the manufacturing.	M	L	5		30-Jan-22
9	Chris	27-Jan-22	Testing causes water damage on arduino or other electronics	Electronic system won't be able to work and the current covid shipping delays make it difficult to get replacements.	Chris	H	H	20	Mitigate	Develop in depth testing strategies that separate electronic components and water. Additionally the team can access extra arduinos that have already been sourced.	M	L	5	Nitya has extra arduinos and others available in E-Shop	30-Jan-22
10	Trevor	25-Jan-22	Code corrupts or is lost	Failure to meet key deliverables	Trevor	M	H	15	Mitigate	Team created robust backup procedures for code and CAD on Github and GrabCad	L	L	1	GrabCad monitored by Nitya, Github monitored by Trevor	30-Jan-22
11	Trevor	24-Feb-22	Global conflict escaltes to the extent that the US institutes a draft	Nitya and Jennifer will be left to pick up the pieces	Trevor	L	L	1	Accept		L	L	1		1-Mar-22
12	Jennifer	15-Feb-22	Another team steals parts already acquired by the team	The team will have to locate and possibly purchase new parts	Jennifer	H	M	14	Mitigate	Team locked up important components in a locker	L	L	1		1-Mar-22
13	Trevor	17-Feb-22	Arduino catches on fire during testing	Testing will be set back	Trevor	L	H	11	Mitigate	Trevor has done extensive research to ensure the correct amount of current and connections will be used with the Arduino. Mike Sherwood will also be consulted to go through the circuitry.	L	M	6		1-Mar-22
14	Chris	21-Feb-22	Water gets on test setup	Then the test setup will stop working, possible safety hazard	Chris	M	H	15	Mitigate	Plastic enclosure will be made for test bench electronics	L	L	1		1-Mar-22
15	Chris	17-Feb-22	Test bench breaks during transport	Team will be unable to test in house	Chris	M	H	15	Mitigate	Build test bench stand with wheels so the sink won't have to be picked up	L	L	1		1-Mar-22
16	Nitya	14-Feb-22	Driven gears break during machining	Team will be unable to build faucet coupling system on time	Nitya	M	M	10	Mitigate	Team purchased extra gears to have as backup	L	L	1		1-Mar-22
17	Eugenio	2-Feb-22	If a team member gets stuck abroad during their spring break trip	The team will be unable to meet deliverables on time	Eugenio	L	H	11	Mitigate	Eugenio and Jennifer who are both going abroad for spring break will bring their laptops and anything else they would need to participate in the team if people get stranded due to Covid	L	L	1		1-Mar-22
18	Eugenio	12-Apr-22	Test bench water pump stops working	The team will be unable to test in house	Eugenio	M	H	15	Mitigate	Team purchased extra pumps to have as backup	L	L	1		12-Apr-22
19	Eugenio	12-Apr-22	Valve lever extender breaks during testing	Testing will be set back	Nitya	M	M	10	Mitigate	Team will 3D print extra valve levers to have as backup	L	L	1		12-Apr-22
20	Eugenio	12-Apr-22	Go over budget limit	Ask for permission for funds beyond scope of project	Eugenio	L	L	1	Accept				#N/A		12-Apr-22
21	Eugenio	12-Apr-22	Virtual communication causes final recordings of product to be unclear	Product will not be presented effectively	Chris	L	M	6	Mitigate	Set earlier deadlines and start recording the Fau-Set early on. Ensure presentation is practiced multiple times	L	L	1		12-Apr-22
22	Eugenio	12-Apr-22	Prototype is not tested and validated against customer needs/at Bernadette's	Prototype will not meet technical specifications or be presentable at an acceptable standard	Eugenio	L	H	11	Mitigate	Perform extensive testing on prototype and verify initial test plan	L	M	6		12-Apr-22
23	Eugenio	12-Apr-22	Wiring fries during testing	Testing will be set back	Jennifer	M	M	10	Mitigate	Team will purchase the required materials in order to replace fried wiring	L	L	1		12-Apr-22
24	Eugenio	12-Apr-22	Disregard for documentation and organization	Testing will be unsafe due to loose parts and poor documentation/failure to meet deliverables	Eugenio	L	M	6	Mitigate	Maintain clean PEARL lab area, update documents consistently	L	L	1		12-Apr-22

Figure D.1. Risk Register

Appendix 2: Business & Marketing

This appendix contains the market analysis and value proposition of the Fau-Set and explains how DRP Engineering plans to break into the market. The market analysis and product cost has not changed since the preliminary design review report however the value proposition has been updated with a new profit margin and recommendations for the next phase.

E. Market Analysis

Salons and barbershop are a large industry in the United States. With 874,000 salons and 109,000 barbershops each having 2-3 shampoo bowls, the Fau-Set has the opportunity to sell over 3,000,000 units. The salon industry on its own is a 40-billion-dollar industry with customers spending upwards of $50 just for shampoo. Other treatments such as perms and hair dying can cost hundreds of dollars and take many hours and multiple trips back and forth to the shampoo bowl [5][11].

To better understand the problem, DRP Engineering partnered with Bernadette’s Babeshop, a salon in Lafayette, Indiana, and its co-owner Katie Perry. After meeting with Katie and going to the salon, the team was able to generate personas to better understand their customer. Three personas were generated: one of Katie Perry, one of an elderly client, and one of a typical working mom, seen in Figures E.1-3.

Katie Perry

Salon Co-Owner

Katie Perry is a co-owner of Bernadette's Babeshop in Lafayette, Indiana. She graduated from Purdue with a graphic design degree but went to cosmetology school after and started working at a national salon chain. Her clientele there grew and 9 years ago she was able to start her own salon, Bernadettes. It was so successful she was also able to start a barbershop, Third Street Barbershop, down the street.

"When the salon is busy, I feel like I'm being pulled in all directions."

As a stylist and entrepreneur, her duties include taking care of customers at the front desk, cutting customers hairs, and shampooing the clientele. She also has to take care of the day to day business operations at Bernadette's and Third Steret Barbershop. She is constantly on her feet having to try and adjust the clients shampoo water temperature due to multiple shampoo bowls being used at the same time, occasionally burning herself in the process. She is always interested in new products that she can use to make her life at the salon easier and considers them an investment in her small business.

Experience Using Shampoo Bowls

- Manual Temperature Control
    - Unnecessarily trivial and tedious process
    - Every customer has individual preferences
- Brands:
    - eMark Beauty Shampoo Bowl
    - At Home Temperature control faucet

Motivations for Using Fau-Set

- Increase customer satisfaction
- Easier work day
- Increase conversation quality between salonist and customer

Expectations for Fau-Set

- Easy to understand user interface
- Worthwhile investment
- Effective and complete water resistant seal
- Accurate temperature measurements
- Doesn't require extensive installation or plumbing modification

Figure E.1. Salon Owner Persona

Juliana Bravos

Bernadette's Babeshop Regular

Juliana is a local downtown staple since retirement. She is a regular in multiple shops of downtown Lafayette, IN - especially Bernadette's where she goes to get her cut and color every week. Juliana considers the salon one of her primary social outings of the week - she gets to spend hours talking to her friends about the juicy gossip of the town.

"I look forward my weekly salon appointments, but it's gotten harder to stay comfortable the older I've gotten."

Everytime she goes to get her hair cut, she loves when she gets her hair shampooed. However, as she is getting older, her scalp is becoming much more sensitive and she has to regularly tell her stylist to decrease the water temperature. She worries that sometimes she might get burnt, but trusts that the stylists know what they're doing.

Experience Using Shampoo Bowls

- Manual Temperature Control
  - Constantly having to ask her stylist to adjust temperature
  - Uncomfortable at times because of hot water
- Brands:
  - Uses whatever her stylist has/recommends

Motivations for Using Fau-Set

- Feel safer at the salon
- No need to disrupt conversation to ask for temperature adjustment

Expectations for Fau-Set

- Keeps client safe
- Adjustable for client
- Does not affect the shampoo experience or salon experience by interfering with noise

Image Source:
https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.istockphoto.com%2Fphoto%2Fportrait-of-carefree-70-year-old-hispanic-woman-gm1211337943-351252929&psig=AOvVaw0xqDFumiLGKZ7COAeLxF1W&ust=1643922174981

Figure E.2. Salon Client Persona

Bess Heth

Bernadette's Babeshop Customer

Bess Heth is a 34 year old civil engineering professor at Purdue University. She is married to her husband Matthew who is a civil engineer at a local engineering firm. Their adopted daughter Heather just started kindergarten last fall. She has been getting her haircut at Bernadette's Babeshop since she was a graduate student at Purdue and her entire family goes there monthly to get a fresh cut.

"When I go to a salon, I want it to be quick and relaxing."

As a professor and a mom, Bess wants to be in and out as quickly as possible while also savoring every relaxing moment of the shampoo and head massage. Now that she's found Bernadette's Babeshop she is a loyal customer and won't go anywhere else to get her hair cut. Her daughter Heather loves going to the salon to get her hair cut and sit in the "big girl hair cut chair". When Bess isn't at the salon, she loves building legos with Heather and baking.

Experience Using Shampoo Bowls

- Manual Temperature Control
    - Interrupts her conversation with her stylist in order to select the correct temperature
    - Can take too much time to get the right temperature
- Brands:
    - Uses whatever her stylist has/recommends

Motivations for Using Fau-Set

- Adjust water temperature slightly while getting her hair washed
- Increase conversation quality between her and the stylist
- Save time having to get the perfect temperature by hand

Expectations for Fau-Set

- Easy to understand client interface
- Unobtrusive to the relaxing shampoo experience
- Speeds up the hair washing process

Figure E.3. Salon Client Persona

After generating personas for key potential customers, it is clear that the salon industry needs a way to moderate temperature at their shampoo bowls. Most existing patents, like the mixing valve patent shown in Figure E.4 require extensive plumbing modification and installation. Although this patent is self-powered by the water flow, the plumbing modification is extensive enough to outweigh the benefits of not requiring a power source [13].

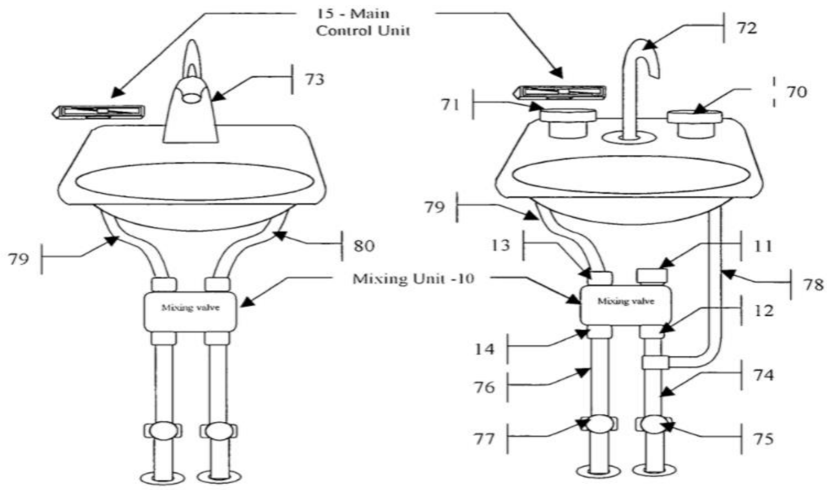


Figure E.4. Mixing Valve Patent

Consumer products on the market such as the Alea Smart Faucet, Figure E.5 are incredibly expensive with a retail price of over $900 and they are unable to interface with the extendable showerhead of a shampoo bowl. [1]

Figure E.5. Alea Smart Faucet

Table E.1 shows a comparison of two competitors to the Fau-Set. Although they have their pros and cons, none of them can work with a shampoo bowl which is the key goal of the Fau-Set.

Table E.1. Comparison of Fau-Set's Main Competitors

Product	Alea Smart Faucet	Mixing Valve Patent
Pros	• Accurately controls temperature	• Accurately controls temperature • Self-powered
Cons	• Unable to interface with shampoo bowl • Retail Price of $964.10 • Must replace entire faucet to install	• Unable to interface with shampoo bowl • Extensive plumbing modification necessary for install

Using the knowledge from the market research, DRP Engineering believes the Fau-Set is able to break into the market and service the booming salon industry. Conversations with stylists like Katie Perry and analysis of the competition led to the creation of key engineering requirements and constraints (see Appendix G) such as installation requiring no major plumbing modifications.

F. Value Proposition

Table F.1. Value Proposition Breakdown

Manufacturing Cost	$ 401.40
Final Selling Price	$ 499.00
Gross Profit Margin	25%

The approach used by DRP Engineering to analyze the financial performance of the Fau-Set once it hits its market was made through primarily deciding on a final selling price. To ensure fulfillment of customer's needs the Fau-Set was constantly benchmarked with patents and products out in the market in order to determine a price range of approximately $500. This makes it cheaper than other competitors but still reasonably priced for the salon industry which invests frequently in new products that enhance their customer experience. Barber chairs, for example, can cost upwards of $800. Plus, with customers paying upwards of $50 for just a blowout and sometimes $100 or more for a cut and color service, stylists would be able to afford an investment in a Fau-Set [3, 4, 5, 11]. The final profit margin of 25% is consistent with the faucet industry and places the product cost at $499 (Table F.1).

If moved into mass production, the Fau-Set cost could be less given the 3D printed parts becoming injection molded. Additionally, making the Fau-Set attach to different shampoo bowls by modifying the outer faucet attachment casing expands the market to salons across the US and opens door for the Fau-Set to work outside of salons. From pet grooming, to childcare, to people with disabilities the ability to control the temperature of a faucet or shower with minimal plumbing modifications gives the Fau-Set a larger market than just salons.

Appendix 3: Design Process

This appendix contains the key engineering and system requirements and details DRP Engineering's concept generation and down-selection phase which led to the creation of a final design.The FMEA, BOM and sourcing plan, CAD, analysis, and validation plan have all been updated since the CDR phase.

G. Engineering Requirements & Constraints

Key requirements were determined based on customer preferences and engineering constraints. Requirements were created for the major components of the design including the faucet, user interface, showerhead, client interface, electronics, and installation as listed in Table G.1. Since the CDR, the engineering requirements have not been seriously adjusted as the design has instead been adjusted to meet the engineering requirements. For a full account of how the Fau-Set stacks up against these engineering requirements, see Appendix L.

Figure G.1: Temperature Required Range and Preset Values

Table G.1. System Requirements for Each Subsystem

	System Requirements
General	Control the temperature of the eMark Beauty Tilting Shampoo Bowl at Bernadette's Barber Shop
	Securely mounted to the shampoo bowl
	Vary the temperature of the water between 60 and 115°F
	Reach within 2°F of the expected temperature in less time than the average stylists takes for temperatures between 85 and 115°F
	Should be waterproof
	Have a structural factor of safety of at least 1.5
	Operational for at least 5,500 cycles without needing maintenance
Faucet	Shall not physically impede the shampoo bowl, stylist, or customer
	Shall not exceed 5 kg
	Should allow the stylist to still manually override and control the temperature and flow rate of the faucet
	Should not be exceedingly loud
User Interface	Allow the customer to set the temperature
	Display when the expected temperature is met
	Display the current temperature
	Must be easy to read
	Must be able to change temperature with wet hands, when gloves are being used, and when there is product on the gloves
	Must allow for four main preset values (regular, sensitive scalp, fashion colors, and color-out) and can be modified based on the stylist's need (shown in Figure G.1)
Shower Head	Should communicate with the controlling device
	Should attach to the head of the shower
	Should have a tolerance of at least 2°F
Client Interface	Must be easy to use for the client.
	Must have absolute control of the water temperature
Electronics	Powered using 120 V AC power outlet
	All other electronic components should input either 5 or 12 V
Installation	All components should be repaired or replaced using common hand tools
	Installation should not require external plumbing

H. CAD

This section contains the CAD for the Fau-Set. It also has the brainstorming, down-selection, and initial sketches section which remain unchanged from the CDR. An FDR Design Changes section was added to detail the design changes that transpired in the past 8 weeks. Additionally, the Buy vs Make, Tolerancing, and Materials tables have all been updated. All updated CAD drawings and operations sheets can be found attached to this submission.

Brainstorming

The team used an exercise called 'brain writing' to generate ideas for concepts. With this, each member sketched three separate ideas on a piece of paper. Once the first iteration was done, the papers were passed to a different person who would add on to each idea. Once the papers had made their way back to the original writer, all ideas and steps along the way were organized into different groups based on similarity of function and subsystems. The best ideas were organized into one group for further purposes of down selection. An image of these top ideas is shared in Figure H.1.

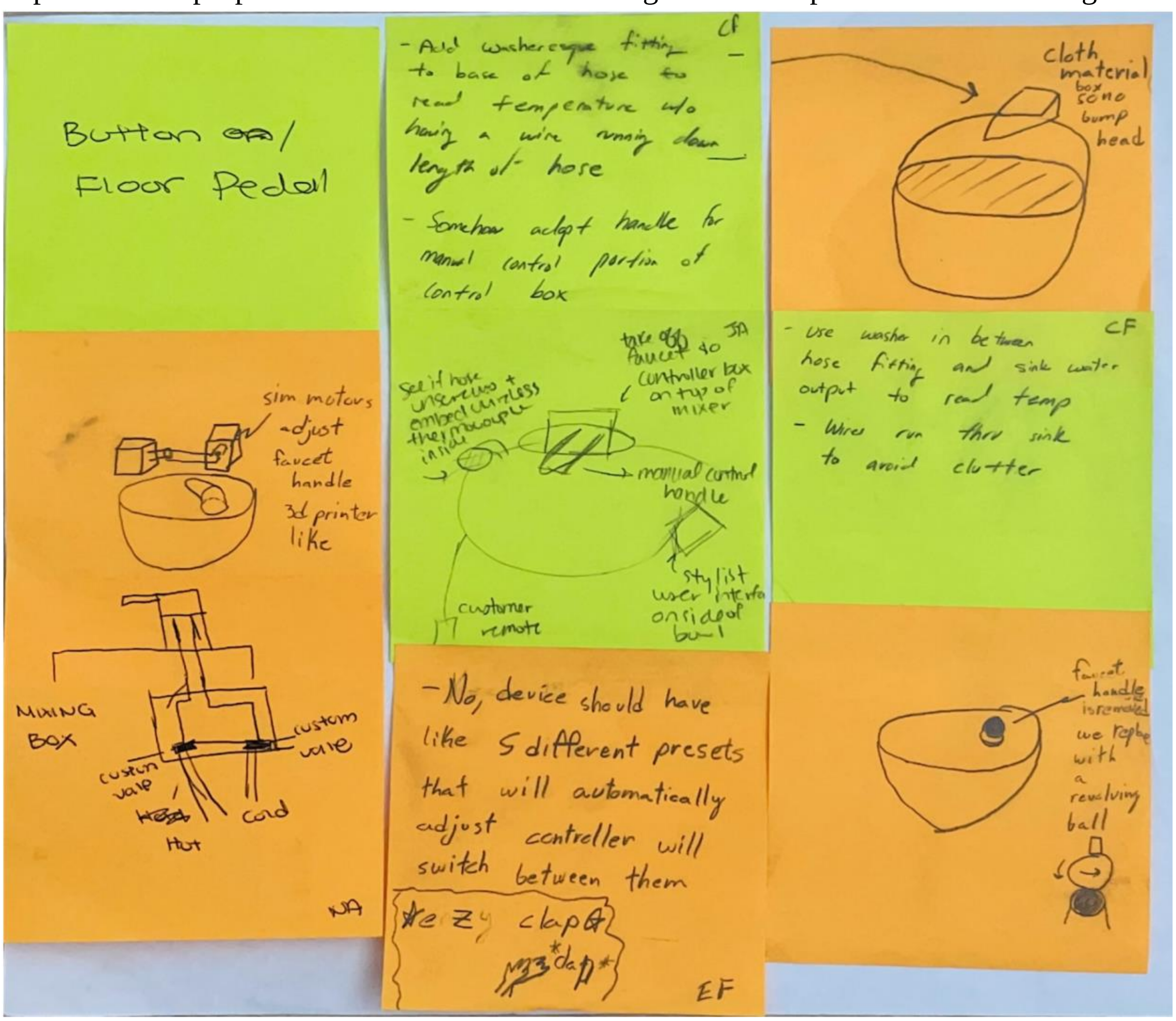


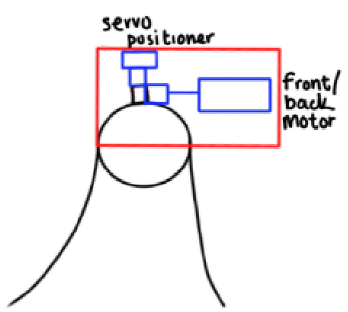
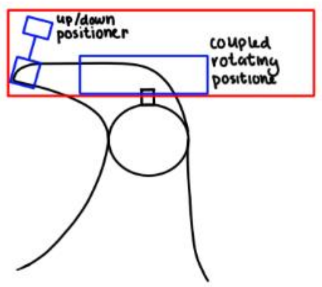
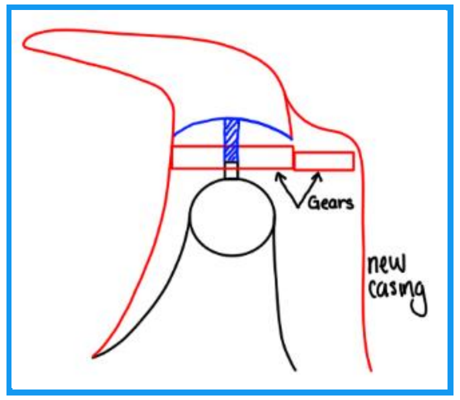
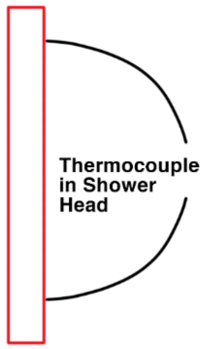
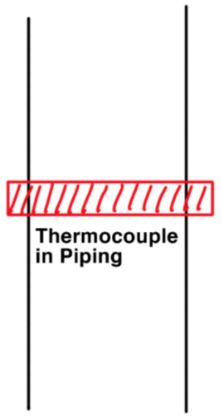
Figure H.1. Top ideas from brain writing exercise

The main takeaways from this exercise were again the different sub functions that the team needed to identify were placement of the thermocouple, placement of electronics, the method by which the device interfaces with the faucet, and the method by which the user interacts with the UI.

