Project Report

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Executive summary

The purpose of this report is to provide the details of the design and build of a project that was performed by a group of senior engineering students at the University of Texas at Tyler, known as Team 7 or Cross Discipline Engineering. The project was sponsored by given to the students by HVAC Manufacturing. HVAC manufacturing requested the design and build of a rotary coaxial actuator system that will be used in industrial and commercial HVAC applications to control the position of a dual or a single damping blade in different HVAC units. In addition, the system would provide the provisions to collect and communicate data related to HVAC, wirelessly to the cloud, using internet of things (IoT) concepts. Both Single and dual-coaxial systems were designed and approved for prototype manufacturing by the end of the Fall semester. A prototype for both systems was built during the Spring semester when the world came to a standstill because of the COVID-19 Pandemic. In spite of this major challenge, the team managed to complete the manufacturing of both prototypes using 3D printing and laser cutting of acrylic material. Moreover, the team completed the testing of these actuators and delivered both as final products in a working condition to HVAC. Final specifications of the systems were within range of HVAC requirements. Recommendations for future improvements of both systems were also provided to HVAC manufacturing

Concept Statement

To design and build a rotary coaxial actuator system that will have the ability to control a dual or single damping HVAC terminal unit allowing for an advanced overall control of air flow. In addition, a secondary focus will be to integrate IoT connectivity to allow for wireless monitoring and data exchange between the system and the cloud.

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Nomenclature

The following table is the list of nomenclature you will see throughout the report with the corresponding meaning shown.

Table 1: Nomenclature table with meaning behind terminology

Word / Acronym / Abbreviation	Meaning
ESP32	ESP32-WROOM-32D microprocessor by Espressif systems
IoT	Internet of Things
Ref Des	Reference Designator – This is labeling system commonly used on electrical schematics
SAV	Smart Air Valve
IAV	Intelligent Air Valve
PLA	Polylactic Acid – 3D printer filament
USB	Universal Serial Bus
PCB	Printed Circuit Board
CDE	Cross Discipline Engineering

Introduction & Background

Team 7, also known as Cross Discipline Engineering (CDE), is a group of senior engineering students that is comprised of three electrical and three mechanical engineers. The sponsor of this project, HVAC Manufacturing Inc, has tasked the team to design a rotary coaxial actuator system that will control terminal units in both commercial and industrial HVAC applications. The need for this actuator is due to demand for more accurate control of single and dual blade terminal units. There are limited options for these units in terms of controlling air flow. However, the following actuators are currently on the market, but each with their own weaknesses:

- Rotary Actuator for a single damping design
  - Not Accurate enough
  - Not applicable in a dual blade damper application
- Linear Coaxial Actuator
  - Not accurate enough
  - Using a linear actuator for rotational motion causes additional problems

HVAC dampers on the market today can be extremely inefficient in certain applications. For this project, C.D.E. designed an actuator with two separate gear trains that work together to complete the task of moving the HVAC damper with an improved accuracy. Another important aspect of the project was to have a microprocessor that will handle all the computing processes and feedback control. The team has had the opportunity to work with a microprocessor and PCB, associated with the project, that has been specifically designed for this application by HVAC Manufacturing. This gave the team a solid base to build and progress off of, while also giving insight into HVAC Manufacturing's expectations and standards. The report includes the details of the design of the system, as well as the process to build and test the system, with all related information such as Bill of Materials, FEAs, and economic feasibility. The

report also includes the sign-off sheet and a final status report in Appendix I which will allow the acceptance and delivery of the system per the mutual agreement between Team 7 and HVAC Manufacturing Inc. The poster created by the team for use during the lyceum is included in Appendix I as well.

Requirements & Specifications

When given the project idea, HVAC Manufacturing had given the team a set of specifications that was approved by their design and engineering team. Table 2 includes required specification and Table 3 includes optional specifications as well as specifications that were allowed to change over the course of the project.