Down Selection & Sketches

The best sub function ideas were organized into a morphological chart (Table H.1). Reasoning on each individual selection came from our key system requirements, a combination of engineering requirements and customer feedback. The chosen option for each is highlighted in green. Planned analysis for this final concept comes in the form of calculating controller values such as settling time and percent overshoot as well as the necessary gear ratios and a shape synthesis of the outer shell to determine the necessary thickness. The summarized final design from the end of the PDR is seen in Figures H.3-6.

Table H.1. Morphological Chart
Selected options are highlighted in green

Subsystem	Option 1	Option 2	Option 3	Option 4	Justification:
Power	120 V AC Power Outlet	Commercial Battery Pack	Custom Li-Ion Battery Pack		Outlet availability right by sink, no recharging for customer
User Interface Inputs	Touch Screen	Buttons	Dial	Foot pedals	Easy to use while wearing gloves and with product, allows for presets
User Interface Placement	Side of bowl	Counter top	Side of counter	Portable System	Doesn't obstruct shampoo bowl tilt, extra space on counter. No worry about full waterproofing.
Handle Modification				Replace entire valve system	Minimizes footprint on shampoo bowl, still allows for user control, minimizes impact on existing plumbing
Client Controls	Touch Screen	Remote w/ buttons	Remote w/ dial	Install in chair	Don't have to hold it over your head in order to operate it, tactile so you can feel it even while you're laying down, only need small adjustments
Temperature Sensor					Hose head detaches so it's easy to reproduce with a slot for a thermocouple
Temp sensor communication	Wired	Wireless			No battery pack needed for temp sensor, location to thread the wire
Flow rate control	Controlled by user	Controlled by motor	Motor control with manual override		More modification for each user and it's not currently an issue for the stylists
Correct temp notification	Alarm	Light color change	Vibration		Cheap, stylists don't have to be looking at it, can implement warning system

			Functional Requirements													
		Direction of Improvement	▼	▲	□	□	▲	□	▼	□	□	▼	Customer Competitive Assessr			
Relative Weight	Customer Importance	Customer Requirements	Product Cost	Factor of Safety/Water Resistance	Usability of UI	Number of Control Methods	Ease of Installation	Resolution	Settling Time	Customizability	Compatible Designs	Interference w/ Faucet Assembly	The Fau-Set	Market Solutions	Self-Powered Mixing Valve Patent	Existing Faucet Design
9%	6	Inexpensive	●	○	▽	●	▽	○	○	○	▽	○	7	1		9
13%	9	Sturdy/Robust/Waterproof	○	●	▽	○	○	▽	▽	▽	▽	▽	9	9	9	9
13%	9	Easy to Use (UI)	▽	▽	●	●	●	○	●	○	▽	○	9	7	7	4
12%	8	Multiple Control Inputs	●	○	●	●	○	▽	▽	○	▽	▽	9	1	1	1
7%	5	Easy to install	▽	○	▽	▽	●	▽	▽	▽	○	●	6	1	1	5
10%	7	Fine Temp Resolution	○	▽	●	▽	▽	●	○	●	▽	▽	5			4
13%	9	Quick Adjustment	▽	▽	●	▽	▽	○	●	▽	▽	▽	6			1
6%	4	Programmable Presets	▽	●	●	▽	▽	○	▽	●	▽	▽	9	1	1	1
9%	6	Interfaces w/ Shampoo Bowl	▽	▽	●	▽	▽	▽	▽	●	●	▽	9	1	1	9
7%	5	Nonintrusive	▽	○	▽	○	●	▽	▽	▽	●	●	6	1	1	9
		Importance Rating Sum (Importance x Relationship	311.8	323.5	605.9	411.8	373.5	264.7	350.0	367.6	244.1	261.8				
		Relative Weight	9%	9%	17%	12%	11%	8%	10%	10%	7%	7%				
		The Fau-Set		0.81	1.53	1.08	0.66			0.9	0.63	0.42	**6.03**			
		Market Solutions		0.81	1.19	0.12	0.11			0.1	0.07	0.07	**2.47**			
		Self-Powered Valve Patent		0.81	1.53	0.12	0.11			0.1	0.07	0.07	**2.81**			
		Existing Faucet Design		0.81	0.68	0.12	0.55			0.1	0.63	0.63	**4.37**			
		Technical Competitive Assessment														