Table 2: List of Customer Approved Specifications

Specification Number	Specification	Required or optional	Value/Limit or yes/no	Units	Acceptance Test/Criteria
1	Max Torque needed to turn round damper	Required	23.9	in*lbs	Measure torque with digital torque wrench to confirm. A value that is equal to or greater than 23.9 inch * lbs is acceptable.
2	Max Torque needed to turn rectangular damper	Required	44	in*lbs	Measure torque with digital torque wrench to confirm. A value that is equal to or greater than 44 inch * lbs is acceptable.
3	Estimated max torque needed to turn dampers with mechanical loss included	Required	55	in*lbs	Measure torque with digital torque wrench, add 25% for mechanical loss. A value that is equal to or greater than 55 inch * lbs is acceptable.
4	Voltage from transformer	Required	24	VAC	Confirm with multimeter
5	Diameter of damper shaft - inner	Required	0.315	inch	Measure with digital calipers to confirm diameter
6	Diameter of damper shaft - outer	Required	.5	inch	Measure with digital calipers to confirm diameter
7	Dimensions of enclosure	Required	19.0x9.0x6.6	Inch (LWH)	Measure through CAD drawing and confirm with physical enclosure
8	Will the same type of motor be used for both inner and outer damper?	Required	Yes		Confirm both motors are identical by part number
9	Current determined by a potentiometer, then replaced by fixed resistor	Required	Yes		Measure resistance of potentiometer and replace with appropriate resistor
10	Reset button	Required	Yes		Reset button should bring the motors back to the 'home' position, meaning the angle of the dampers should return to zero degrees
11	Real Time tracking of the dampers	Required	Yes		The tracking of the dampers should consist of measuring the angles of each damper individually and then report this position

Table 3: List of Optional Specifications

Specification Number:	Specification	Required or optional	Value/Limit or yes/no	Units	Acceptance Test/Criteria
12	IoT Connectivity	Provisional	Yes		The MPU should have the ability to report data wirelessly via Wi-Fi or Bluetooth
13	Ability to remove one motor assembly	Optional – Included	Yes		One of the motors should be easily removable to allow for easy adaptability in a single damper application
14	Motor Torque – Pullout Torque	Optional	1	in*lbs	Verify through testing. Once assembled with gear train, can the assembly turn the damper?
15	Motor Step Size	Optional	0.9	Degrees	Does this step size allow for the greatest amount of accuracy? Can this be improved by changing the step size?
16	Dimensions of Motor	Optional	40X40X20	mm(LWH)	Verify with digital calipers
17	Dimensions of actuator assembly	Optional	11x6.5x6.5	Inches(LWH)	Will be determined during finally assembly and experimental testing. Measure through CAD and appropriate tools
18	Speed of the damper opening/closing	Optional	27.9	seconds	Verify RPM of damper with appropriate tools. Note: This value is based off the RPM of the motor and the delays in the program. This is approximate as the speed of the MPU will also affect the speed of the dampers.
19	Gear Ratio	Optional	1:180		Design using inventor. Will the final gear train when paired with motor turn the damper at an acceptable speed?
20	Type of material used for gear train	Optional	Nylon 6,10		Verify the material is able to handle the torque
21	Amount of time between tracking intervals	Optional	5	minutes	Verify that the tracking of the damper throughout its movement is functioning and correct. Is the accuracy of the unit acceptable?
22	Analog Damper Position Control Signal	Optional	0 – 10	VDC	Measure and confirm with multimeter

Constraints

The following table contains the constraints that the team consider during the design phase of this project. Each constraint has a corresponding comment to further explain.

Table 4: List of Constraints and Their Corresponding Values

Constraint	Value/Limit	Units	Comments
Maximum Amperage from Transform	4.16	Amps	Maximum of 100VA from the transformer @ 24VAC
Noise Level	As low as possible	dB	A housing around the actuator will greatly reduce the overall noise of the actuator
Dimensions of sheet metal enclosure	19.0x9.0x6.6	Inch (LWH)	This limits the overall size of the actuator assembly
Budget	As Low as Possible		Looking into off the shelf gears
Heat	As Little as Possible		The use of heatsinks may be necessary

List of Relevant Standards Used

Given that this is a design for manufacturing, the team wanted to follow related standards commonly used in the industry in order to for the product to be universally transferable between any engineering groups or manufacturing facilities. In addition, these standards guarantee a quality level for the product that would make it ready for use or certification in as many systems as possible. These standards include the following:

- IEEE 802.11 (2016) Wireless Networking (Appendix II)
  - The purpose of this standard is to provide wireless connectivity for fixed, portable, and moving stations within a local area. This standard also offers regulatory bodies a means of standardizing access to one or more frequency bands for the purpose of local area communication. The standard was adhered to by the manufacturer when designing the wireless communication components of the ESP32 and programming its protocol.
- IEEE 802.15.4 (2015) Wireless Sensor/Control Networks (Appendix II)
  - The standard provides for ultra-low complexity, ultra-low cost, ultra-low power consumption, and low data rate wireless connectivity among inexpensive devices. In addition, one of the alternate physical layers (PHYs) provides precision ranging capability that is accurate to one meter. Multiple PHYs are defined to support a variety of frequency bands. The standard was adhered to by the manufacturer while designing the ESP-32 Espressif Systems microprocessor with Wi-Fi capabilities.
- AGMA 933 (2017) Basic Gear Geometry
  - The standard provides an understanding of design, dimensioning, cutting and measurement of gear teeth. This standard also summarizes the important geometrical relations for an easy understanding of gear geometry.
    The standard was employed during the gear train design. It was also referenced when looking for off-the-shelf alternatives.
- ANSI/AGMA 101 (2011) Gear Nomenclature

- The purpose of this standard is to define symbols, terms, and abbreviation that are commonly use in communication and specification of internal and external gear teeth. This standard provides this by using words and images.
  The standard was implemented in the final report and during discussion with HVAC Manufacturing representatives.

These standards are listed in the entirety in Appendix II.

Final Design Details and Considerations

After testing and modifying the design of the Co-axial actuator, the team finalized a design and built a prototype. The design of the team's co-axial actuator provides the ability to remove the upper portion of the gear train and adapt to a single damper application. Included below is a diagram of the assembled product without the housing; The finalized design of the actuator is shown in its entirety in Appendix III.

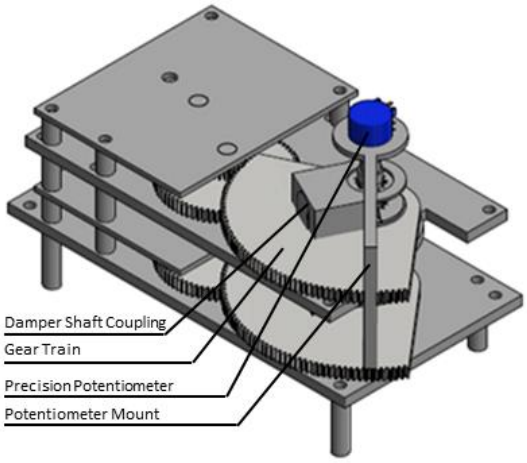


Figure 1: Assembled Co-Axial actuator without housing

The electrical part of the final design includes a PCB carrying a microprocessor, motor drivers, and an analog-to-digital convertor. The PCB controls a set of stepper motors and also receives feedback from a precision potentiometer to help with damper positioning and has the provisions for IoT communication.

Design Description

The actuator is controlled by two analog 0-10vdc signals that linearly relate to the angle of the damper shafts. Every 50mV is equal to .5 degrees at the damper shaft meaning 9V is 90 degrees, and 9.05-10VDC can be used for other functions and do not relate to the damper angles. These signals are interpreted by a microcontroller that has been programmed to output a corresponding digital signal to a set of electric stepper motors. These motors provide a rotational movement that turn a gear train that is connected to the damper blade shafts.

Design Considerations

Strength, rigidity, longevity, functionality, and size all had to be considered for the overall design of the actuator assembly. The gear train had to be rigid and strong enough to handle up to 1800 cubic feet per minute (CFM) of air while on a flow stand during testing. The material selected for the gear train must be able to last the life of the damper unit and be resistant to wearing down over repeated movements. The housing structure must be rigid enough to prevent the assembly from flexing while the dampers are in movements, which could cause fluctuations in accuracy. The overall size also had to be small enough to fit inside a 19”x6”x9” metal enclosure, with enough room to install a PCB microcontroller and associated wiring. The PCB microcontroller must be functional enough to take a voltage input and accurately correspond that to a damper movement of the correct angle.

Mechanical parts

The mechanical components of the actuator assembly consist of three main parts; the gear train, the plates, and the housing

- Gear Train – The gear train is connected to an stepper motor that will turn the damper shaft to create enough torque to turn the damper shafts.
- Plates – The plates, coupled with a series of aluminum stand-offs, will help retain the gear train and motor assembly in a fixed stationary position and allow for the stacking of two motor assemblies to conserve space. It also allows for the entire assembly to affix to the metal enclosure.
- Housing- The housing will protect the actuator from elements such as dust and other foreign matter, while reducing audible noise.