Correlations	
Positive	+
Negative	-
No Correlation	

Relationships		**Weight**
Strong	●	9
Medium	○	3
Weak	▽	1

Direction of Improvement	
Maximize	▲
Target	□
Minimize	▼

Figure H.2: House of Quality

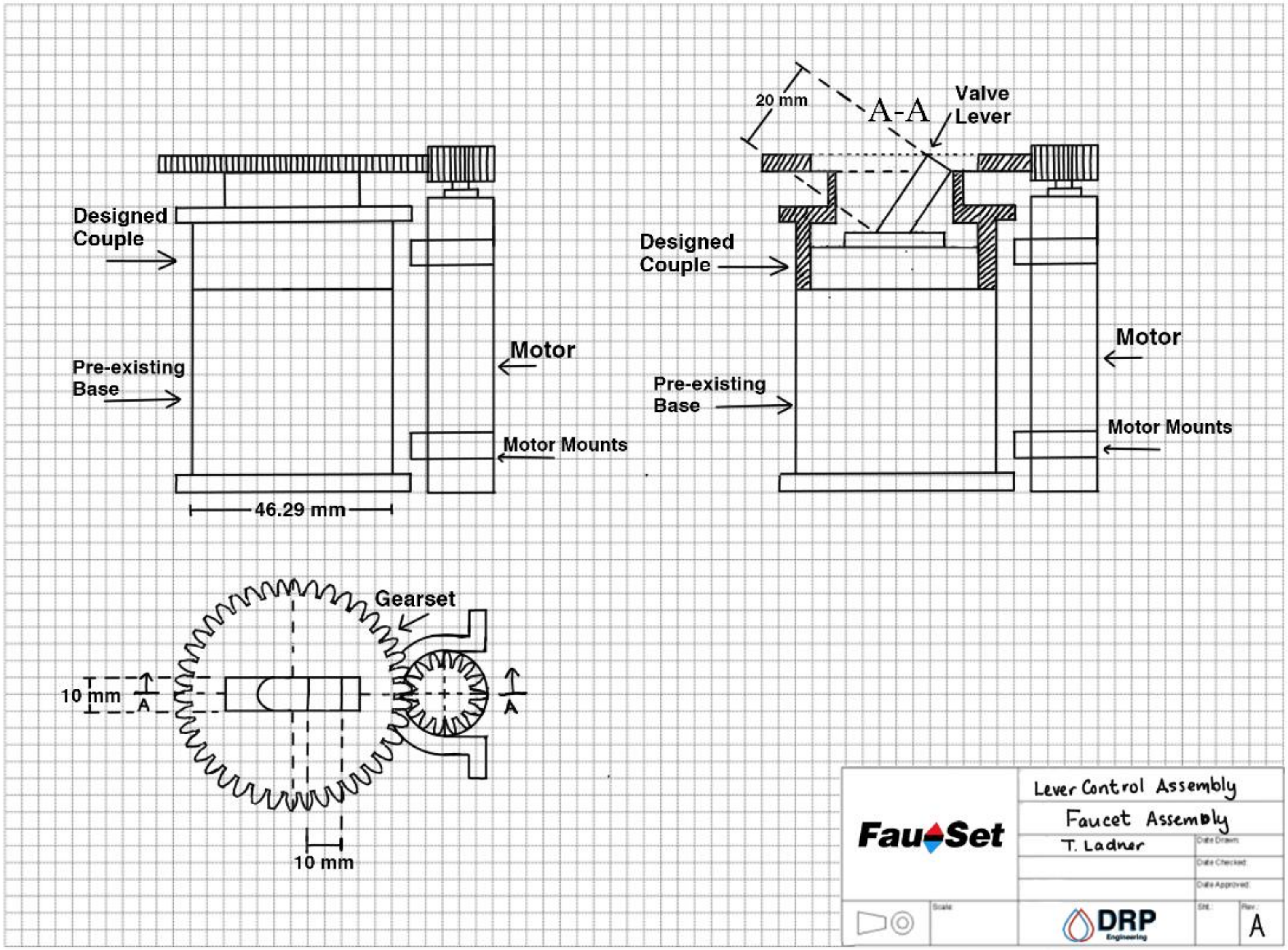


Figure H.3. Level Control Assembly Drawing

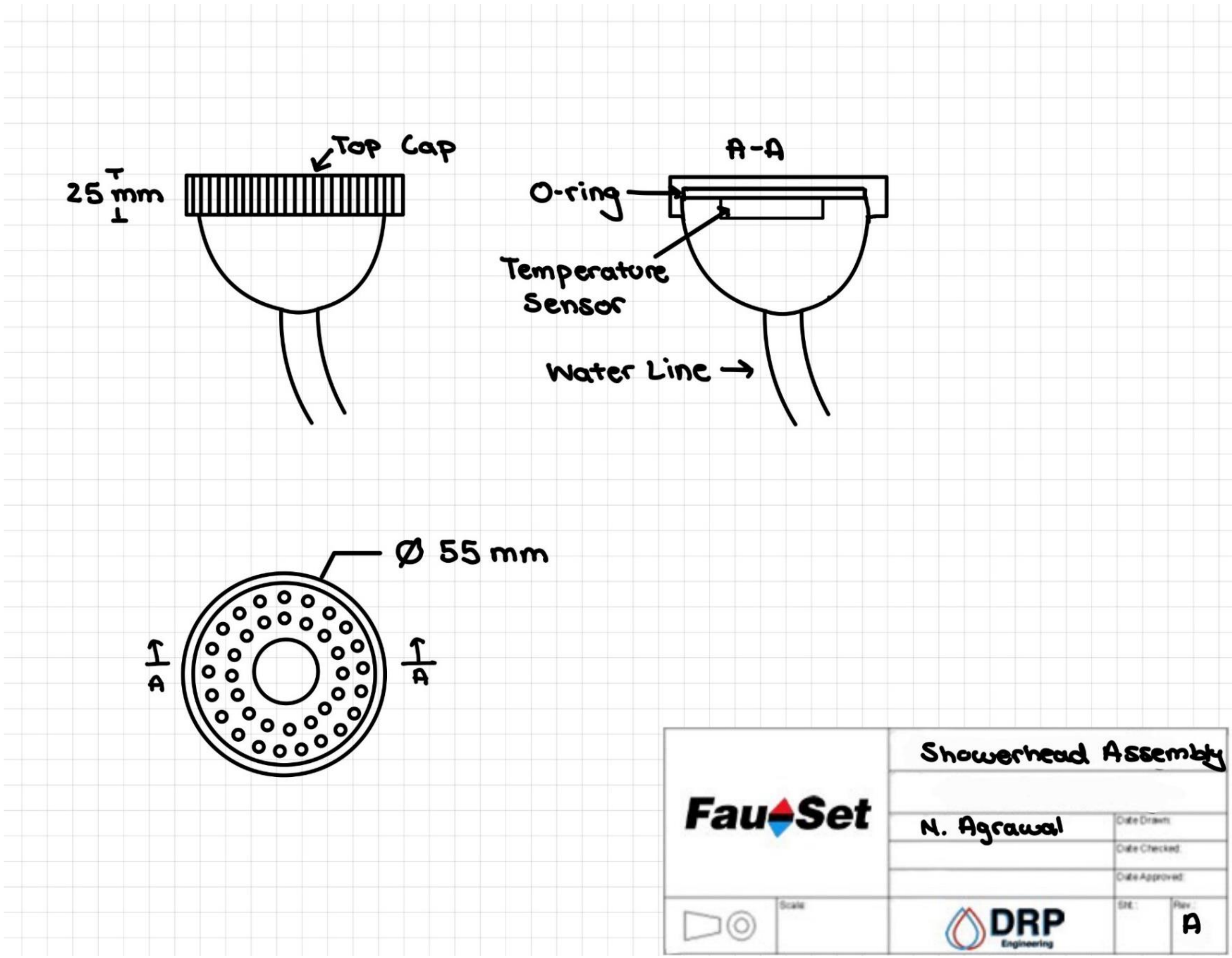


Figure H.4. Showerhead Assembly Drawing

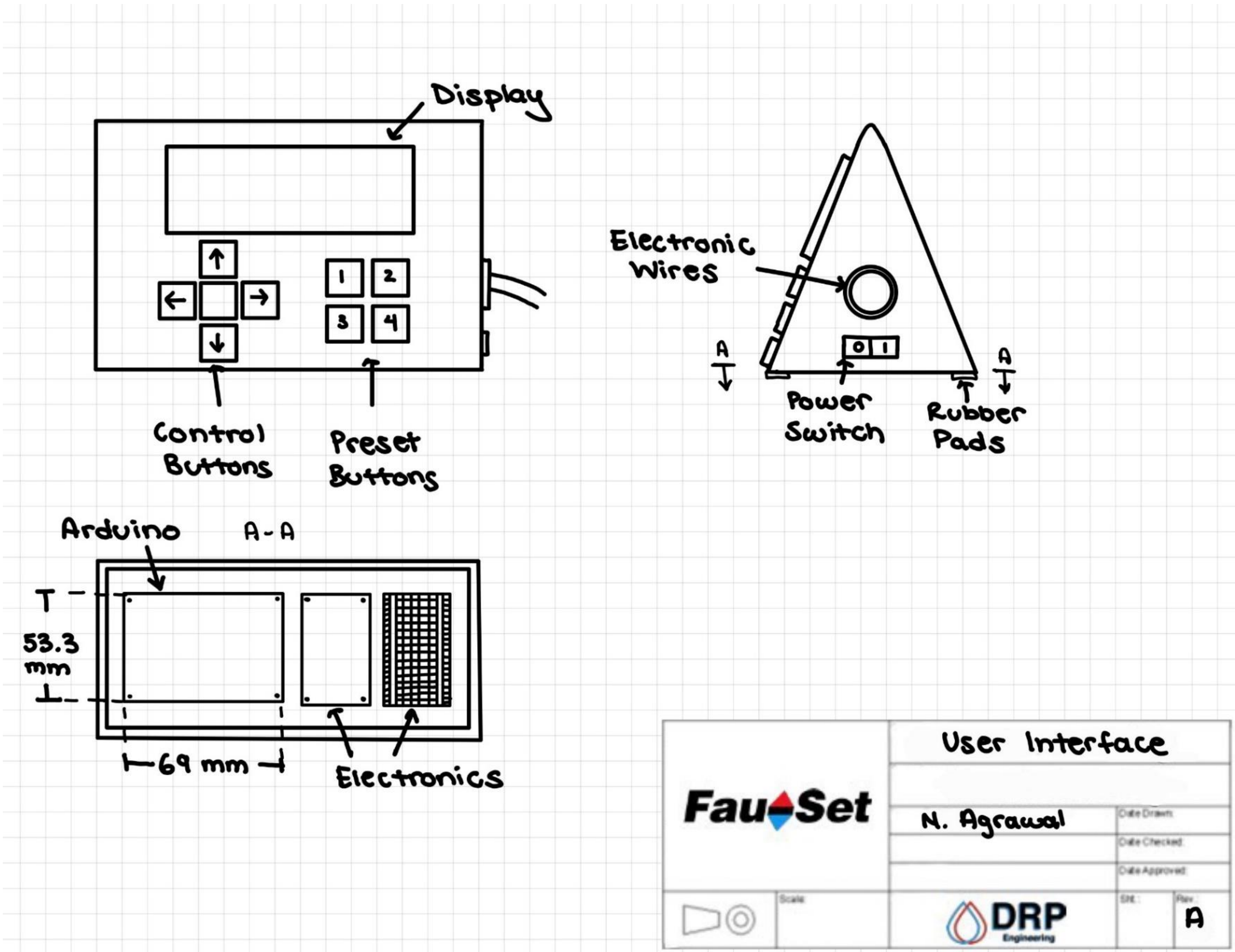


Figure H.5. User Interface Drawing

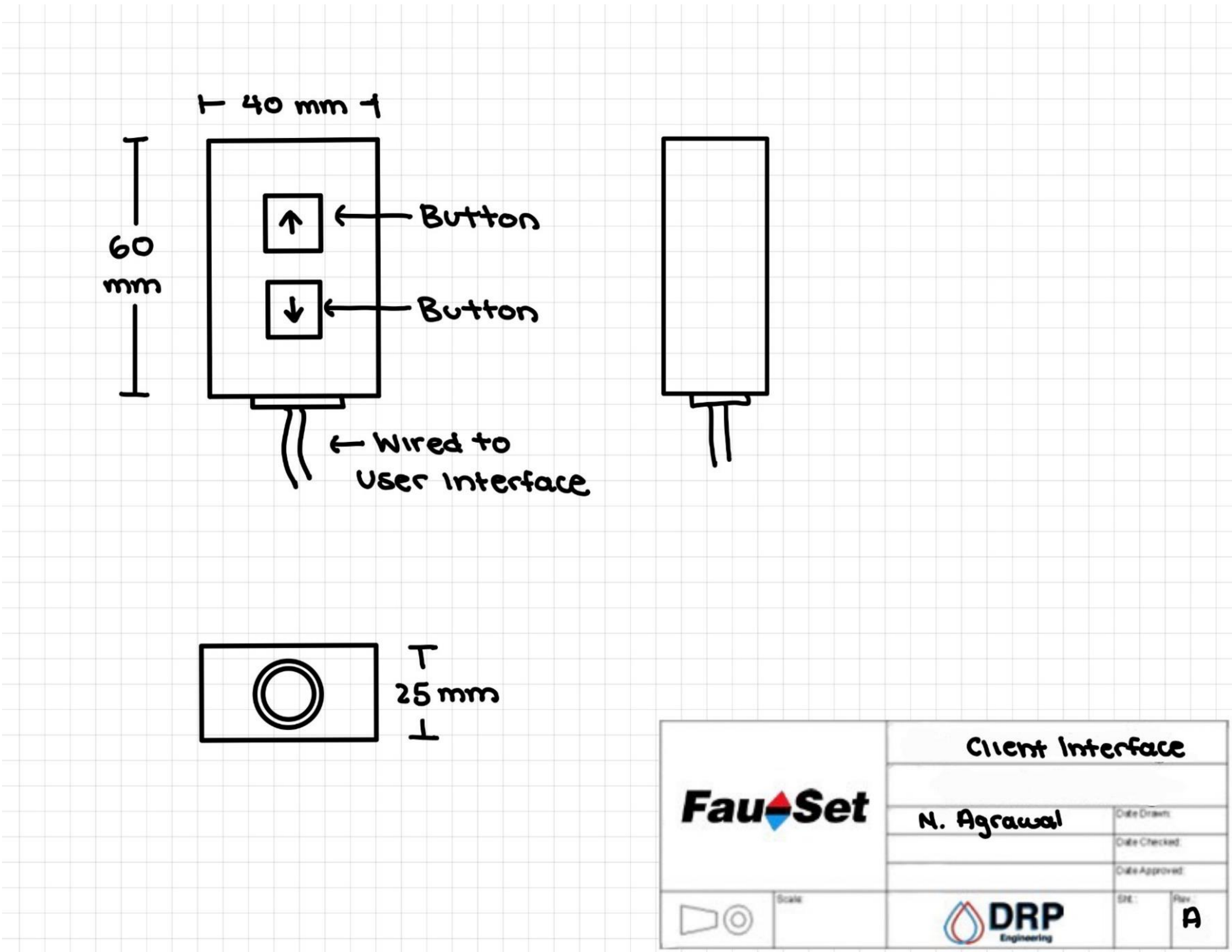


Figure H.6. Client Interface Remote Drawing

CDR Prototyping & CAD

Faucet Attachment System

The faucet attachment system couples to the existing valve lever to control the rotation of the faucet handle while still allowing the stylists to control the flow rate by moving the handle back and forth. To create this design, the existing faucet base with the valve lever was utilized and a new shaft coupler was designed. The shaft coupler screws onto the base and will house the driven gear from the motor system. For the faucet to still maintain its full range of motion a valve lever extender will be 3D printed. The original faucet handle will be reattached to the valve lever extender using a set screw. Because these components were critical in the functionality of the Fau-Set, they were rapidly prototyped using 3D printing. The prototypes were successful in demonstrating the functionality of the system and through iterations of the print, the tolerances for the parts were determined. It was decided in the CDR, that the final design would see a shaft coupler machined out of aluminum for the purpose of tighter tolerances. The driven gear would be a purchased part made of steel and modified to give it the slot, allowing for the back and forth motion.

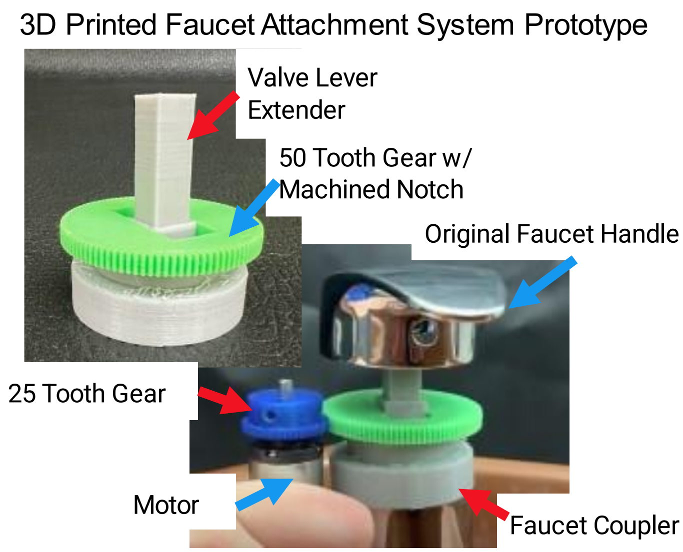


Figure H.7: Faucet Attachment System Prototype

The next major design consideration was the motor assembly. The driving load was calculated as 1.5 Nm by multiplying the maximum force needed to rotate a faucet according to the ADA (22.2 N) with the length of the existing faucet assembly (.07 m) [14]. Along with meeting the driving load condition, the end to end gear ratio was also minimized in order to ensure the final solution would be back drivable. The last major design requirement for the motor assembly was a small profile so that it would fit next to the faucet base on the shampoo bowl (maximum diameter of 50 mm) and couple to the faucet valve lever. Different types of motors, including stepper motors, gear motors, and servos were considered. While stepper motors are back drivable and can provide the required torque, once the stylist overrides the temperature control and rotates the system, the motor will lose its positional data. This will require an additional encoder to ensure the stall torque is not reached for the motor and with all the constraints, the dimension for the stepper motor exceeded the size requirement. Servos were also considered, however, similar to stepper motors, in order to reach the desired torque specification, the motor size would exceed the requirements. Brushed and brushless DC motors were considered, but instead of attaching and sizing a gearbox on top of the system, a gearmotor was chosen. Gearmotors have a smaller profile, reach the desired torque values, and can come with built in encoders.

The motor is driven by a single motor drive board that is able to control the direction and speed via PWM input from the Arduino. The motor driver was found to have a dead band of approximately 25% of the input. Once the PWM reaches above that value, the motor begins to have output movement. This value will be checked again in the full assembly as part of the same analysis to design the controller as is further discussed in Appendix I. The driver chosen ensures that the motor can be supplied a full $12V_{DC}$ as it requires. This motor driver was chosen after consulting the E-Shop staff. It is a motor driver frequently used for similar applications and was already in stock in the E-Shop minimizing the cost and lead time for the team. [10]

Various gearmotors (some sourced from the electronics room in PEARL and others that could be purchased commercially) were then analyzed using an excel spreadsheet. A 50:1 metal gearmotor from Pololu will be purchased for this application and will be coupled with a 1:2 gear ratio (25 tooth: 50 tooth). This assembly will provide around 2 N*m at 51% efficiency of the motor when powered with 12 V which exceeds the engineering requirement. Other gearmotors with torque requirements that were closer to 1.5 N*m had the same dimension and price so exceeding the torque requirement came with no additional cost to the team. The end to end gear ratio is also low allowing for back drivability and the diameter and length of the motor fits the size requirements. A bushing will also be fitted to transfer loads from the driving gear into the top casing.

In order to measure angular position, different types of encoders were evaluated. A standard potentiometer could be added to the system, but it would require an extra gear to be added to the gear train to couple to the shaft of the potentiometer. In order to avoid adding extra gears as they can lead to backlash, a hollow shaft potentiometer was sourced. However, to allow the valve lever to move forward and backwards, the diameter of the hollow shaft would have to be at least 12 mm. Hollow shaft potentiometers with those criteria have an external diameter that will exceed the size requirements. An encoder attached to the bottom of the gearmotor was chosen because it can collect over 3200 counts per revolution while maintaining a small final profile.

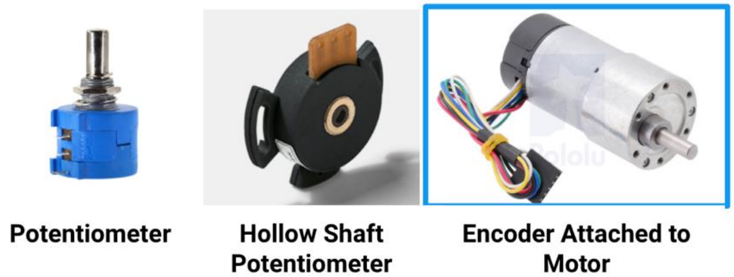


Figure H.8: Different Types of Encoders Evaluated

The casing was designed around all the components in order to protect the stylist from moving parts and protect the electronics from water damage. When the shaft coupler screws onto the faucet base, a flange from the coupler would push down onto a flange on the bottom casing to secure the casing to the faucet base. The motor would be secured to the bottom casing through custom clamps and M4 screws. The top casing will be secured to the bottom casing using M4 screws as well. The top casing would allow the original faucet handle to rotate forward, backward, and side to side. A gasket between the top and bottom casing will also help to minimize water damage. Because the bottom housing will carry all the loads during driving load conditions, FEA was conducted to ensure the part didn't fail. Iterations to the base housing were completed to increase the wall thickness and minimize stress concentrations and the bottom casing is now designed with a factor of safety of 2 (Appendix I).

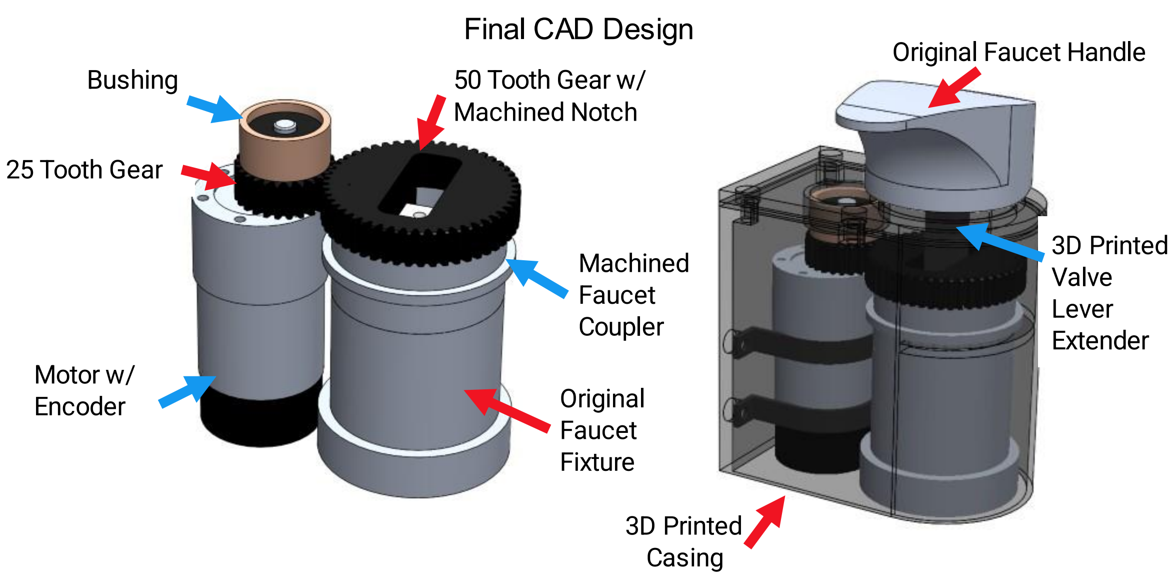


Figure H.9: Faucet Attachment Components

It was decided that the gears, motor, and bushing would be purchased commercially. The casings and valve lever extender will be 3D printed and when the Fau-Set is sold commercially, all 3D printed components will be injection molded. The shaft coupler would be machined from aluminum 6061 and the gears machined in the center to better fit the assembly. For final assembly of the system, the bushings, 25 tooth gear, and motors would be fastened together first. They will then be clamped to the bottom casing which will slide over the existing faucet base. The shaft coupler would then be tightened to secure the bottom casing. The 50-tooth gear, valve lever extender, top casing, and the original faucet handle would then be secured (Figure H.9, H.10).

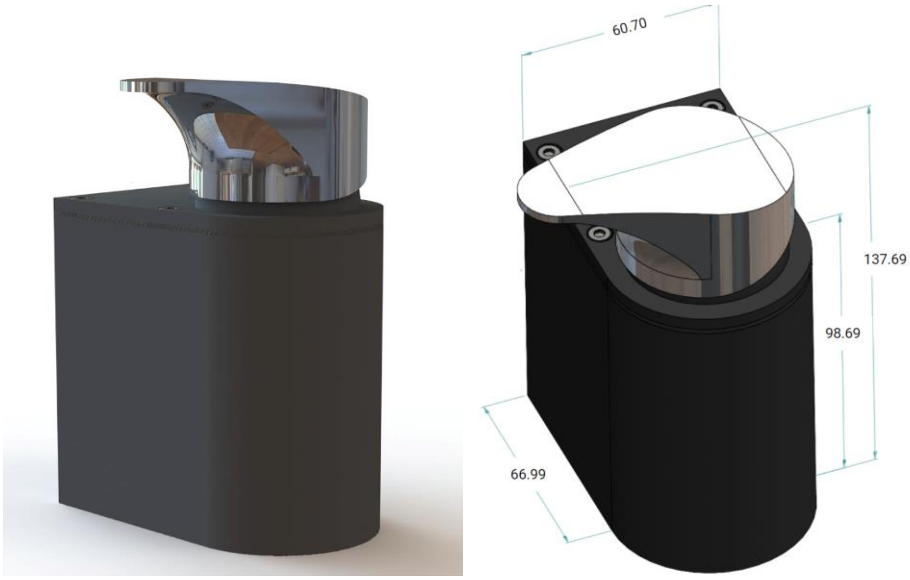


Figure H.10: Faucet Attachment System CAD & Key Dimensions (in mm)

Shower Head

To measure the temperature of the water leaving the system, a thermistor was designed to be imbedded into the shower head. Instead of modifying the existing shower head, a new shower head was created as it allowed for more freedom in imbedding the thermistor. To ensure that the designed shower head could fit around the tubing, the component was rapidly prototyped. The thread size was measured using a thread gauge and multiple iterations with varying tolerances were 3D printed. The hole diameters were also modified and tested to ensure the final flow rate matched the expected flow rate. After testing both 3D printed holes and drilled holes, the team decided that drilling holes would provide the most consistent flow rate. The prototype was successful in demonstrating the shower head fit and functionality could be met.

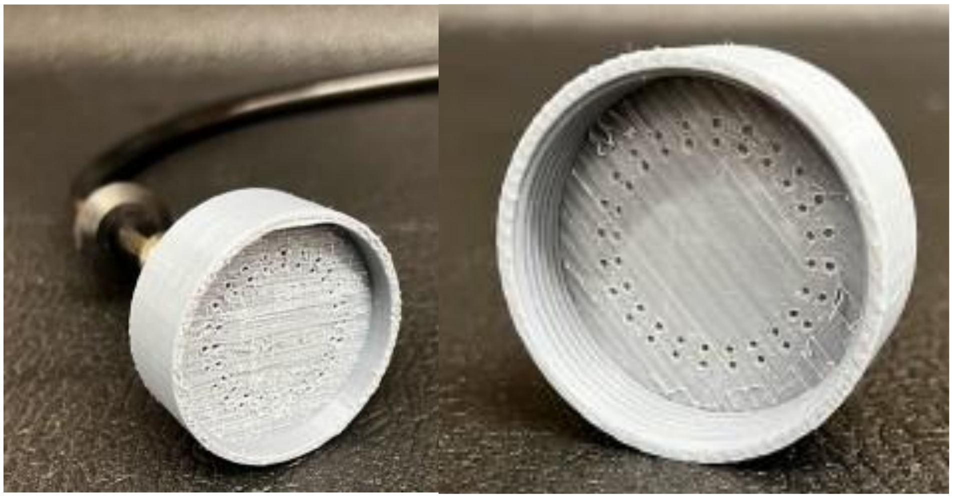


Figure H.11: Showerhead Prototype

In determining how to accurately measure the temperature of the water, the team was focused on deciding between a thermocouple and thermistor. The team ultimately decided on the choice of a thermistor due to its relatively lower cost than thermocouples, it had an adequate temperature range as the system will never be operating in extreme temperature settings, and it had a much simple process of enabling use. A thermocouple was going to require the use of an op-amp to increase the micro voltage while the thermistor only requires a resistor of the same resistance. With this in mind, the team settled on two 10 kΩ thermistors. One was much larger than the other. The two were purchased to compare whether there was a significant difference in accuracy to the temperature determined by a calibrated thermocouple and the measured reading from the thermistor. They were compared using the same algorithm based on example code. [12] In testing, it was found that the accuracy for both as nearly identical and was within the 2°F tolerance as outlined in the engineering requirements. This allowed for the selection of the smaller thermistor for ease of design in the shower cap. The two thermistors compared can be seen in figure H.12.

Figure H.12: Thermistor Size Comparison

Multiple locations for the thermistor were considered, such as adding it to the edge of the shower head, inside of the tube, and at the center of the shower head. Adding the thermistor to the center of the shower head was chosen as it would not affect the flow rate and would provide the most accurate temperature readings. The final shower head houses the thermistor in the center using a press fit. An O-ring is used to minimize water leakage and is placed on a raised platform to allow the thermistor wire to pass through underneath. The hole drilled at the edge of the shower head to allow the wire to pass through will be filled with epoxy or putty to minimize water leakage. The wiring for the thermistor will run along the tubing under the shampoo bowl and into the user interface. This was chosen over embedding it inside of the hose as the Fau-Set installation would be more difficult because stylists would have to replace the entire hose. At most salons, such as Bernadettes, the hose is hard to detach because the shampoo bowls are tight against a wall so it is easier to just run a wire next to the hose instead of in it. The O-ring used is the same one as the existing shower head assembly purchased. The shower head will be 3D printed and when sold commercially it will be injection molded. The holes along the front face will be machined as they are smaller than the tolerance of 3D prints.

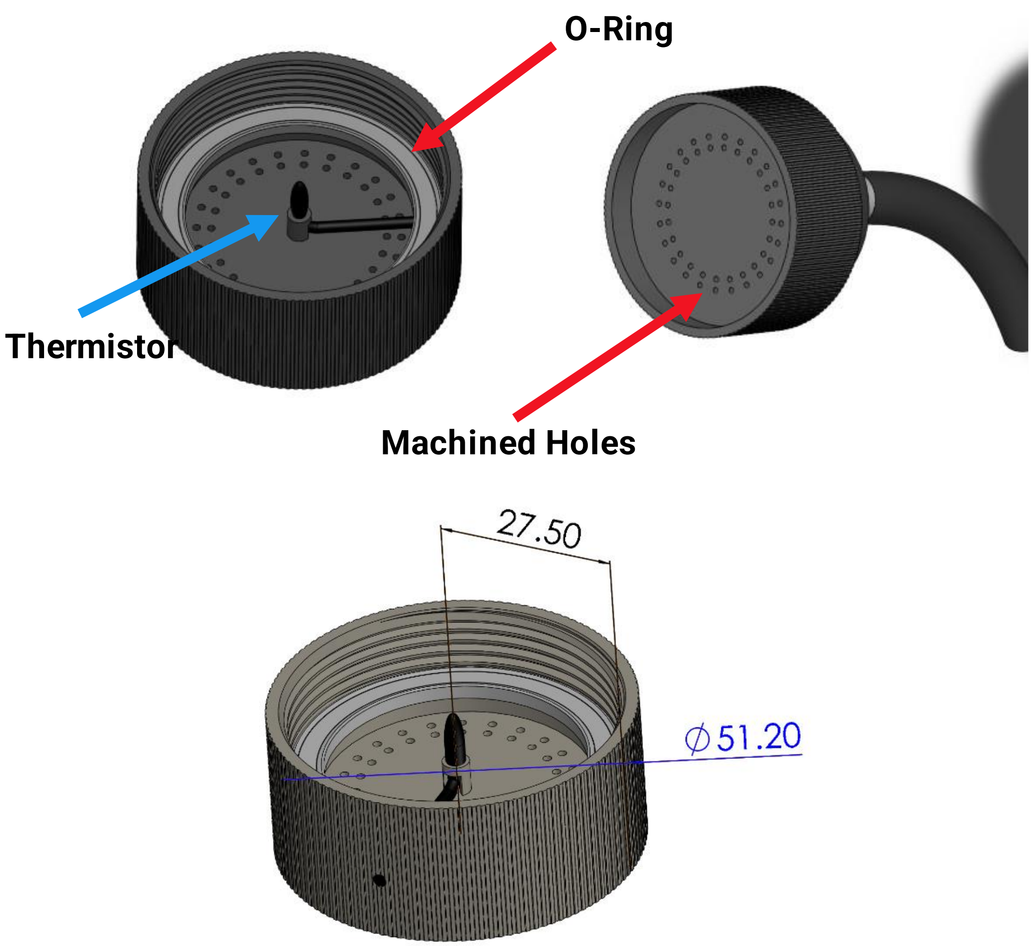


Figure H.13: Showerhead CAD (dimensions in mm)

Overall the final shower head assembly is successful in meeting all the engineering design requirements. The most critical requirement of not modifying the plumbing of the shampoo bowl was met. The shower head designed also will function and fit as the existing solution and can measure the temperature of the water leaving to ±2°F for the control system.

User Interface

Another main component of the Fau-Set is the User Interface (UI), moderated by the Stylist, the UI will be used to control the temperature through manual degree control and preset buttons (Preset temperatures can be seen in Appendix G). A cardboard prototype was developed to determine the appropriate size for the UI (Figure H.14) The prototype was designed to take approximately the same space as two shampoo bottles and will sit on the counter behind the shampoo bowl. Multiple screen layouts were developed for the UI. After making the prototype it was determined either a larger screen or a second screen needed to be added to improve readability. The cost requirements for a large enough screen made adding a second small screen the best option as the screen that had the ideal size and power requirements had a 30-week lead time and were more than twice the price of the total cost of two screens. Having two screens allows one to show the set temperature and one to show the current temperature.

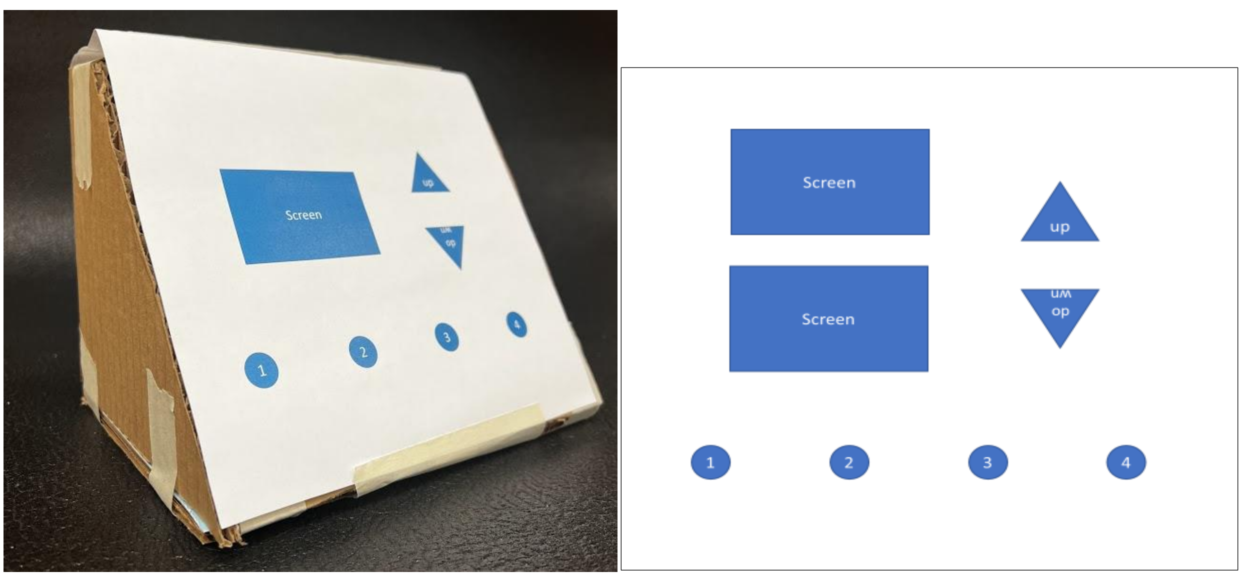


Figure H.14: Cardboard Mockup of User Interface and Chosen Screen Layout

A button mockup was also developed in the prototyping stage to demonstrate the capabilities of the user interface and client remote (Figure H.15). An Arduino Uno was used to power 8 buttons. The preset buttons are coded to the 4 preset values (seen in Figure G.1). Initial values for them are 88°F for the fashion colors setting, 95°F for the sensitive scalp setting, 105°F for the default setting, and 110°F for the color out setting. The stylist control buttons are a simple incremental feature that adjust temperature up or down by 1°F. The final 2 buttons, used in the client remote, operate very similar to the stylist buttons. However, they only change the temperature in 0.5°F increments and have a maximum limit of 3°F in either direction. This ensures that the client is able to retain some control and have a say in temperature without having to interrupt the salon experience while also not risking the water not being an adequate temperature for the needed process. This code was built based on code found in [9].

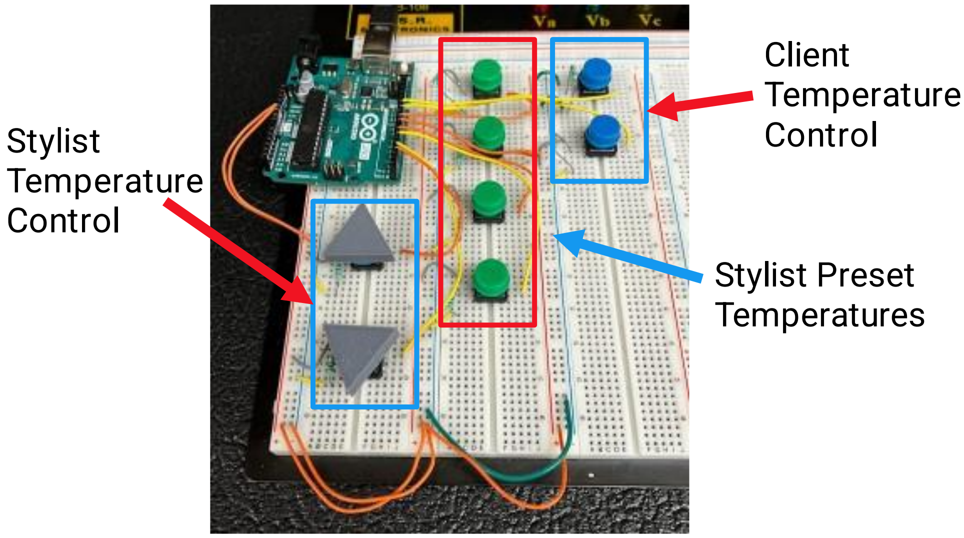


Figure H.15: Wiring Mockup of User Interface and Client Remote

Because of the information learned in the prototyping phase, it was determined that the User Interface could be 25mm shorter and still house all of the necessary electronics and wiring. Additionally, the Arduino Uno would not be sufficient to control two screens, a motor controller for the faucet attachment system, and 8 buttons. The team therefore decided to switch to an Arduino Mega. The new dimensions for the client remote and user interface can be found in Figure H.16.

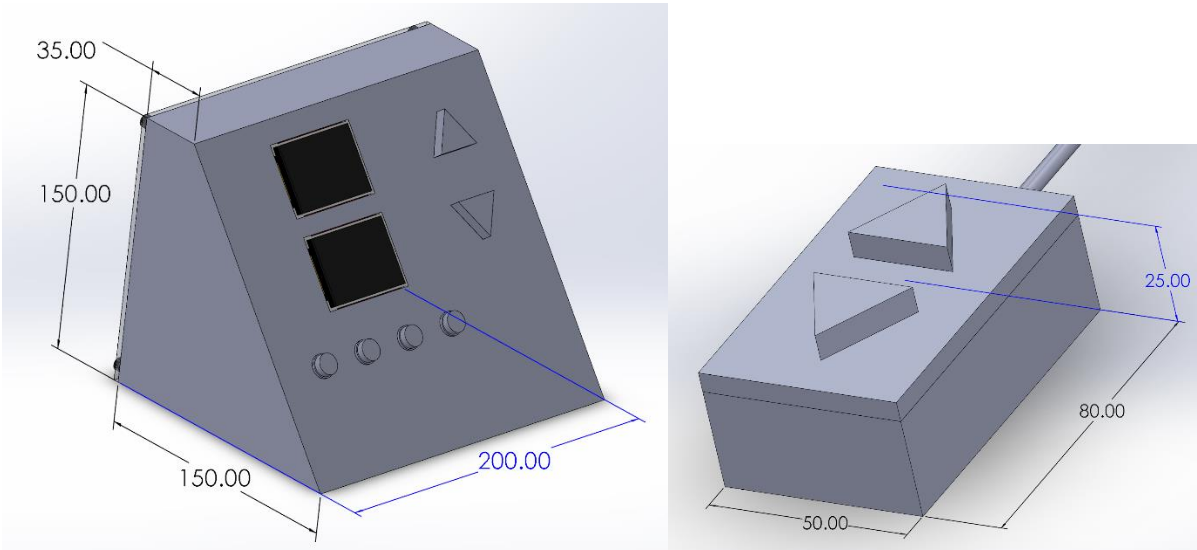
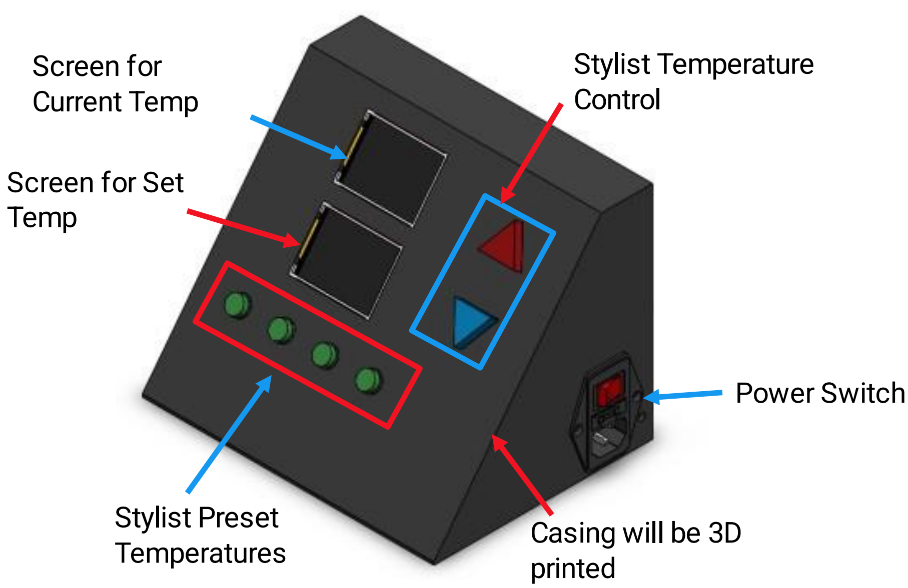


Figure H.16: Dimensions of User Interface and Client Remote (in mm)

The UI itself will be 3D printed using PLA and contain all the buttons, screens, Arduino mega, power supply, motor driver, power switch, and wiring in order to run the Fau-Set (Figure H.17). All these components will be purchased. This is all concealed with a removable back side which is made to be waterproof with a gasket. The back will be held with a set of M3 screws. The Arduino mega and power supply are also held down using M3 screws. M2 screws were used for motor driver. It was also determined that the possibility of drifting of the gears in the faucet attachment system was great enough that a home position reset function should be available in the UI. To initiate this function, the stylist must hold down the stylist temperature control arrow buttons. The client remote (Figure H.18) will be hardwired to the user interface as planned in the prototyping phase.



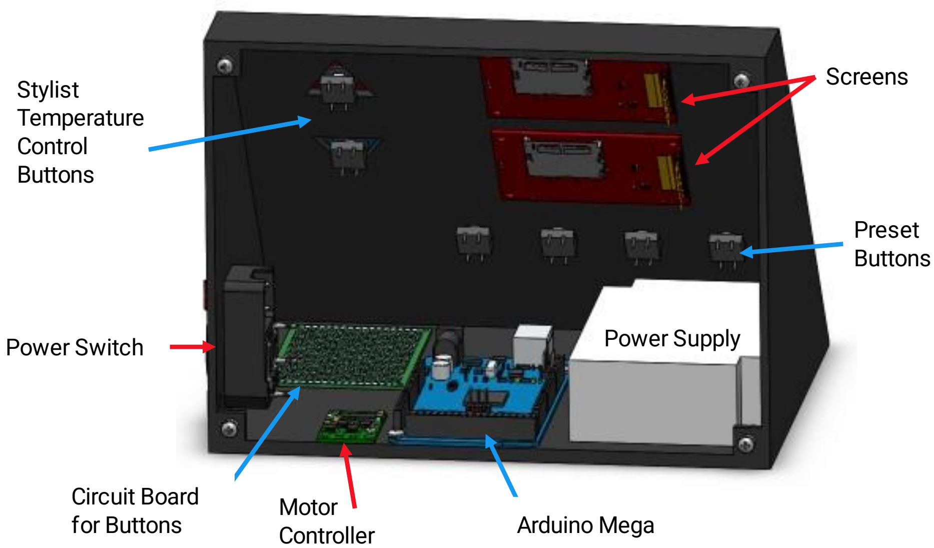


Figure H.17: Isometric and Interior Back View of User Interface

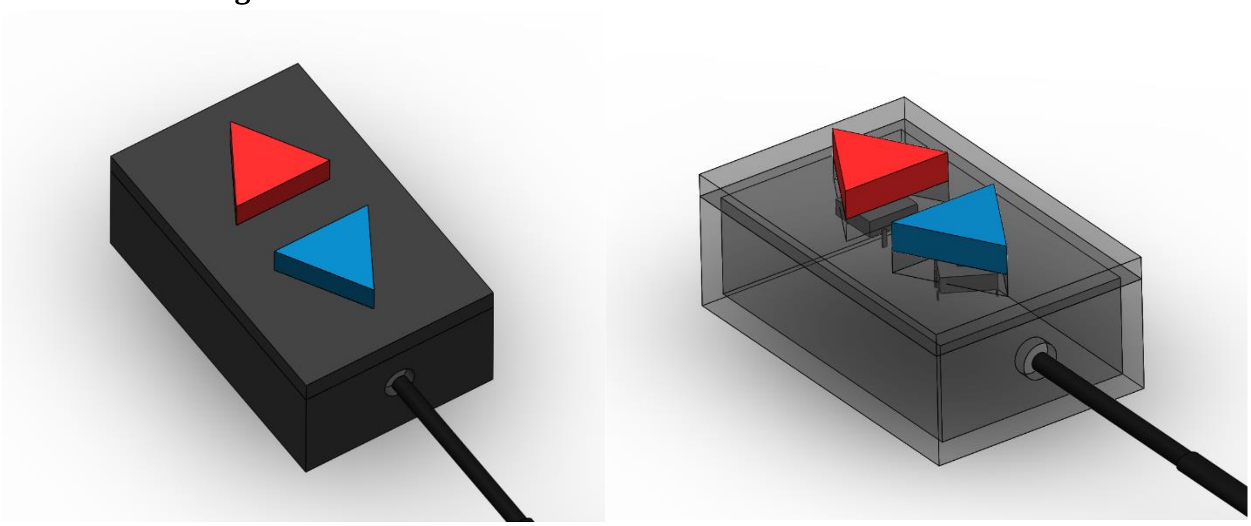


Figure H.18: Client Remote CAD

The wire layout for the Fau-Set was also mocked up in this phase as shown in Figure H.19. This layout was then added to the user interface CAD as shown in Figure H.20. This shows that the user interface can still fit all of the electronics even though it is smaller than originally planned. The control system for the faucet and user interface will be developed in the final design review phase using the methods described in Appendix I.

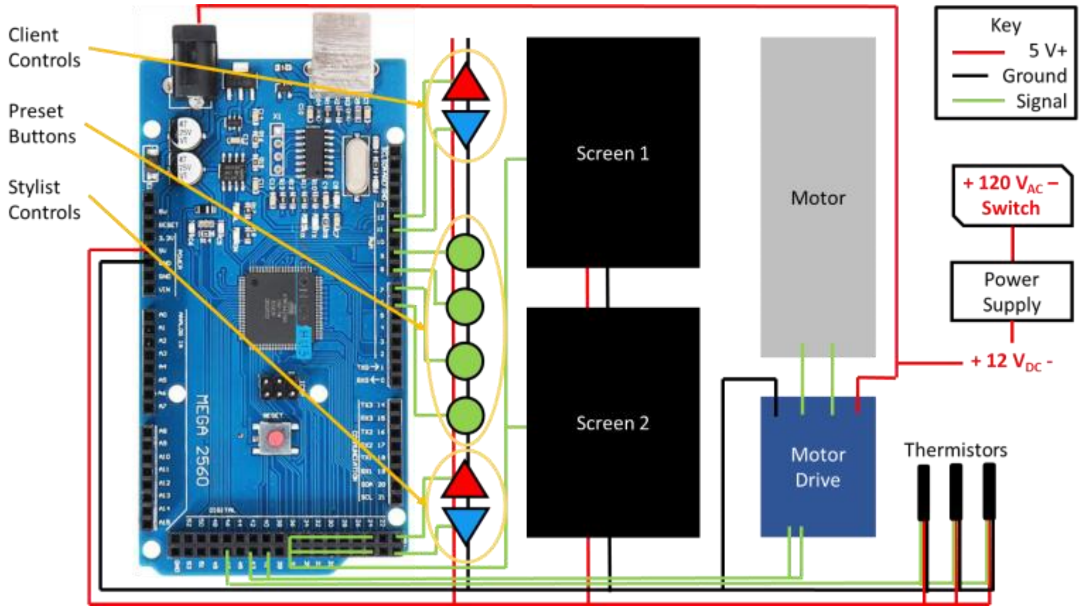


Figure H.19: Wiring Diagram of Fau-Set

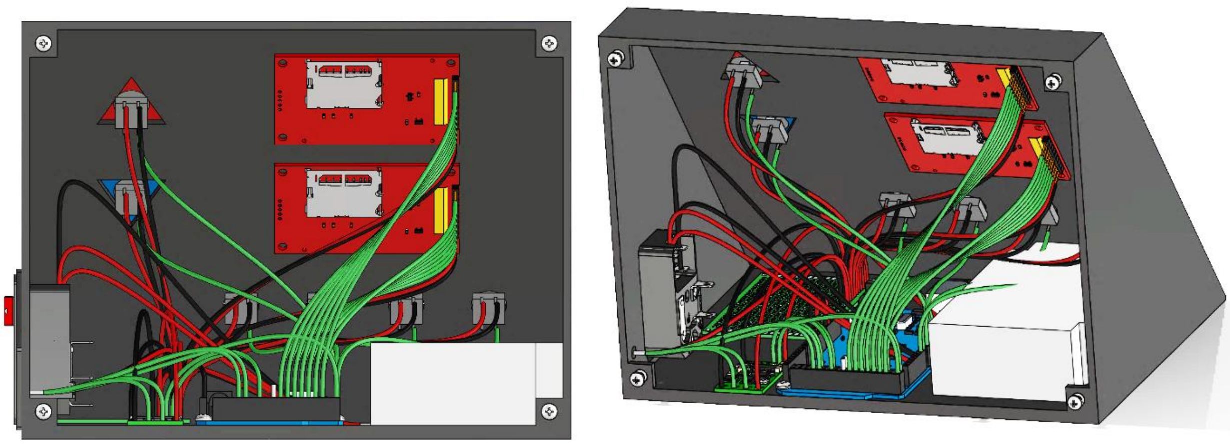


Figure H.20: Wiring CAD of User Interface

FDR Design Changes

Faucet Attachment System

Components were further iterated in order to ensure better fit and function when manufactured and assembled. Minor design changes to the faucet attachment system include that the height and geometry for the valve lever extender was modified in order to ensure that it could reach its full range of motion, forward and backward, without interfering with the shaft coupler and casing. To waterproof the modified faucet system, a waterproof fabric was designed, manufactured, assembled to attach between the top casing and valve lever extender. The fabric provided the necessary stretch to allow the valve lever extender to rotate in all directions while ensuring water did not enter from the top of the casing. A limit switch was also attached to the slotted, driven gear so when the valve lever was in the off position, the system would enter standby mode. Having a standby mode allows the stylist to take manual control of the faucet and prevents the system from continuously adjusting to reach the desired temperature when the water is not flowing. The final assembled faucet attachment is shown in Figure H.21.