Gear and Housing Design

From the beginning, there was a strong push for finding off the shelf gears which proved to be a huge task because the team needed a set of compound gears to meet the requirement of size and torque requirement of 55-inch pounds. This requirement was 55 times more than the output of the stepper motor that was chose and due to size constraints, a larger motor would not be feasible. There proved to be very limited options for compounded gears that were readily available off the shelf. Of those found, none would work for this project due to them being very costly or much too large to fit within the enclosure. It was apparent that the gears were going to have to be custom made. There were a few options available for a custom gear manufacturing such as 3-D printing, laser cutting, or injection molding. Using Injection molding would be the most cost effective and most reliable option.

The last aspect to the gear design was knowing that the last gear will turn a maximum of 91 degrees, so it must be taken in consideration. Considering that this was the largest gear, it made sense to reduce the size by using a 105-degree section, of the complete gear, in order to help decrease the space it would otherwise require. Designing a gear with a 105-degree parameter allows for 15 degrees of play from the 91-degree rotation required.

The team’s prototype for the housing structure is made up of acrylic, rather than PLA. However, the finalized material, which is discussed further in the report, will not be acrylic. Acrylic was chosen to prototype with because of its affordability and because it easy to work with and manipulate to make changes. Constructing with PLA made the structure much larger and cumbersome in order to retain the

strength and stability needed to hold the gear train assemblies. Constructing with acrylic would slim down the design and give the structural stability and strength requires.

The team wanted to create a simple and efficient housing design to make manufacturing and assembly easy. The housing consists of flat plates with holes cut out and can be easily created using a laser cutter or water jet. The holes are needed for the various gear shafts to pass through, and for locations of the metal standoffs that will be sandwiched between two plate to help ensure a rigid design. Using this design significantly reduces the cost of manufacturing.

To prevent dirt and dust particles that would obstruct the actuators, or cause premature wear of the gears, the team decided to create an enclosure that would go around the entire actuator assembly. This will help reduce maintenance and increase the lifespan of the assembly, thus saving the customer money.

PCB & Electrical Design

The team chose the following electrical components for the actuator and PCB design:

- ESP32 Microprocessor
- DRV8825 Stepper Motor Driver
- ADS1115 Analog to Digital Converter
- 17HS08-1004S Stepper Motor
- Bourns Potentiometer

Through the use of the ADS1115 ADC and ESP32 microprocessor, the PCB has the ability to read two 0-10vdc analog signals and determine the number of steps each stepper motor should take to rotate the damper shafts to the exact angle requested with each .05 V corresponding to .5 degrees at the damper shaft. Once the ESP32 receives the analog control signal, it then sends the information to the DRV8825 stepper driver which will step each motor simultaneously till the angles are correct at the damper shaft. After turning the blades to the angle, the potentiometer is used to adjust the angle to correct error.

Final Functional and Black Box Diagrams

Functional Diagram

Figure 2 shows a functional block diagram of the co-axial actuator. One of the gear train and motor sets is marked on the diagram to indicate that this actuator provides the ability to remove the second gear train and motor to allow for use in a single damper application. Shown also on the diagram is provisional support for IoT.