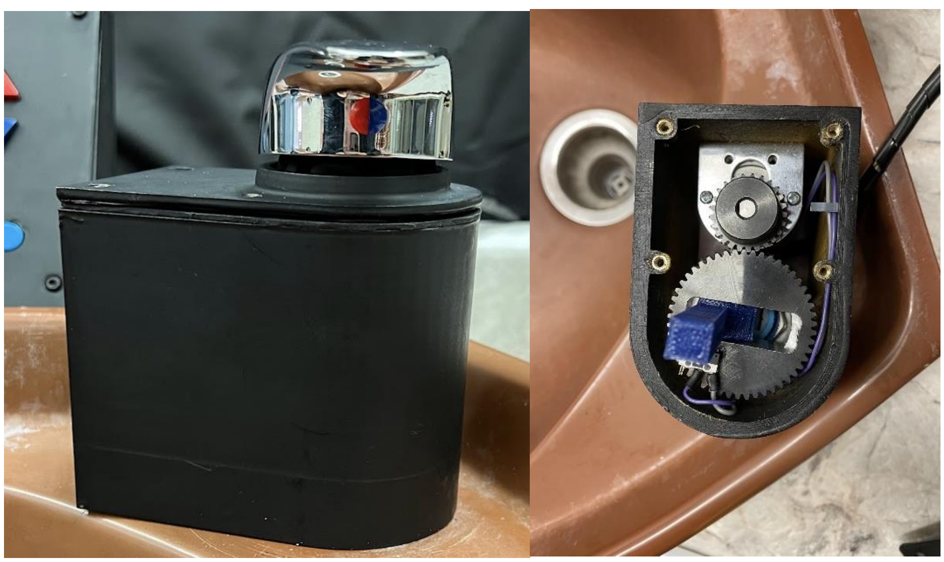


Figure H.21: Faucet Attachment System Exterior and Interior

Shower Head

From the CDR phase, the design for the shower head was completed, however, the design needed to be modified in order to have better fit and function. One of the key design requirements was to ensure that the flow rate was enough to wash an individual's hair. Even with the limited water pressure from the aquarium pumps in the test setup, the team was successful in modifying the diameter and number of holes in the custom 3D printed shower head in order to reach this requirement. As it was harder to print small holes in the shower head because of the minimum tolerance of the printers, the holes were drilled during post-processing.

Another key requirement for the shower head was to ensure that the thermistor would press fit into the inside of the shower head while maintaining a position that allows it to maximize contact with the water flowing out. In order to achieve this, multiple iterations of the shower head were quickly 3D printed and assembled as shown in Figure H.22. Threading issues occurred during initial testing where the shower head would fall out due to the high water pressure and force and was resolved through reducing the diameter of the threads and adjustments made through over 10+ prints of the shower head.

Figure H.22: Final 3D Printed Showerhead System with Implanted Thermistor

User Interface

In the CDR phase, the team discovered that the user interface height could be reduced by 25 mm to have a smaller footprint while still accommodating the electronics. Other changes made during the FDR phase was redesigning the front panel to be removal in order to allow easy access to the electronics when prototyping and assembling. The electronics were also placed in various shelves with heavier electronics such as the power supply placed at the bottom in order to increase stability of the user interface. Further dimensions and tolerances were designed and tested in order to ensure space was used efficiently and ensure that wires had enough of a bend radius.

Another button was also added for standby mode and the displays and buttons were physically laid out on a perfboard to better visualize the final layout. Through the new setup, the front panel hole cutouts were modified. The overall new design, shown in Figure H.23, made it easier to manufacture the components, prototype the electronics, and assemble the final system.

Figure H.23: Final User Interface with CAD

Client Remote

In order to make the client remote more ergonomic, the height of the remote was reduced, and the edges were filleted. Further the buttons were laid out on a perfboard and the width between them was modified in the CAD in order to align the hole cutouts. Similar to the user interface, the tolerances for the triangle cutouts were increased in order to allow the button to be easily pressed and released as shown in Figure H.24.

Figure H.24: Final Client Remote with CAD

Electronics

During testing, the TFT screens used in the user interface were experiencing lots of noise and current issues causing them to white out. To remedy this issue, the circuit was split into three parts: an Arduino circuit, a motor circuit, and a circuit for all of the 5V components such as the buttons and screens. Separating the circuits along with soldering all connections instead of using connectors, replacing all wire with stranded wire, and adding shielded wire to the motor and screens eliminated the noise issue between the screens and the Arduino. It also fixed the overheating issue with the Arduino as the Arduino was no longer providing 5V to components as originally planned. The updated schematic is shown in Figure H.25.

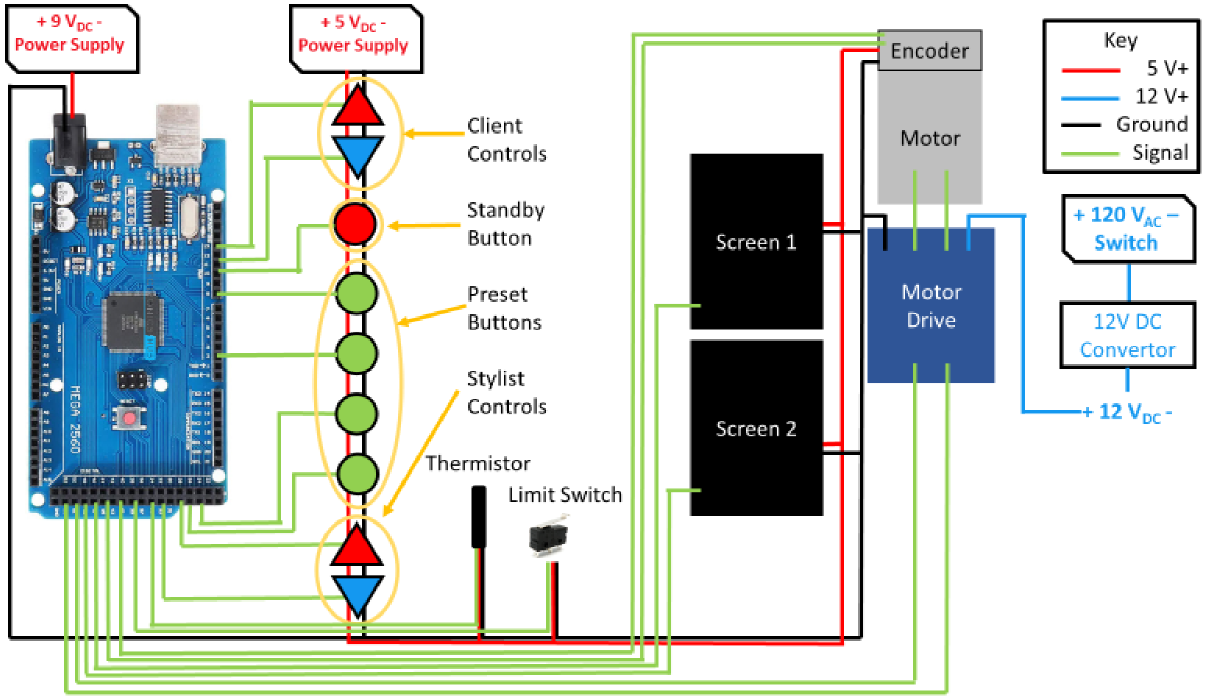


Figure H.25: Updated Electronics Schematic

Buy vs Make, Tolerancing, and Fits

Table H.1 shows the buy vs make analysis for the parts of the Fau-Set. Most parts are purchased with the majority of the made parts being 3D printed and only one machined. The materials each of these components are made out of can be found in Table H.2. Table H.3 shows the key fits and tolerances for the Fau-Set. The team followed the ANSI Standard Limits and Fits to develop these tolerances [2].

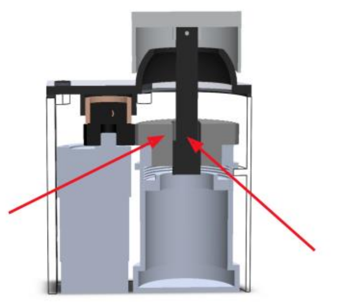
Table H.2: Make vs Buy

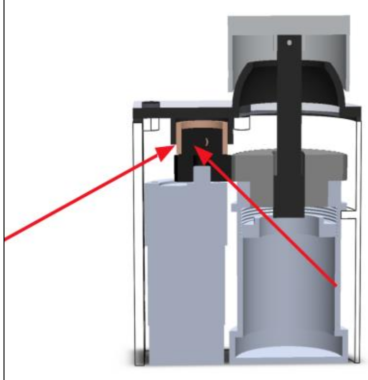
Assembly	Part	Make/Buy	Vendor
	Faucet Base	Buy	Amazon
	Faucet Handle	Buy	Amazon
	Shaft Coupler	Make	-
	Valve Lever Extender	Make	-
	50:1 Gearmotor	Buy	Digikey
	50 Tooth Gear	Buy	McMaster
	25 Tooth Gear	Buy	McMaster
	Bushing	Buy	McMaster
Faucet Assemb	Clamps	Buy	Pololu
	Base Casing	Make	-
	Top Casing	Make	-
	Gasket	Buy	Amazon
	Waterproof Fabric	Buy	Amazon
	Screw: M4 x 0.7 mm; 10 mm	Buy	Amazon
	Screw: M4 x 0.7 mm; 12 mm	Buy	Amazon
	Nut: M4 x .7 mm	Buy	Amazon
	Motor Controller	Buy	Walmart
	Shower Head	Make	-
Shower Head	Thermistor	Buy	Digikey
	O-ring	Buy	Amazon
	Screen	Buy	Adafruit
	Buttons	Buy	Digikey
	Button Caps	Make	-
	SD Cards	Buy	Amazon
	Front Casing	Make	-
	Back Casing	Make	-
	Gripper Feet	Buy	Amazon
	Client Remote Casing	Make	-
User Interface	Arduino Mega	Buy	Arduino
	Screw: M3 x 0.5mm; 8 mm	Buy	Amazon
	Screw: M3 x 0.5mm; 6 mm	Buy	Amazon
	Screw: M2 x 0.4mm; 6mm	Buy	Amazon
	Threaded Insert: M3 x .5 mm	Buy	Amazon
	Threaded Insert: M2 x 0.40 m	Buy	Amazon
	Motor Controller	Buy	Pololu
	Power Supply: TLD1040-12	Buy	Digikey
	Perfboard	Buy	Digikey

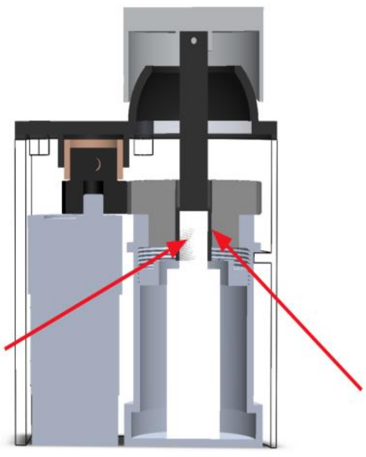
Table H.3: Materials Table

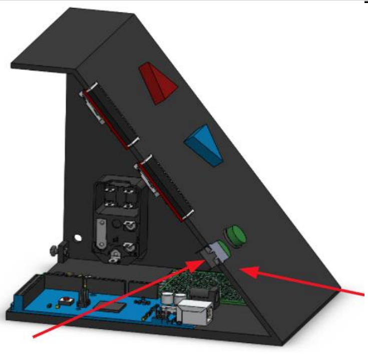
Assembly	Part	Materials	Finished Size (mm)
Faucet	Faucet Base	Aluminum 6061	52.7 x 71.5
	Faucet Handle	Aluminum 6061	85 x 51 x 35
	Shaft Coupler	Aluminum 6061	51 x 21.5
	Valve Lever Extender	PLA	13.5 x 13.5 x 71.188
	50:1 Gearmotor	Electronics	36.8 x 92.1
	50 Tooth Gear	Black-Oxide Steel	52 x 20
	25 Tooth Gear	Black-Oxide Steel	27 x 20
	Bushing	Bronze	24 x 16
	Clamps	PLA	57.7 x 37.9 x 8
	Base Casing	PLA	98.354 x 62.7 x 93.1
	Top Casing	PLA	98.354 x 62.7 x 30.63
	Fabric	Polyester Spandex	70 mm diameter
	Gasket	Neoprene	98.354 x 62.7 x 1.59
	Screw	Alloy Steel, Black Oxi	M3 x .5 mm; 8 mm
	Thermal Insert	Brass	M3 x .5 mm
	Nut	Black-Oxide Steel	M3 x .5 mm
Shower Head	Shower Head	PLA	55 x 23.6
	Thermistor	Electronics	3 x 40
	O-ring	Silicone	49 x 2.14
User Interface	Screen	Electronics	40.63 x 66.35 x 6.05
	Buttons	PLA	11.5 x 12.1
	Front Casing	PLA	200 x 150 x 3
	Middle Casing	PLA	200 x 150 x 35
	Back Casing	PLA	200 x 150 x 3
	Client Remote Casing	PLA	80 x 50 x 30
	Arduino Mega	Electronics	101.6 x 53.34 x 24.89
	Screw	18-8 Stainless Steel	M3 x 0.5mm; 8 mm
	Screw	18-8 Stainless Steel	M2 x 0.4mm; 6mm
	Nut	Black-Oxide Steel	M3 x .5 mm
	Threaded Insert	Brass	M3 x .5 mm
	Threaded Insert	Brass	M2 x 0.40 mm
	Motor Controller	Electronics	33.02 x 20.32 x 20
	Power Supply: TLD1040-12	Electronics	95 x 70 x 32
	Perfboard	Electronics	100 x 100 x 1.5

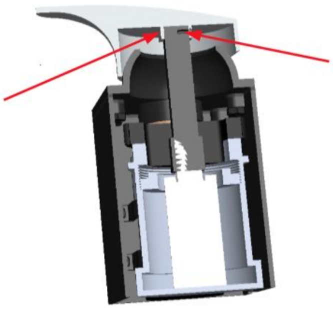
Table H.4: Table of Fits and Tolerances

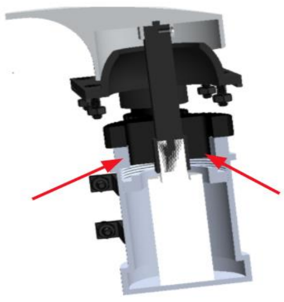
Slotted Gear - RC7						
		Block Hole	Size/Tolerance	Valve Lever Extende	Size/Tolerance	Actual Size
	MMC	0.54	0.548±0.0008	0.538	0.5405±0.0025	0.5406
	LMC	0.5416		0.543		

Gear Bushing - LC3						
		Bushing	Size/Tolerance	Gear	Size/Tolerance	Actual Size
	MMC	0.787	0.788±0.001	0.787	0.783±0.004	0.784
	LMC	0.789		0.779		

Valve + Valve Extender - RC1						
		Original Valve	Size/Tolerance	Valve Extender	Size/Tolerance	Actual Size
	MMC	0.41	0.41015±0.000	0.40975	0.409655±0.0001	0.4095
	LMC	0.4103		0.40955		

Button Holes in User + Client Interface -						
		Original Valve	Size/Tolerance	Valve Extender	Size/Tolerance	Actual Size
	MMC	1.61	1.61125±0.001	1.607	1.6078±0.0008	1.608
	LMC	1.6125		1.6054		

Valve Extender + Faucet Handle - RC1						
		Original Valve	Size/Tolerance	Valve Extender	Size/Tolerance	Actual Size
	MMC	0.41	0.41015±0.000	0.40975	0.409655±0.0001	0.4097
	LMC	0.4103		0.40955		

Gear + Coupler - RC7						
		Original Valve	Size/Tolerance	Valve Extender	Size/Tolerance	Actual Size
	MMC	1.378	1.378±0.00125	1.375	1.375±0.0008	1.378
	LMC	1.3805		1.3734		

Manufacturing
Manufactured components within the Fau-Set were made by one of two methods: machining and 3D printing. The machined components, the slotted gear, and the shaft coupler, were made on the mill and lathe, respectively. The slot in the gear was cut by making repeated passes in the shape of the slot, an operation that took 5 hours to complete, as shown in Figure H.26. This shape was not to the exact dimensions of the slot, either. Rather, it was 0.010" shy of specification. While the bulk of the material was removed via conventional milling, a faster process, this last 0.010" was removed via climb milling in order to produce a more desirable surface finish. Climb milling is not a practical use of a lathe, and thus the desired surface finish was attained by disabling the automatic feed and instead doing so very slowly, and by hand. Additionally, the specifications that were followed came from the tables of fits and tolerances shown in Figure H.4.

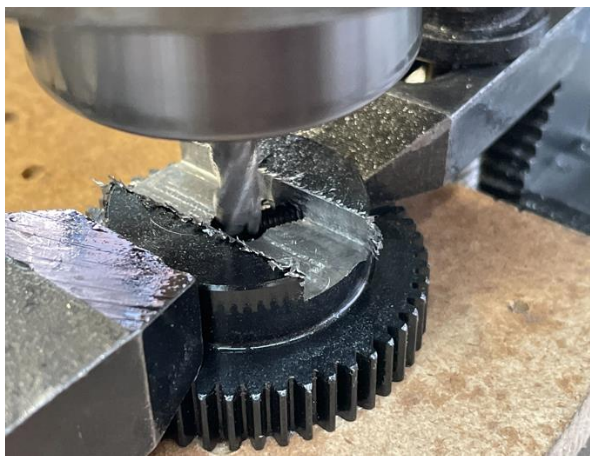


Figure H.26: Manufacturing Slot in Driven Gear

The 3D printed parts required more fine tuning and iteration as the FDR phase continued, as changes were seen in the valve lever, the user interface, and the client remote. However, once the final versions of each component were printed, they were given a coat of smoothing epoxy before sanding and painting. Using this epoxy gave the parts a professional look, mimicking that of an injection molded part.

Assembly
After design iterations and manufacturing, all components were assembled. Thermal inserts were pressed into the 3D prints, wires were cable managed using protective sleeves, and all components were screwed down. After assembly, putty was added to the shower head hole where the wire was leaving in order to allow the system to be waterproof. All systems were individually tested through the design process in order to ensure functionality were met before full system testing.

The modified faucet system was successful in meeting all key requirements. After manufacturing and assembling components such as the motor bracket, shaft coupler, and gears to the casing, the system was tested and was successful in providing enough torque to rotate the valve lever. User testing was completed in the FDR phase to ensure that the faucet was easy to rotate when in standby mode. Another key design innovation that was successfully met was coupling to the existing faucet base while retaining manual control of the flow rate. Through full system assembly and testing, the process for clamping the casing proved successful as the casing would be tightly secured and forces from the motor were transmitted to the casing in order to prevent burnout when stall torque was reached. The final assembly also maintains a small profile and fits within the given space on the shampoo bowl and retains the original faucet handle and base. Installing the final faucet system also takes less than 5 minutes and is easy for the end user as only a maximum of three tools is needed. Overall, the final faucet assembly was successful in coupling to the existing shampoo bowl, being easily serviceable by the end user, autonomously setting the water temperature, and retaining all features and functionalities of the original faucet.