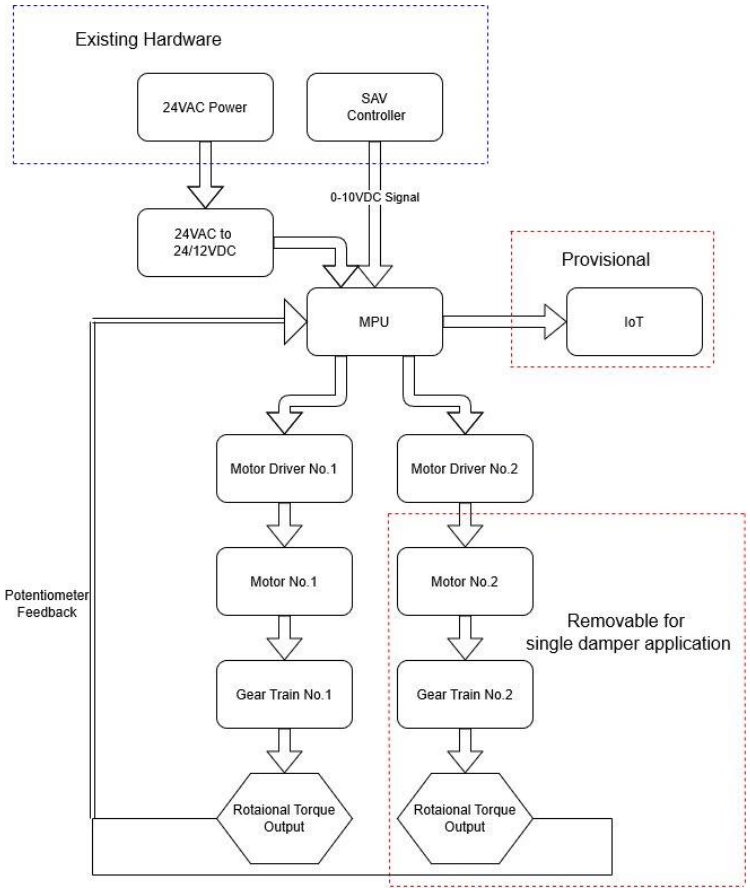


Figure 2: Finalized Co-Axial Actuator design diagram

Black Box Diagram

Figure 3 shows the basic concept of how the terminal unit works through the use of a black box diagram.

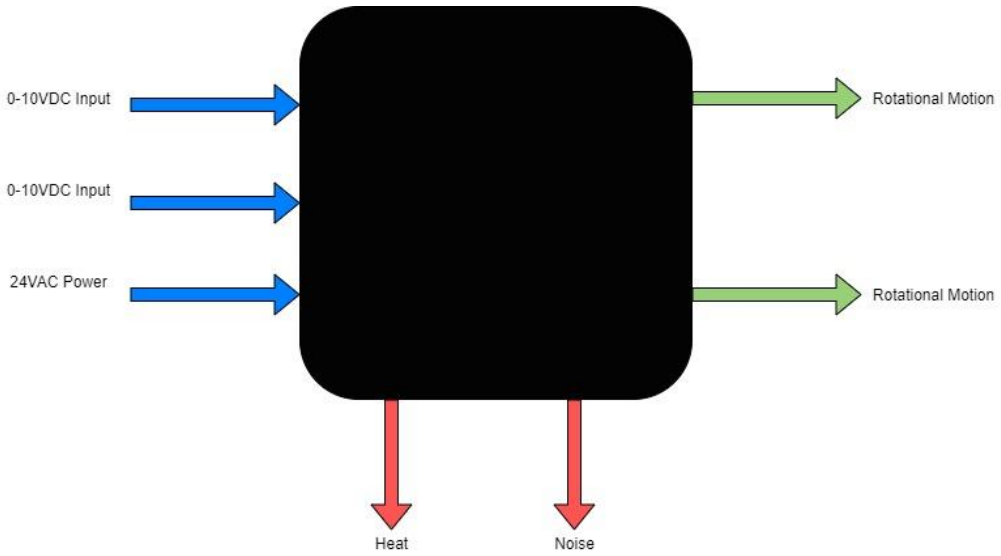


Figure 3: Black Box Diagram of the Coaxial Actuator

The black box diagram shown the two 0-10VDC control signals for the damper blades, re[resenting the desired position of the blades and the 24VAC as the power for the unit and the rotational motion to enable execution of the command. The diagram shows the rotational motion to reach the desired position as the output; as well as byproducts of the operation causing loss of energy such as noise and heat.

Final design calculation results

Gear Ratio and Torque Calculations

The following formula was used to determine the torque that each gear is subjected to damper shafts:

$$\frac{T_1}{T_2} = \frac{N_1}{N_2}$$

Eq. 1: Torque Output to Number of Teeth Relation

Where T represents the torque and N represents the number of teeth of that gear. The subscript represents the gear being referred to. The following table includes the torque values, gear ratio, and the final gear ratio between the input and output gear of the gear train.

Table 5: Torque and gear ratio calculations table without mechanical losses

	Compounded Gear 1	Compounded Gear 2	Compounded Gear 3	Compounded Gear 4	Final Gear Ratio
Teeth of smaller gear	10	15	17	N/A	1:180
Teeth of larger gear	N/A	40	75	153	
Gear Ratio	1:1	1:4	1:5	1:9	
Torque (in*lb)	1	4	20	180	

Backlash calculations

The results of the backlash calculations are shown in table 6. This is the backlash of the final gear train design with gear one being the gear connecting to the stepper motor, gear four being the gear on the damper shaft, and gears two and three being the gears in between. The normal backlash is equal to 0.002 in., the circumferential backlash is 0.0021 in., and all gears yielded a radial backlash of .0029 in.. These types of backlash are shown to be the same here because the pressure angle, and helical angle, are held constant throughout the gear train at 20° and 0° respectively. However, the angular backlash varies due to the introduction of reference diameter into the equation.

Table 6: Backlash of Final Gear Train Design

Gears	Normal backlash (in)	Radial backlash (in)	Circumferential backlash (in)	Angular backlash
1	0.002	0.0029	0.0021	0.024°
2	0.002	0.0029	0.0021	0.006°
3	0.002	0.0029	0.0021	0.003°
4	0.002	0.0029	0.0021	0.0015°

Selection Reasoning

NEMA17 Stepper Motor

The main requirements needed for the stepper motor was that it had the ability to output enough torque that a viable and relatively small gear train can be created to turn the damper shafts. The NEMA 17 stepper motor part number 17HS08-1004S by Stepperonline outputs approximately 1 inch lb. of pull-out torque at 125RPM and is only 40x40x20 (LWH) mm in size. For the amount of torque created, this stepper motor is very small in size and the gear train with a ratio of 1:180 can easily turn the shafts. This torque is created at a current of 1A which is below the maximum output from our motor driver. Specifications for this motor is included in the Appendix IV.

ADS1115 External Analog to digital Converter

The team originally planned to use the on-board ADC of the ESP32, after the initial ADC testing discussed in Appendix V, the team discovered it was not accurate enough to work for this application. The ADS1115 from Texas instruments was chosen as the external ADC for the PCB because of its ability to read up to four analog inputs between 0 and 5V with up to 16-bit precision. This is significantly more accurate than the 12-bits of precision that the on-board ESP32 ADC had. The ADS1115 also has a linear response to analog inputs making the programming significantly easier, as well as the ability to communicate with the ESP32 via serial communications allowing for less PCB circuitry.

ESP32-WROOM-32D Microprocessor

The ESP32 was selected as the microprocessor for the printed circuit board due to the following reasons:

- Multi-programming language support
- 34 I/O Ports
- On-Board analog to digital converter
- Low power consumption
- IoT capable

The ESP32 supports the use of Arduino IDE, which allows the team to use already commonly found stepper motor driver libraries in the programming of the microprocessor and is a much more powerful board then the Arduino Uno. The ESP32 also complies with the appropriate IEEE standards required as shown in Appendix II.

Table 7: Comparison of ESP32-WROOM-32D and ATmega328 Arduino Uno MPU

Specification	ESP32-WROOM-32D	ATmega328
Processor speed	240Mhz	16Mhz
On-board IoT Antenna	Yes	No
Number of On-board ADC ports	16	6
Number of I/O Ports	34	14
Multi-Programming langue capability	Yes	No

Table 7: Comparison of ESP32-WROOM-32D and ATmega328 Arduino Uno MPU Continued

Minimum Recommended power supply current	500mA	500mA
Operating Voltage	3.3V	5.0V
Cost	$3.80	$2.08

When comparing the ESP32 to the ATmega328, as shown in the above Table 7, it is clear that the ESP32 is much more powerful and has more capability. The ESP32 is slightly more expensive but will reduce overall cost by not needing as many external components due to its capabilities.

DRV8825 Stepper Motor Driver

For stepper motor drivers, the team was looking for a driver capable running on a wide range of input voltages and a minimum of one-amp output current; The DRV8825 from Texas instruments fits the bill.

Table 8: DRV8825 from Texas Instruments basic specifications

Specification	DRV8825
Input Voltage	8.2-45V
Maximum Output Current	Up to 2.5A at 24V
Micro-stepping Capable	Yes

With the DRV8825, the team has the ability to adjust the current sent to the stepper with the use of a simple external potentiometer and a small amount of additional circuitry. This satisfies the required specification set at the beginning of the semester, which states to set the current with a potentiometer and replace the potentiometer with a resistor.

Bourns 6639 Potentiometer

The Bourns 6639 precision potentiometer was chosen because the manufacturer shows it has a virtually infinite resolution, as shown in manufacturer specification sheet in Appendix IV. This infinite resolution is used in sensing the incremental angular differences between damper shafts. The potentiometer sends very minute millivolt signals to the microprocessor as feedback. This feedback is interpreted, and an angle correction is made. This level of precision is essential in fulfilling the requirement given by the sponsor, which was to have a 0.1 degree of accuracy in the angle of the damper blade. This particular potentiometer was small enough and had a shaft that could be mounted through a plate, which would be considered when designing the potentiometer mount.