Initial testing was also conducted on the shower head and all key requirements were met. The flow rate was an acceptable amount, the system did not leak water from any of the sides, and the shower head screwed onto the existing shower head successfully. The thermistor was also press fit well into the system and was able to measure outgoing water temperature. Both the user interface and client remote was successful in housing all the electronics, with the displays being easy to read and the buttons being easy to click for the end user.

I. Analysis

The primary analysis completed was through the determination of the control loop. This began with determining the transfer function of the system plant model. This was calculated by applying a unit step input to a representative setup of the system. The representative setup featured the primary casing, original faucet, motor, both gears, the valve lever extender, and the handle. The encoder then returned the angular position of the output shaft based on the unit step input. Recording this with time, the instantaneous velocity over each interval between recording points was calculated. Figure I.1 shows the results of this instantaneous velocity calculation represented in blue. The raw data was then matched with a third order best fit plot to represent the velocity over the given time, seen in red in the figure.

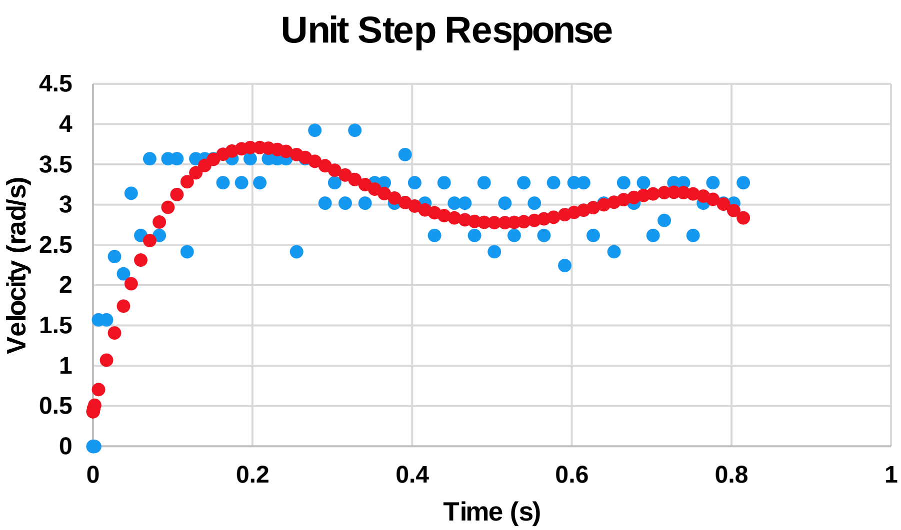


Figure I.1 Unit Step Response Results

This allowed the calculation of the transfer function. Visually, we are able to determine that the response can be represented by a second order transfer function as it has a small amount of overshoot before reaching the steady state value. With this in mind, two primary values were needed to be calculated: the damping ratio and the undamped natural frequency. The damping ratio can be calculated by using the overall system percent overshoot. The percent overshoot is the difference between the peak value and the steady state value divided by the steady state value. This then leads to equation 1 to determine the damping ratio.

$$\%OS = e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}}$$

With the known value for the damping ratio determined, the natural frequency is found according to equation 2 where t_r is the difference in time between where the system is at 90% of the steady state and where the system is at 10% of the steady state.

$$\omega_n = \frac{2.2}{t_r\zeta} \qquad \textit{Equation 2}$$

These are able to give yield the final second order transfer function for the plant model. The form is seen in equation 3 with the resulting actual results in equation 4.

$$P(s) = \frac{K\omega_n}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad \textit{Equation 3}$$

$$P(s) = \frac{109.845}{s^2+58.51s+1323.359} \qquad \textit{Equation 4}$$

With this known plant model, the desired controller can be found. With a focus on reducing the settling time and minimizing the overshoot for safety reasons, the desired closed loop poles are -0.697 and -7.303 respectively yielding the closed loop denominator seen in equation 5. Using the Diophantine equation (equation 6) with the controller form of a PD controller seen in equation 7, coefficients for the derivative and proportional controllers can be found.

$$s^2 + \frac{8}{3}s + 5.087 \qquad \textit{Equation 5}$$

$$N_P N_C + D_P D_C = D_{CL} \qquad \textit{Equation 6}$$

$$C(s) = K_D s + K_P \qquad \textit{Equation 7}$$

Working through these equations to solve for the controller coefficients ultimately yields coefficients of roughly -0.5 for the derivative controller and -12 for the proportional controller. These coefficients are implemented into the control loop as a means to determine the overall level of power that the controller should apply to the system for the proper response to reach the desired system temperature.

With the controller created, it could be implemented into the control loop. Figure I.2 features a flowchart for the control function and how it operates in the code. The controllers begin by looking at whether or not it is within the desired range. If it is, it skips and loops back until it no longer is. When it is not in range, it determines the direction to set the motor in by using the sign of the error value. It then sends the error value through he PD control loop and is scaled to between 0 and 1. This is then scaled to as much as 5 for the PWM size added to the dead band of the motor system. This allows for small amounts of power control. The length of time the motor is set to on is then determined by how large the error is as well. Finally, before setting the motor based on the results of the control loop, the error is compared to the last error and will make small adjustments to the PWM based on whether it is approaching the set point or not. The control loop then outputs the results for direction and PWM level to the motor.

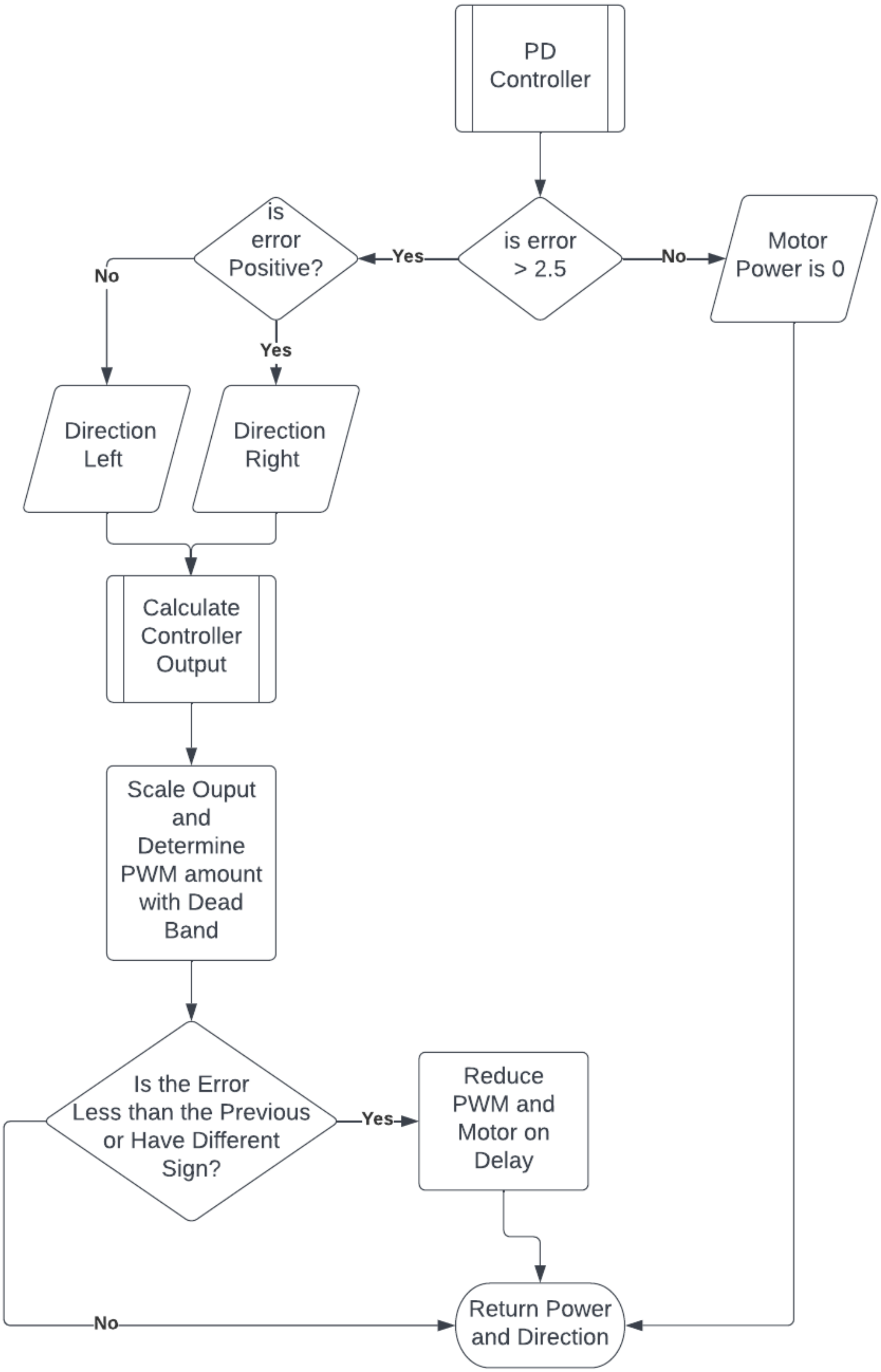


Figure I.2 Control Loop Flowchart

The primary loop algorithm can be found in Figure I.3, but essentially is constantly checking whether or not the system is within the desired range or whether or not the system is in standby more. When the system is in standby mode, it shuts the motor off and puts it into coast mode to allow for full user control of the faucet handle with no issue. The loop when not in standby is constantly updating the screens, checking to see if the user has pressed a button, and outputting results from the control loop to the motors. It then includes a pause when not within the set range for the thermistor to catch up to the system due to its reaction time. When the temperature measured is within the acceptable range, the system enters a long pause in which nothing occurs except for updating the screen and checking buttons to ensure that the user does not wish to change anything.

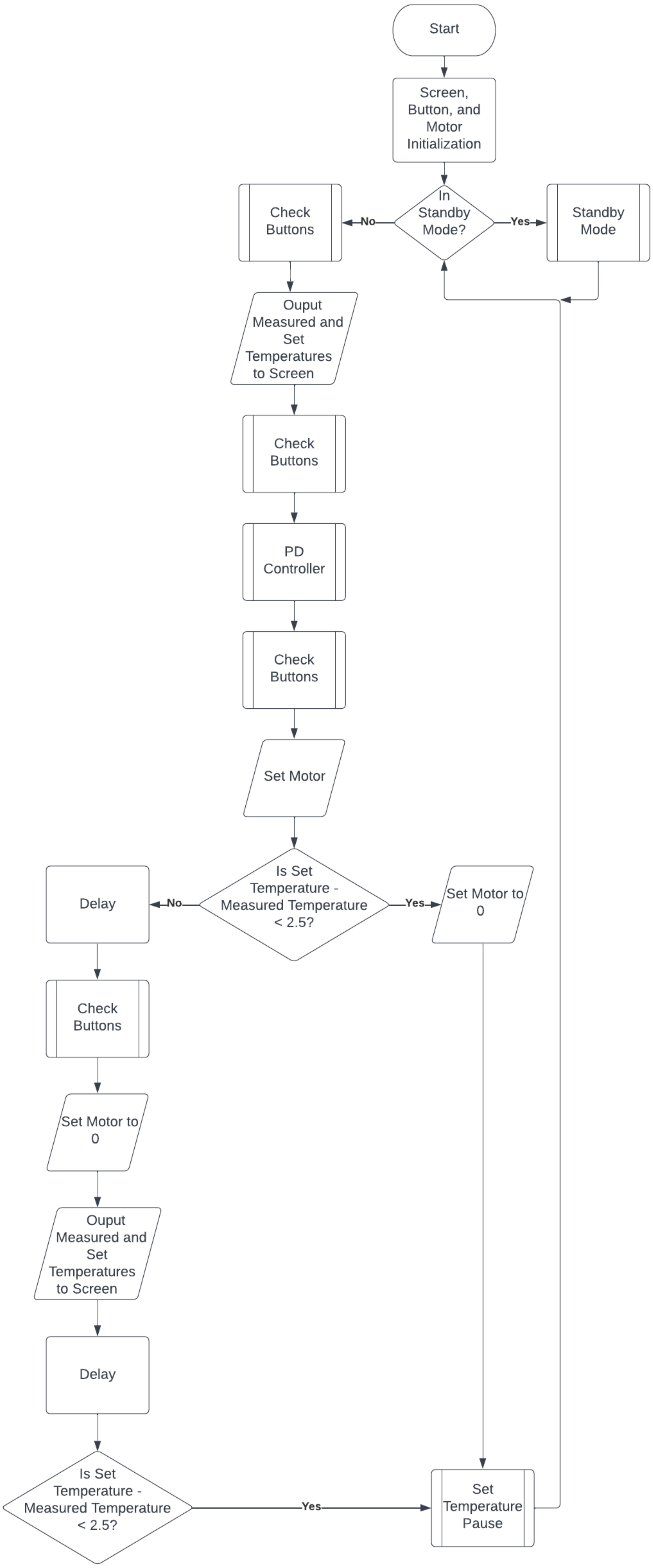


Figure I.3 Primary System Loop

Another necessary analysis was the determination of the motor specification as well as the gear ratios that would connect it to the output shaft. The main constraints and variables considered in this process were the size of the motor, the output torque of the motor, and the space taken up by the gear train itself. The chosen motor also needed to be back drivable in order to allow for manual override of the system. Rather than measuring the force needed to manipulate the faucet, the ADA (Americans with Disabilities Act) standard of 5 lbs (22.24 N) was used [14]. Multiplying this value by the length of the faucet handle (0.07 m) resulted in a target torque at the valve stem of 1.56 Nm. Coupling the motor to the output shaft via a gear train opened the possibility of using a gear reduction to increase the output torque of the system. The initial motor selection based on availability within the department offered a torque of 0.4 Nm that could be stepped up to the target value with a gear ratio of roughly 1:4. However, drafting this arrangement in CAD revealed that the selected gears were unable to mesh. The radii of the motor and the faucet base were longer than the combined radii of the two gears, making it impossible for them to connect. It was also decided that the motor should have an encoder built in, as it was the least invasive method of determining the position of the output shaft. After considering more powerful motors that were both back drivable and consisted of an encoder, the team arrived at one with 2.04 Nm of torque. This allowed for more freedom in terms of gear reduction and gear sizing, as power was less of a constraint on the system. The final gear ratio that both allowed the gears to mesh and output a sufficient torque is a ratio of 1:2. While the motor is capable of providing more power than is realistically needed, the excess is kept as a factor of safety and an assurance that the system will be able to function despite any frictional losses that may occur.

Loads applied to the faucet assembly were also analyzed to reduce component failure. The system receives loads when the faucet handle is pulled upward or rotated side to side by the stylist, however, the loads are translated into the base of the faucet system attached to the shampoo bowl. The major driving load, however, is when the motor stalls. In this condition, the bushing will translate 164.8 N into the top casing which will be translated into the bottom casing as that is attached to the faucet base. The motor will also translate 111.35 N through the clamps into the bottom casing. (Figure I.4)

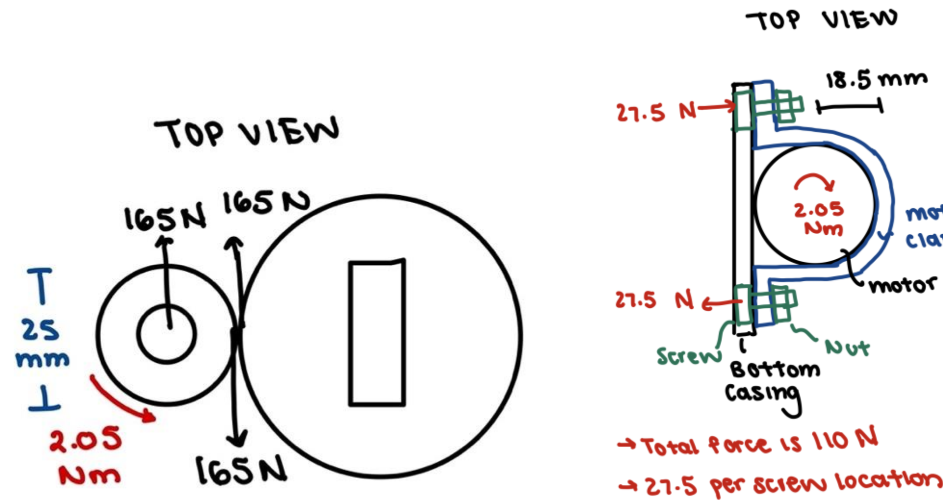


Figure I.4: Free Body Diagram used for FEA

Because the casing on the faucet attachment system carries all of the load holding the faucet to the sink, it was critical to run a static structural analysis to ensure the 3D printed part wouldn't fail. As shown in Figure I.5, the original casing design fails at a factor of safety of around .34, which does not meet the engineering requirements. To improve the design, the casing was made thicker (Figure I.6) and stress concentrations were reduced by adding chamfers. Now the casing has a factor of safety of 2 which exceeds the engineering requirements.