Potentiometer Mount

The potentiometer mount was a crucial design aspect as it had a significant impact on the design of the actuator housing. The purpose of the potentiometer was to measure the angle between the outer and inner damper within the terminal unit. This was difficult to conceptualize at first, but the team progressed the concept of designing a wing to link the shafts together. This seemed to be the least invasive, and easiest to build given the complexity. The team went about this design by first obtaining an adapter to connect the small damper shaft to the shaft of the potentiometer. This was done by ordering

two different sized shaft clamps and welding them together in order to connect to the different sized clamps. The wing was designed so that one side connects to the larger shaft that rotates the outer damper while the other side is attach to the body of the potentiometer. Connecting it this way will allow for damper movement, while the potentiometer is held firmly in place. This is important because it allows the team to accurately measure the distance between the two shafts based on a voltage reading through the potentiometer.

Gear Train Material

The team decided that the best decision for prototyping was to switch from 3-D printing with PLA to use acrylic by using the laser cutter at the university. This decision was made due to a few 3-D printed parts breaking or wearing prematurely throughout the testing process. It was decided that the prototype should be constructed out of something more durable and more consistent than the PLA. Though the acrylic was great for prototyping, it will only be used during the prototyping phase as it does not have the capability to withstand the forces within the system over time.

When the design progresses to the production phase the material will be manufactured using the injection molding process. The material selection for this injection process was a difficult task, as numerous simulations were done in SolidWorks to obtain a finite element analysis for several materials. The simulation models of the top two materials have been included in Appendix VI. Of these two materials, the team has chosen to use the material Nylon 6,10. The simulations in the above-mentioned appendix shows three different categories of study which are the Von Mises Stress, the Bending Stress Deformation, and the Factor of Safety analysis. When evaluating the figures for the Von Mises Stress and Bending Stress Deformation, the simulations look almost identical, only varying slightly on the contact for the last set of gears. This tells use both materials would be acceptable according to the simulations. The material selection came down to the safety factor simulation. It is understood when looking at the simulations for the factor of safety that a factor of 2.0 or higher is deemed to be 100% safe by mechanical guidelines. According to the figures, the factor of safety for Nylon 6,10 is 2.97 whereas the factor of safety for ABS Polycarbonate is 1.72. Though ABS Polycarbonate is significantly cheaper than Nylon 6,10, the factor of safety drives the decision to choose Nylon 6,10 as the material to build the gear with. The team can say with confidence that the Nylon 6,10 will withstand the test of time.

Housing Material

The damper unit is typically installed above the ceiling in many business-oriented buildings, so noise from the actuator is concern. To help with the noise generated by the gear train actuator assembly, a simple enclosure was designed to surround the actuator assembly that would fasten directly to the unit's sheet metal enclosure, as shown in Appendix III. The actuator enclosure will be composed of a polycarbonate material due to its rigidity and material properties that help with sound deadening. Unlike the gears, the thermoforming manufacturing method that would be used to create the enclosure. Due to size of the size of the enclosure required the injection molding would not be an ideal method. Thermoforming is found to be both durable, cost effective and will help minimize space within the sheet metal enclosure. The polycarbonate material will also be used for the plates that will sandwich the gear train to hold them in place, in conjunction with a series of aluminum standoffs and steel keyed shafts.

List of risks involved & Failure Mode Analysis

There are several failure modes that could occur during the operation of the actuator. Some of these failures will not cause major issue while other will cause severe damage to the actuator assembly and others have very little probability of occurring. The following table is a list of actuator failure modes with their corresponding risk preference number.

Table 9: Failure Mode Analysis with Risk Preference Number

Failure Mode		Severity	Probability of Occurrence	Probability of Detection	Risk Preference Number
Gears	Wear	5	4	5	100
	Scoring	2	2	8	32
	Pitting	9	2	9	162
	Tooth Fracture	10	1	10	100
	Bending Fatigue	8	4	4	128
	Incorrect Material usage	10	2	6	120
Circuit Board	Power Loss	10	2	10	200
	Failure to Read Input	5	3	4	60
	Incorrect Programing	7	2	6	84
	Wiring Disconnecting	7	1	8	56
	Motor Failure	10	1	10	100
	Driver Failure	10	1	10	100
	Low Voltage	10	2	10	200

Based on Table 9 shown above, it is apparent that the most important things to consider are a power loss to the circuit board, low voltage and the pitting within the gear train. A full power loss, without taking this into consideration and paying close attention when designing the board, could not only cause the system to malfunction but also cause overall hardware damage to the system rendering it useless. Overlooking a low voltage occurrence when designing the board can cause components to burn out as well. Pitting is one of the most important things to account for within the mechanical system since this directly effects the life expectancy of the system. Pitting is caused by the continuous meshing of the gears which causes them to wear down faster. This is directly affecting the bending fatigue as over time there will be less material to support the constant stresses introduced by the operation of the system which makes choosing the correct material that much more important.