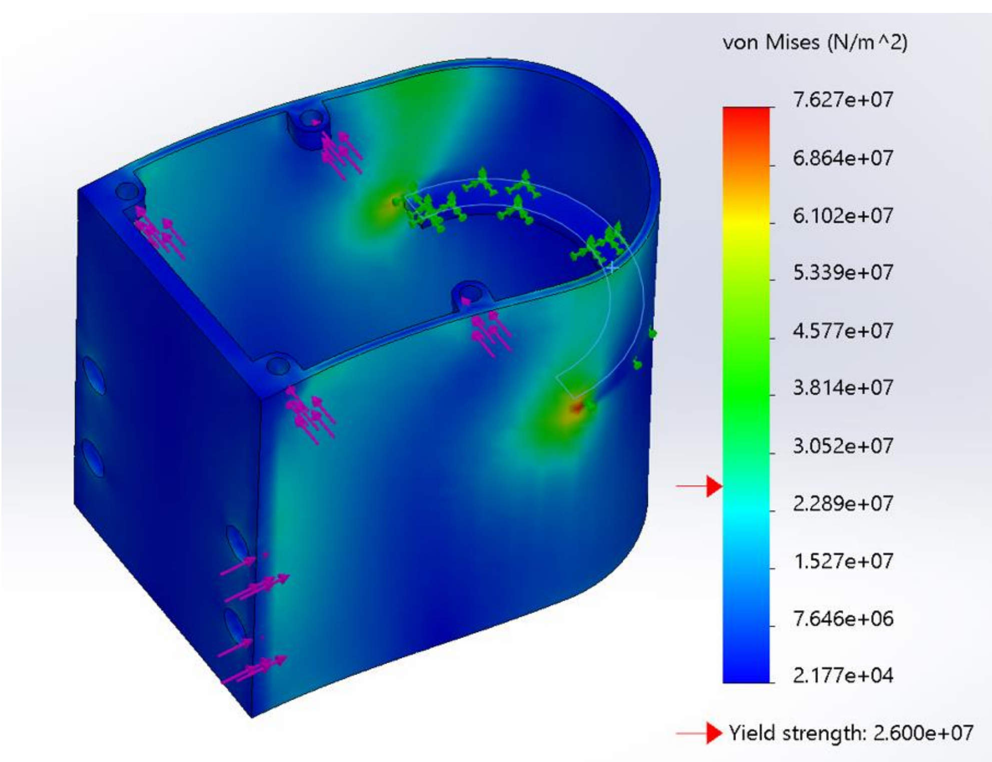


Figure I.5: Original (thinner) Casing FEA

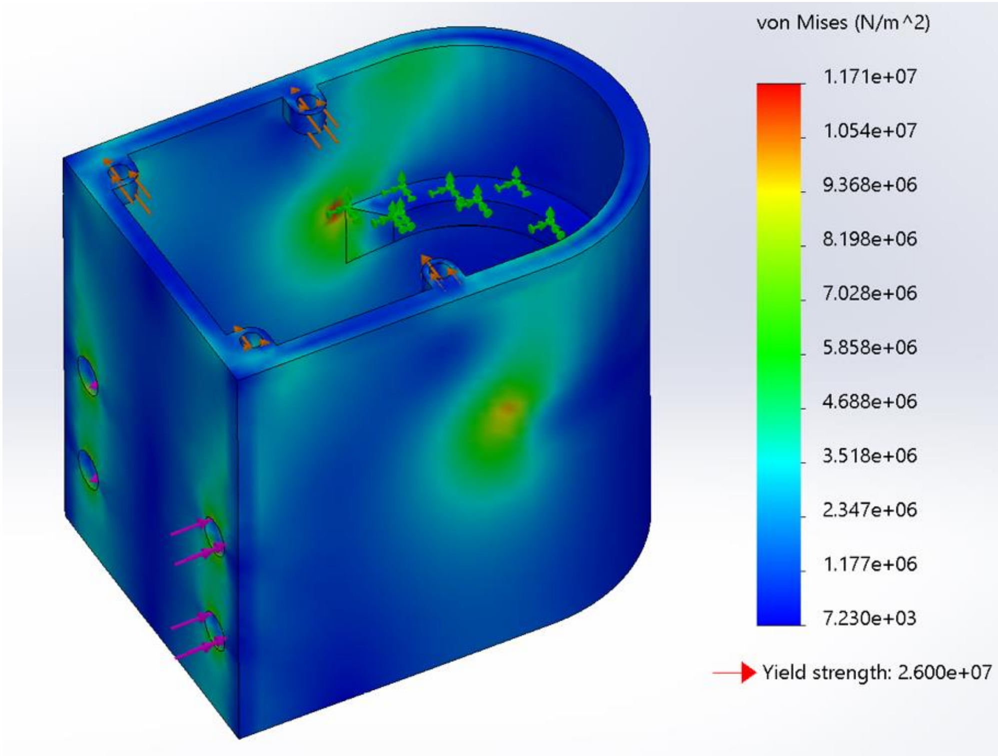


Figure I.6: Modified (thicker) Casing FEA

<u>J. FMEA</u>

The DFMEA is an incredibly critical document for the successful determination of what needs to be tested on the prototypes and in what capacities. It is also incredibly helpful in determination of what the highest priority in consideration for design and testing should be. The DFMEA (Figure J.1) used in this design process is fairly straight-forward. In the center of the page is the most key components - the failure mode and its effect. Essentially, what can go wrong in the device. To that section's left is a breakdown of the subsystems and components in the assembly. For every failure mode, appropriate columns are marked with a checkbox for what applies to that given failure mode so that in testing, all of those can be checked to ensure the failure does not present itself. To the right of the failure mode section is the risk scoring section. In this section every failure mode is assigned a value of 1-10 for severity of the failure mode, how likely it is to occur, and how easily detectable the failure mode is. The determined values from these - as discussed and determined by the team - are then multiplied together to find the risk priority number or RPN. The higher this number is, indicates a higher need to prioritize in design and testing this failure mode to ensure that it does not occur. As current, there are three severe failure modes (RPN ≥ 100) that need to have high priority. They are: device burns user, the device receives water damage, and the gears do not mesh ideally. Designing around these failure modes will ensure a more robust design to begin with. Also, on this DFMEA are the indicated tests that refer to the design verification plan (discussed in Appendix L). The DFMEA spreadsheet is also attached to this submission.

Faucet System	Faucet Handle	Faucet Valve	Faucet Casing	Faucet Gearset	Faucet Fitting	UX	UX Buttons	UX Screen	UX Warning	Remote	Electronics	Control System	Power	Thermocouple	Motor	Installation	Failure Mode	Effect	Severity	Occurence	Detection	RPN	Test	Prevention Method
☑	☑	☐	☑	☑	☑	☑	☐	☑	☐	☐	☑	☐	☐	☐	☑	☑	Device is Too Big	Unable to mount successfully on the bowl, place components on the shelf, or loss of tilting motion in bowl.	2	5	1	10	1.1	Size reduction techniques in digital twin and prototyping.
☑	☑	☐	☑	☑	☑	☑	☐	☑	☐	☐	☑	☐	☐	☐	☑	☑	Device is Too Heavy	Unable to mount successfully, cumbersome for users.	1	7	2	14	1.2	Choosing lightweight materials and reducing size of the digital twin and prototyping.
☑	☑	☑	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	Device cannot be operatured manually.	Device doesn't meet need for user override, possibility to hav technical issue and hurt client.	7	7	2	98	1.4, 1.5, 1.8	Choosing a motor that requires low torque to move.
☑	☐	☐	☐	☑	☐	☐	☑	☐	☑	☐	☑	☐	☐	☐	☑	☐	Device is too Loud	Worsens client's experience at the salon.	5	2	1	10	1.6	Using components that do not have high interference and a motor that requires low power motors.
☐	☐	☐	☑	☑	☐	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☐	Device receives water damage	Device can lose functionality, damage to interal sensors, motors, and controller.	10	7	6	420	1.7, 2.4	Using solid plastic components and rubber gaskets.
☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☐	Device Breaks	Device is no longer operable for user and must replace faucet entirely.	10	2	1	20		Using sturdy materials, focusing the most fragile components to have the strongest materials.
☐	☐	☐	☐	☐	☐	☑	☐	☑	☑	☐	☐	☐	☐	☐	☐	☐	Device is hard to read	Stylist cannot choose proper setting, temperature can be set incorrectly, possible harm to client.	4	5	1	20	2.2, 2.5	Using brightly colored and lit screens. Using 2 screens to ensure that no text is too small.
☐	☐	☐	☐	☐	☐	☑	☑	☐	☐	☑	☐	☐	☐	☐	☐	☐	Device is hard to change	Stylist not able to make necessary adjustments, can cause harm to client.	6	2	1	12	2.1, 2.4	Using very tactile buttons to make clear changes for the user.
☐	☐	☐	☐	☑	☐	☑	☐	☑	☑	☐	☑	☑	☑	☑	☑	☐	Device burns user	Harm to user, bad client experience, lack of trust in company, possible worse harm even.	10	5	2	100	3.1, 3.3	Including a warning system for certain temperatures and including a client control feature.
☐	☑	☐	☐	☐	☐	☑	☑	☐	☐	☑	☐	☐	☐	☐	☐	☐	Device can't be used with wet hands	Stylist not able to make necessary adjustments, can cause harm to client.	7	1	4	28	2.4	Using buttons and no touch screen.
☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Gears don't mesh ideally	Home position begins to drift and motor will overdrive.	6	3	10	180		Gears chosen to prevent issues.

Figure J.1. Full DFMEA

K. BOM & Sourcing Plan

This appendix contains the current bill of materials and sourcing plan for the Fau-Set which has been updated since the CDR. This section also compares the FDR and CDR BOM. The CAD Drawings and Ops Sheets can be found attached to the report submission.

To estimate costs for all manufactured parts, a cost estimation calculator is used for each of the machining and 3D printing processes. Machining was chosen it is the most feasible and straightforward process to make cuts. In addition, 3D printing has been chosen as it was cost effective, fast, and scalable. For mass production, all 3D printed parts would be injection molded. The FDR BOM, as shown in Figure K.1, has a final total cost of $401.40. Since the CDR BOM, Figure K.2, some components were added such as waterproof fabric for the faucet attachment system. Additionally, some components like the microSD cards were determined to be unnecessary for running the tft screens and therefore removed in the FDR. Other parts such as pads to stick on the bottom of the UI were added during the FDR phase to give the Fau-Set a more finished look.

CAD Drawings and Ops Sheets

Please see the pdfs attached to this submission to see all finalized CAD Drawings and ops sheets for the Fau-Set.

BILL OF MATERIALS

Team Name: DRP Engineering
Project Title: Fau-Set
Date: 4/21/2022

Item No.	Part No.	Part Name	Units	Qty	Material / Description	Source	Catalog No.	Unit Cost ($)	Unit Processing	Assembly Cost ($)	Line Total Cost ($)
1	A1	Mechanical Assembly	-	1	Assembling all mechanical parts	-	-	-	-	15.00	15.00
2	A2	Electrical Assembly	-	1	Assembling all electronics	-	-	-	-	15.00	15.00
3	P1	Gearmotor	pcs	1	Drives the faucet subassmebly	Digikey		39.95	-	-	39.95
4	P2	Bushing	pcs	1	In faucet assembly	McMaster		5.48	-	-	5.48
5	P3	Thermistors	pcs	1	Measures the temperature of water	Digikey		2.47	-	-	2.47
6	P4	Arduino Mega	pcs	1	Controlling motors, user interface, and thermocouple	Digikey		43.00	-	-	43.00
7	P5	Screen	pcs	2	Used for User Interface	Adafruit		24.95	-	-	49.90
8	P6	Buttons	pcs	8	User Interface and Customer Remote	DigiKey		0.48	-	-	3.84
9	P7	50 tooth gear	pcs	1	Faucet Subassembly	McMaster		30.03	-	-	30.03
10	P8	25 tooth gear	pcs	1	Faucet Subassembly	McMaster		16.64	-	-	16.64
11	P9	Gasket Material	pcs	1	Faucet Subassembly	Amazon		1.47	-	-	1.47
12	P10	Class 2 power supply	pcs	1	Converts outlet power to 12volts for motor and arduino	Digikey		48.40	-	-	48.40
13	P11	Motor controller	pcs	1	Controls motors	Walmart		7.98	-	-	7.98
14	P12	Screws	pcs	1	interface	Amazon		2.89	-	-	2.89
15	P13	Thermal Inserts	pcs	1	Thermal inserts to hold together user interface	Amazon		14.84	-	-	14.84
16	P14	Brackets to mount	pcs	1	Brackets to mount gearmotor in faucet assembly	Pololu		7.95	-	-	7.95
17	P15	Pads/Gripper Feet	pcs	1	Gripper feet for bottom of UI to stop it from sliding	Amazon		6.99	-	-	6.99
18	P16	Limit Switch	pcs	1	Limit Switches, tell the system when the Fau-Set is off	Amazon		6.99	-	-	6.99
19	P17	Waterproof Fabric	pcs	1	Used to waterproof the Fau-Set	Seattle Fabrics		16.95	-	-	16.95
20	M1	Faucet and Electronic	-	1	Aluminum 6061 Stock. Raw material for manufacturing faucet				39.33	-	39.64
21	M2	Faucet Handle	-	1	product				10.19	-	10.22

Total Purchased Parts $	305.77
Total Purchased Parts with 8.5% Overhead $	331.76
Total Custom Manufactured Parts with 35% Overhead $	39.64
Total Assembly Cost $	30.00
Total Cost $	401.40

Figure K.1. FDR Project Bill of Materials

CDR BILL OF MATERIALS

Team Name: DRP Engineering
Project Title: Fau-Set
Date: 3/8/2022

Item No.	Part No.	Part Name	Units	Qty	Material / Description	Source	Catalog No.	Unit Cost ($)	Unit Processing Cost ($)	Assembly Cost ($)	Line Total Cost ($)
1	A1	Mechanical Assembly	-	1	Assembling all mechanical parts	-	-	-	-	15.00	15.00
2	A2	Electrical Assembly	-	1	Assembling all electronics	-	-	-	-	15.00	15.00
3	P1	Gearmotor	pcs	1	Drives the faucet subassmebly	Digikey		39.95	-	-	39.95
4	P2	Bushing	pcs	1	In faucet assembly	McMaster		5.48	-	-	5.48
5	P3	Thermistors	pcs	1	Measures the temperature of water	Digikey		2.47	-	-	2.47
6	P4	Arduino Mega	pcs	1	Controlling motors, user interface, and thermocouple	Digikey		43.00	-	-	43.00
7	P5	Screen	pcs	2	Used for User Interface	Adafruit		24.95	-	-	49.90
8	P8	Buttons	pcs	8	User Interface and Customer Remote	DigiKey		0.48	-	-	3.84
9	P9	50 tooth gear	pcs	1	Faucet Subassembly	McMaster		30.03	-	-	30.03
10	P10	25 tooth gear	pcs	1	Faucet Subassembly	McMaster		16.64	-	-	16.64
11	P11	Gasket Material	pcs	1	Faucet Subassembly	Amazon		1.47	-	-	1.47
12	P12	microSD Cards	pcs	2	Run the user interface screens	Amazon		7.28	-	-	14.56
13	P13	Class 2 power supply	pcs	1	Converts outlet power to 12volts for motor and arduino	Digikey		48.40	-	-	48.40
14	P14	Motor controller	pcs	1	Controls motors	Walmart		7.98	-	-	7.98
15	M1	Faucet and Electronic Housing	-	1	Aluminum 6061 Stock. Raw material for manufacturing faucet				72.33	-	72.33
16	M2	Faucet Handle	-	1	Printer Filament: PLA. Raw material for prototype and final product				20.19	-	20.19
								92.52			

Total Purchased Parts $	263.72
Total Purchased Parts with 8.5% Overhead $	286.13
Total Custom Manufactured Parts with 35% Overhead $	72.33
Total Assembly Cost $	30.00
Total Cost $	388.46

Figure K.2: CDR Project Bill of Materials

L. Validation

A series of 20 tests were then created to fully validate the Fua-Set using the newly built test stand. These standards were created to ensure all of the customer requirements were met and to ensure no failures outlined in the DFMEA. The testing was split into four main categories: faucet assembly, user interface, electronic systems, and installation of device. Most of these tests were developed to meet the criteria laid out for both engineering and customer requirements, including setting time, temperature range, and waterproofing. The ratings for the tests also varied having multiple be subjective ratings coming from random users and others being measured values. It was expected that through the rigorous design process underwent by the team, all of the validation criteria should be met. Some of the key criteria included setting temperature within 30s, installing with at most 3 tools and in less than 5 minutes, and being temperature accurate within 2.5 degrees.

Through the first few rounds of testing, the usability of the device was seeming to not meet the criteria laid out. Without even running the subjective rating test, it was apparent that there was room for improvement as the buttons needed to be held for the system to register that they were receiving the signal. The second test that presented issues was that of the installation ease. Early versions of the prototype struggled to easily screw on with the coupler and mount and would take substantial time to do so due to its low fidelity. However, the final machined version actually reduced the installation effort and the time to install significantly. The final test that seemed would be difficult to pass was the setting time. Through most of the iterations of the algorithm, the system took much too long to set if it even set at all. This was expected to be in large part for a few reasons, primarily the rate at which the thermistor senses and returns temperature change and the algorithmic structure of the code. However, after largely restructuring the code, it ultimately set the temperature within the required amount of time by sacrificing the update rate for the screens.

A full breakdown of the results as well as a summary of each procedure and requirements to pass can be seen in figure L.1. It was expected based on the carful considerations made during the design process that each of these requirements could and would be met. While the previously mentioned tests did present issue, ultimately the design changes made to the system accounted for these issues and the system passed every test. A summary of these results can be found in Table L.1

Table: L.1: Key Fau-Set Testing Results

Requirement	Minimum Value	Testing Result
Manual Control Rating	7/10 Minimum	7.8
Waterproof	No Water	No Water In System
Ease of Use Rating	4/5 Mimimum	4.14
Temperature Accuracy	±2.5°F	±2.5°F
Settling Time	30s or Less	28.7s Average
Installation Ease	Less than 5 Minutes	4 min 12 sec Average

Test Number	Subsystem	Component	Test Name	Test Description	Standard to Pass	Test Date	Result	Pass?
1	Faucet							
1.1	Faucet	Overall	Dimensionalization Test	Measure the primary dimensions of the overall system primary components.	Must be no closer than 3mm in any direction of the shampoo bowl or its surorunding components.	4/2	12 cm	P
1.2	Faucet	Overall	Mass Test	Measure the mass of the overall primary system components using a standard scale.	Shall not exceed 5kg.	4/2	.712 kg	P
1.3	Faucet	Overall	Aesthetics Test	Subjective rating of how aestheticaly appealling it is	Shall have an average subjective rating of no less than 7.	4/19	Avg: 7	P
1.4	Faucet	Handle	Manual Control Test	Rating score of how easy it is to change the position of the handle by an unbiased sample of people.	Shall have an average subjective rating of no less than 7.	4/19	Avg: 7.8	P
1.5	Faucet	Handle	Handle Movement Range Test	Measure the number of degrees of motion of the handle for adjusting temperature.	Shall retain full rotational motion as compared to system without device.	4/17	Full Range	P
1.6	Faucet	Overall	Noise Test	Subjective rating of the noises output by the system and how offputting they are.	Shall have an average subjective rating of no less than 7.	4/17	Avg: 7.4	P
1.7	Faucet	Casing	Waterproof Test	Amount of water to get within the system components that would cause damage to the system.	Shall allow NO water into primary systems.	4/12-4/17	No Water	P
1.8	Faucet	Overall	Standby Test	Subjective rating of how easy it is to move the handle while in standby move	Shall have an average subjective rating of no less than 7.	4/19	Avg 7.8	P
2	User Interface							
2.1	User Interface	User Controls	Usability Test	Subjective rating of how easy it is to use the user interface and controls	Shall have an average subjective rating of no less than 4.	4/12	avg: 4.14	P
2.2	User Interface	Display	Readability Test	Subjective rating of how easy it is to read the display.	Shall have an average subjective rating of no less than 4.	4/14	avg: 4.7	P
2.3	User Interface	Power Controls	Power Test	Measurement of voltage and power the system needs to perform properly.	Shall have 12 V DC Supplied	4/14	12.3 V	P
2.4	User Interface	User Controls	Wet Usability Test	Subjective rating of how easy using the user interface is with hands that are wet.	Shall have an average subjective rating of no less than 4.	4/12	avg: 4.14	P
2.5	User Interface	Labels	Label Readability Test	Subjective rating of how easy it is to read and understand any labels	Shall have an average subjective rating of no less than 4.	4/19	avg: 4.2	P
3	Electronics							
3.1	Electronics	Temperature Sensor	Temperature Reading Accuracy Test	Accuracy of temperature returned by the sensors as compared to external thermocouple.	Temperature reading of thermocouple must be within 2 degrees fahrenheit of actual temperature.	4/17	1.2 F	P
3.2	Electronics	Power	Power Input Ease Test	Subjective rating of how easy it is to ensure that the system has power. i.e. easy to plug in or change batteries.	Shall have an average subjective rating of no less than 8.	4/12	avg: 5	P
3.3	Electronics	Control System	Temperature Setting Accuracy Test	Temperature accuracy of settling temperature compared to desired temperature.	Shall be within 2.5 degrees fahrenheit of desired temperature at settling time.	4/17	2.5	P
3.4	Electronics	Control System	Temperature Settling Time Test	Measure the length of time to reach the settling temperature over 10 set temperatures	Shall reach set temperature within 30 seconds	4/19	28.7s avg	P
3.5	Electronics	Wiring	Wiring Safety Test	Visual Check if all wires are connected properly and there are no exposed leads or ends.	Shall have no exposed leads or wire ends.	4/17	pass	P
4	Installation							
4.1	Installation	Overall	Installation Ease Test	Can be installed in minimal time.	Can be installed in less than 5 minutes on a minimum of 3 samples.	4/16	avg: 4:12	P
4.2	Installation	Overall	Installation Security Test	Subjective rating of how secure the system is once installed.	Shall have an average subjective rating of no less than 4.	4/17	avg: 4.8	P

Figure L.1. Design Verification Plan Master Document

In the CDR phase a test setup was built in the PEARL labs using buckets with hot and cold water and a donated shampoo bowl from Bernadettes (Shown in Figures L.2 & L.3).

Figure L.2. Testing Apparatus for Testing in Purdue PEARL Labs (front view)

Figure L.3. Testing Apparatus for Testing in Purdue PEARL Labs (top view view)

In the FDR phase, a more robust setup was constructed using a laminate countertop and framing lumber (Figure L.4). Additionally, stronger pumps (600 L/H as opposed to 240 L/H) were purchased so the water flow rate more closely mimicked that at Bernadettes. This more robust test setup allowed for testing to occur at the PEARL labs instead of Bernadettes. This solution posed a mutual benefit, as testing at Bernadettes would restrict their business capabilities and require significant efforts in the transportation of equipment to and from Purdue.

Figure L.4: Front and Back of Final Test Stand

M. List of Standards

In regards to manufacturing, the most prevalent written standards came from the table of fits and tolerances shown in figure H.4. These defined the final dimensions for each of the parts, which was crucial in determining the correct fits for the mechanical assembly. While not written, another important standard was that of having presentable finishes on all manufactured components. As mentioned in the manufacturing section of Appendix 3.H, machined parts had final operations that ensured a smooth finish. 3D printed parts, on the other hand, were epoxied, sanded, and painted to feign the appearance of an injection molded part. This standard even extended to the wiring, wherein each wiring harness was covered with a sheathing across its length and heat shrink at either end to appear cleaner and more professional.

For the purposes of testing the Fau-Set, no specific standards were used to develop the test methods. Through much research, no methods that satisfied the testing needs matched closely to the system requirements were discovered.

N. Fau-Set Software Code

The Fau-Set was programmed using C in the Arduino IDE. The Arduino file is attached to this submission and the code is also pasted below.

```
// INCLUSIONS
#include <math.h>
#include "Adafruit_GFX.h"            //For screens
#include "SD.h"                      //For screens
#include "Adafruit_ILI9341.h"        //For Screens

/// PIN DEFINITIONS
```

```
/// MOTOR PIN DEFINITIONS
const int motorDir = 8;
const int motorPower = 9;
const int enc1 = 3;
const int enc2 = 2;
const int coast = 4;

/// THERMISTOR PIN
const int thermistor_output = A1;

//2, 3, 18, 19, 20, 21 - interrupt ports on arduino mega
////Defining Pins for UI Buttons////
const int upPin = 44;            //12 the input number of the up pushbutton pin
const int downPin = 45;          //13 the input number of the down pushbutton pin
const int preset1 = 35;          //25 the input number of preset 1
const int preset2 = 34;          //23 the input number of preset 2
const int preset3 = 25;          //8 the input number of preset 3
const int preset4 = 24;          //11 the input number of preset 4
const int clientUp = 33;         //22 the input number of the client up button
const int clientDown = 23;       //24
const int standbyBut = 19;

////Setting Ports for Screens//// --> DC and RST can be shared, CS has to be different for each screen
#define TFT_DC 48                //9
#define TFT_CS 53                //53
#define TFT_RST 0                //0
#define TFT2_CS 10 //53          //10

const byte limitSwitch = 18;     //Pin for limit switch - keep it at 2 because it works better, I think it's an interrupt pin0
// GENERAL VARIABLE DEFINITIONS
int dirState;
int powerState;
int counts = 0;
float kp = -12;
float kd = -.5;
float err;
float errD = 0;
```

```
float currentT;
float prevT = 0;
float deltaT;
float scalar;
int prevCounts;
float prevPos;
float pos;
float vel;
float velLim = 3.14;
int thermistor_adc_val;
double output_voltage, thermistor_resistance, therm_res_ln, temperature, temperature_f;
double u;
unsigned long current = 0;
unsigned long baseTime = 10;
int lastErr;
int tDelay;
int i;
int k;
int userChange = 0;
int basePWM;
int basePWMH = 35;
int basePWMHD = 35;
int basePWML = 40;
int basePWMLD = 40;
int inStandby = LOW;
int coastState = HIGH;

/// TEMPERATURE SETTING STATES
int upState;                         // variable for reading the up pushbutton status
int downState;                       // variable for reading the down pushbutton status
int lastUpState = LOW;               // status of the up button
int lastDownState = LOW;             // status of the down button
float setTemp = 105;                 // variable temperature
float oldTemp, measuredTemp, tempDifference;          // oldTemp is the temperature that was previously measured by the thermistor, measuredTemp is the current temp,

/// PRESET AND LIMIT SWITCH STATES
float fashionColors = 88;            // preset 1
float sensitiveScalp = 95;           // preset 2
float defaultTemp = 105;             // preset 3
```

```
float colorOut = 110;                // preset 4
int pre1State;
int pre2State;
int pre3State;
int pre4State;
int last1State = LOW;
int last2State = LOW;
int last3State = LOW;
int last4State = LOW;
volatile byte state = LOW;           //Basically saying the defaut state of the switch
int pressed;
int standbyState;
int lastStandbyState = LOW;

/// CLIENT BUTTON STATES
int clientUpState;
int clientDownState;
int lastClientUpState = HIGH;
int lastClientDownState = LOW;

////Defining Color Codes//// --> Used by screens
#define BLACK 0x0000
#define NAVY 0x000F
#define DARKGREEN 0x03E0
#define DARKCYAN 0x03EF
#define MAROON 0x7800
#define PURPLE 0x780F
#define OLIVE 0x7BE0
#define LIGHTGREY 0xC618
#define DARKGREY 0x7BEF
#define BLUE 0x001F
#define GREEN 0x07E0
#define CYAN 0x07FF
#define RED 0xF800
#define MAGENTA 0xF81F
#define YELLOW 0xFFE0
#define WHITE 0xFFFF
#define ORANGE 0xFD20
#define GREENYELLOW 0xAFE5
//#define PINK 0xF81F
```

```
////GRAPHICS SETUP////
int presetFontSize = 3;
int currentTempFontSize = 10;
int setTempFontSize = 10;

Adafruit_ILI9341 tft = Adafruit_ILI9341(TFT_CS, TFT_DC, TFT_RST);
Adafruit_ILI9341 tft2 = Adafruit_ILI9341(TFT2_CS, TFT_DC, TFT_RST);

void setup() {
  /// PORT INITIALIZATION
  pinMode(motorPower, OUTPUT);
  pinMode(motorDir, OUTPUT);
  pinMode(coast, OUTPUT);
  pinMode(enc1, INPUT);
  pinMode(enc2, INPUT);
  pinMode(upPin, INPUT);              // initialize the up pushbutton pin as an input
  pinMode(downPin, INPUT);              // initialize the down pushbutton pin as an input
  pinMode(preset1, INPUT);
  pinMode(preset2, INPUT);
  pinMode(preset3, INPUT);
  pinMode(preset4, INPUT);
  pinMode(clientUp, INPUT);
  pinMode(clientDown, INPUT);
  pinMode(standbyBut, INPUT);

  Serial.begin(9600);
  delay(1000);

  ////Setup First Screen////
  tft.begin();
  tft.fillScreen(BLACK);
  tft.setRotation(1);
  tft.setCursor(5, 5);
  tft.setTextColor(WHITE, BLACK);  tft.setTextSize(4);
  tft.print("Current Temp:");
  oldTemp = checkTemp();
  tft.setTextSize(currentTempFontSize);
  tft.setCursor(15, 90);
  tft.setTextColor(WHITE, BLACK);
```

```
  tft.print(oldTemp, 1);

  ////Setup Second Screen////
  tft2.begin();
  tft2.fillScreen(BLACK);
  tft2.setRotation(1);
  tft2.setCursor(5, 5);
  tft2.setTextColor(WHITE, BLACK);  tft2.setTextSize(4);
  tft2.print("Set Temp:");
  tft2.print("\n\n");
  tft2.setTextSize(setTempFontSize);
  tft2.setCursor(15, 90);
  tft2.print(setTemp, 1);
  delay(1000);

  /// SETUP MOTOR AND ENCODER TO INITIAL STATE
  analogWrite(motorPower, powerState);
  digitalWrite(motorDir, dirState);
  attachInterrupt(digitalPinToInterrupt(enc1), DC_Motor_Encoder, RISING);
  attachInterrupt(digitalPinToInterrupt(limitSwitch), standby, LOW);
}

void loop() {
  delay(100);
  //tft.begin();
  //tft.setRotation(1);
  //tft2.begin();
  //tft.setRotation(1);
  /// PRIMARY FUNCTION CALLS
  if (inStandby == LOW) {
    coastState = HIGH;
    Serial.println("System is adjusting temperature");
    checkButtons();
    measuredTemp = checkTemp();
    screen();
    checkButtons();
    tempControl();
    checkButtons();
    SetMotor();
    if (fabs(setTemp - measuredTemp) < 2.5) {
```

```
      powerState = 0;
      SetMotor();
    }
    delay(tDelay);

    Serial.println("System is in the loop for the thermistor to catch up");
    powerState = 0;
    SetMotor();
    for (int i = 0; i < 4; i++) {
      checkButtons();
      delay(500); //was 6
    }
    measuredTemp = checkTemp();
    screen();

    if (fabs(setTemp - measuredTemp) < 2.5) {
      k = 0;
      Serial.println("Temperature is within range Pause");
      while (k < 3000 && pressed == LOW) {
        powerState = 0;
        checkButtons();
        if (inStandby == HIGH) {
          k = 3000;
        }
        SetMotor();
        measuredTemp = checkTemp();
        if (fabs(setTemp - measuredTemp) > 2.5) {
          k = 3000;
        }
        screen();
        k++;
        delay(1);
      }
    }
    /// setting the old temperature for continuous upating
    oldTemp = measuredTemp; //Set current measured temp to old temp so it can check the next
time it loops how much it changed
  }
  else {
    standby();
```

```
    checkButtons();

  }
}

/// FUNCTION TO READ ENCORDER VALUES
void DC_Motor_Encoder() {
  int b = digitalRead(enc2);
  if (b > 0) {
    counts++;  /// INCREASES ENCODER VALUE WHEN ROTATING ONE DIRECTION
  }
  else {
    counts--;  /// DECREASES ENCODER VALUE WHEN ROTATING OTHER DIRECTION
  }
}

////Function to Check Temperature Using 10k Thermistor and Send Back Measured Temp, also prints to serial screen////
double checkTemp() {
  thermistor_adc_val = analogRead(thermistor_output);
  output_voltage = ( (thermistor_adc_val * 5.0) / 1023.0 );
  thermistor_resistance = ( ( 5 * ( 10.0 / output_voltage ) ) - 10 ); /* Resistance in kilo ohms */
  thermistor_resistance = thermistor_resistance * 1000 ; /* Resistance in ohms   */
  therm_res_ln = log(thermistor_resistance);
  temperature = ( 1 / ( 0.001129148 + ( 0.000234125 * therm_res_ln ) + ( 0.0000000876741 * therm_res_ln * therm_res_ln * therm_res_ln ) ) ); /* Temperature in Kelvin */
  temperature = temperature - 273.15; /* Temperature in degree Celsius */
  temperature_f = (temperature * 1.8) + 32;
  temperature_f = (temperature_f * 1.1307) - 2.53;
  return temperature_f;
}

/// sets the motor direction and power
void SetMotor() {
  prevCounts = counts;
  analogWrite(motorPower, powerState);
  digitalWrite(motorDir, dirState);
  digitalWrite(coast, coastState);
}
```

```
/// control function that only chooses direction based on temperature and a 1 or 0 value for power if in or out of range
void tempControl() {
  err = setTemp - measuredTemp;

  if (fabs(err) < 2.5) {
    powerState = 0;
  }

  else {
    if (err > 0) {
      dirState = HIGH;
      if (fabs(err) > fabs(lastErr)) {
        basePWM = basePWMH;
      }
      else {
        basePWM = basePWMHD;
      }
    }
    else if (err < 0) {
      dirState = LOW;
      if (fabs(err) > fabs(lastErr)) {
        basePWM = basePWML;
      }
      else {
        basePWM = basePWMLD;
      }
    }

    currentT = millis();
    deltaT = currentT - prevT;
    errD = (err - lastErr)/ deltaT;

    u = (kp * err) + (kd * errD);
    u = fabs(u);
    scalar = u/100;
    powerState = (scalar * 5) + basePWM;

    if (powerState > (basePWM + 5)) {
      powerState = (basePWM +5);
```

```
    }
  }
  prevT = currentT;
  if (fabs(lastErr) > fabs(err)) {
    powerState = (scalar * 3) + basePWM;
    if (powerState > (basePWM +3))  {
      powerState = basePWM + 3;
    }
  }
  if (signbit(lastErr) != signbit(err)) {
        powerState = (scalar * 3) + basePWM;
    if (powerState > (basePWM +3))  {
      powerState = basePWM + 3;
    }
  }
  if (fabs(setTemp - measuredTemp) > 15) {
    tDelay = 650; //850;
  }
  if (fabs(setTemp - measuredTemp) > 10) {
    tDelay = 450; //650;
  }
  else if (fabs(setTemp - measuredTemp) > 7.5) {
    tDelay = 400; //500;
  }
  else if (fabs(setTemp - measuredTemp) > 3) {
    tDelay = 350; //350;
  }
  else {
    tDelay = 170;
  }
  lastErr = err;
  Serial.print("Error: ");
  Serial.print(err);
  Serial.println();
  Serial.print("Control Ouput: ");
  Serial.print(u);
  Serial.println();
  Serial.print("Power Level: ");
  Serial.print(powerState);
  Serial.println();
```

```
  Serial.print("Last Error: ");
  Serial.print(lastErr);
  Serial.println();
  Serial.print("Direction: ");
  Serial.print(dirState);
  Serial.println();
  Serial.print("Temperature: ");
  Serial.print(measuredTemp);
  Serial.println();
  Serial.println();
}

/// Jen's screen stuff
void printToSerial(int set, float temp) {
  //tft2.begin();
  //tft2.setRotation(1);
  if (set == 1) {
    Serial.println("Setting to Fashion Colors Preset");
    tft2.setTextSize(presetFontSize);
    tft2.setCursor(5, 40);
    tft2.print("Fashion Colors ");
  }
  else if (set == 2) {
    Serial.println("Setting to Sensitive Scalp Preset");
    tft2.setTextSize(presetFontSize);
    tft2.setCursor(5, 40);
    tft2.print("Sensitive Scalp");
  }
  else if (set == 3) {
    Serial.println("Setting to Default Temperature Preset");
    tft2.setTextSize(presetFontSize);
    tft2.setCursor(5, 40);
    tft2.print("Default        ");
  }
  else if (set == 4) {
    Serial.println("Setting to Color Out Preset");
    tft2.setTextSize(presetFontSize);
    tft2.setCursor(5, 40);
    tft2.print("Color Out      ");
  }
```

```
  else if (set == 5) {
    Serial.println("Client Adjust");
    tft2.setTextSize(presetFontSize);
    tft2.setCursor(5, 40);
    tft2.print("Client Adjust      ");
  }
  else if (set == 0) {
    tft2.setTextSize(presetFontSize);
    tft2.setCursor(5, 40);
    tft2.print("                ");
  }

  Serial.print("The Current Set Temperature is: ");
  Serial.print(temp);
  Serial.println(" Degrees F");
  tft2.setTextSize(setTempFontSize);
  tft2.setCursor(15, 90);
  tft2.print(temp, 1);
  tft2.print(" ");
}

////Function to Send System to Standby Mode When Limitswitch Is Pressed////
void standby() {
  //tft.begin();
  //tft.setRotation(1);
  tft.setTextColor(RED, BLACK);
  tft.setTextSize(7);
  tft.setCursor(15, 90);
  tft.print("STANDBY");
  tft.setTextSize(10);
  tft.setCursor(15, 90);
  tft.setTextColor(WHITE, BLACK);
  Serial.println("STANDBY");
  powerState = 0;
  coastState = LOW;
  SetMotor();
  checkButtons();
  //measuredTemp = checkTemp();
}
```

```
/// preset buttons
void checkButtons() {
   ///~ BUTTON SECTION ~///

  // Read State of Pushbutton Values//
  int readingUp = digitalRead(upPin);
  int readingDown = digitalRead(downPin);
  int reading1 = digitalRead(preset1);
  int reading2 = digitalRead(preset2);
  int reading3 = digitalRead(preset3);
  int reading4 = digitalRead(preset4);
  int readingClientUp = digitalRead(clientUp);
  int readingClientDown = digitalRead(clientDown);
  int readingStandby = digitalRead(standbyBut);
  pressed = LOW;
//  tft.begin();
//  tft.setRotation(1);
//  tft2.begin();
//  tft2.setRotation(1);

  //// detect current reading status and update temperature ////
  if ((readingStandby != lastStandbyState) || (readingUp != lastUpState) || (readingDown != lastDownState) || (reading1 != last1State) || (reading2 != last2State) || (reading3 != last3State) || (reading4 != last4State) || (readingClientUp != lastClientUpState) || (readingClientDown != lastClientDownState)) {
    current = millis();
  }

  if ((millis() - current) > baseTime)  {
    /// When a button has been pushed down for a length of time, checks if the reading is different from what is expected.
    if ((readingStandby != standbyState) || (readingUp != upState) || (readingDown != downState) || (reading1 != pre1State) || (reading2 != pre2State) || (reading3 != pre3State) || (reading4 != pre4State) || (readingClientUp != clientUpState) || (readingClientDown != clientDownState))  {
      upState = readingUp;
      downState = readingDown;
      pre1State = reading1;
      pre2State = reading2;
      pre3State = reading3;
      pre4State = reading4;
```

```
clientUpState = readingClientUp;
clientDownState = readingClientDown;
standbyState = readingStandby;

/// temperature changes based on which button is pressed
if (upState == HIGH)  {
  setTemp++;
  printToSerial(0, setTemp);
  pressed = HIGH;
}
else if (downState == HIGH)  {
  setTemp--;
  printToSerial(0, setTemp);
  pressed = HIGH;
}
else if (pre1State == HIGH)  {
  setTemp = fashionColors;
  printToSerial(1, setTemp);
  pressed = HIGH;
  userChange = 0;
}
else if (pre2State == HIGH)  {
  setTemp = sensitiveScalp;
  printToSerial(2, setTemp);
  pressed = HIGH;
  userChange = 0;
}
else if (pre3State == HIGH)  {
  setTemp = defaultTemp;
  printToSerial(3, setTemp);
  pressed = HIGH;
  userChange = 0;
}
else if (pre4State == HIGH)  {
  setTemp = colorOut;
  printToSerial(4, setTemp);
  pressed = HIGH;
  userChange = 0;
}
else if (clientUpState == HIGH)  {
```

```
        if (userChange < 6) {
          setTemp = setTemp + 0.5;
          printToSerial(5, setTemp);
          pressed = HIGH;
          userChange += 1;
        }
      }
      else if (clientDownState == HIGH)  {
        if (userChange > -6) {
          setTemp = setTemp - 0.5;
          printToSerial(5, setTemp);
          pressed = HIGH;
          userChange -= 1;
        }
      }
      else if (standbyState == HIGH) {
        inStandby = !inStandby;
      }
    }
  }

  /// Resetting each button state
  lastUpState = readingUp;
  lastDownState = readingDown;
  last1State = reading1;
  last2State = reading2;
  last3State = reading3;
  last4State = reading4;
  lastClientUpState = readingClientUp;
  lastClientDownState = readingClientDown;
  lastStandbyState = readingStandby;

  //tft.begin();
  //tft.setRotation(1);
  //tft2.begin();
  //tft2.setRotation(1);

}

/// Screen Printing
```

```
void screen() {
    ///~ SCREEN PRINTING ~///
  //delay(200);
  //tft.begin();
  //tft.setRotation(1);
  ////Only Prints Measured Temp to Screen if Major Temperature Difference Occurs//// -->
Changing this speeds up processing but makes screens less accurate
  if (abs(measuredTemp - oldTemp) > 0.5) {
    tempDifference = measuredTemp - setTemp;
    if (abs(tempDifference) < 2.5) {
      tft.setTextColor(GREEN, BLACK);
    }
    else {
      tft.setTextColor(WHITE, BLACK);
    }
    tft.setCursor(15, 90);
    tft.setTextSize(currentTempFontSize);
    //tft.print("I'm trying?");
    tft.print(measuredTemp, 1);
    tft.print(" ");
    //delay(5);
    //tft.setCursor(15, 90);
    //tft.println("help");
  }

}
```