Simulation Results

The team designed a simulation of the gearing to determine how the gear train would handle the stress and torque, as shown in Appendix VI. Originally the simulation was of PLA gears that were 3D printed. After running the simulation on PLA, the results studied among the team members and university faculty and It was determined that a 3-D printed gear train will not be consistent with every

print and may have flaws that will create issues further down the line. The team ultimately chose to use the 3-D printed design to show proof of concept and to test the basic functionality of the system.

The team also simulated Nylon 6,10 and ABS Polycarbonate to determine if the gear train would hold up over time. The simulations done were to determine the yield strength, bending stress and factor of safety of the materials. After many simulations using SolidWorks, the results, which are shown in Appendix VI, indicate that Nylon 6,10 could withstand a higher level of stress with the flexibility of bending as well as having a higher factor of safety over its competitor ABS Polycarbonate. Nylon 6,10 was chosen as the final material for the gear train.

Table 10: FEA Material Simulation results

	Nylon 6, 10	ABS Polycarbonate
Max Stress (MPa)	46.8	36.0
Max Bending Deformation (in)	.002	.008
Factor of Safety	2.97	1.72

The team also simulated an overview on how the potentiometer and the wing should be mounted to the actuator. This simulation also displayed an understanding on how the potentiometer is attached to the wing and the course of action that the wing take place. The simulation was done through inventor its purpose was to help with the design of the potentiometer and wing. All of the above-mentioned simulations can be observed in Appendix VI.

Final testing Results

Testing done by Team 7

Final testing of the prototype was done in three phases: required, optional/changing, and detailed. A list of laboratory bench equipment used during this experiment is represented in Table 22 in Appendix V. During testing, the operations and safety manual also found in Appendix V was followed for initial setup, safety precautions, and operations. All of the required and optional/changing specification tests performed are listed in detail in Appendix VII under the Detailed Testing Plans and Expected Outcomes section in Tables 28 and 29. These methods will be discussed in brief with the corresponding results in this section. Due to the guidelines discussed in Table 2 in the Requirements and Specifications section, there are eleven specifications that must be met. Table 11 contains the testing results from Phase one of testing, required specifications.

Table 11: Required Specifications Testing Results

Test description	**Corresponding Specification Number**	**Result**
Actuator Torque Test for Round Damper	1	By connecting our actuator assembly to the largest round HVAC terminal unit, when powered, our actuator was able to open and close the damper blade and fully compress the gasket.

Table 11: Required Specifications Testing Results Continued

Test description	Corresponding Specification Number	Result
Actuator Torque Test for Rectangular Damper	2	Due to not having the physical rectangular HVAC terminal unit, an analog torque wrench was used to measure the raw torque output of our actuator. The specific torque wrench used had a maximum reading of 80 in*lbs, our actuator exceeded the maximum reading of the torque wrench, therefore satisfying the need for 44 in*lbs of torque.
Maximum Torque Output	3	To observe the maximum torque output of the actuator, an analog torque wrench was used to measure the maximum torque output. The specific torque wrench used had a maximum reading of 80 in*lbs, our actuator exceeded the maximum reading of the torque wrench, therefore satisfying the need for 55 in*lbs of torque.
Basic power on and functionality test	4	Using a simple power converter (AC to DC), our PCB was able to fully function on 24V DC.
Verification of measurements and diameters of the inner damper shaft and corresponding gear	5	Physical measurements were taken with digital calipers to ensure the diameter of the inner damper shaft diameter was 0.315 inches. Our results confirm that the inner damper shaft is 0.315 inches in diameter.
Verification of measurements and diameters of the outer damper shaft and corresponding gear	6	Physical measurements were taken with digital calipers to ensure the diameter of the outer damper shaft diameter was 0.5 inches. Our results confirm that the outer damper shaft is 0.5 inches in diameter.
Verification of actuator fitment and enclosure measurements	7	By measuring the control box mounted to the side of the HVAC terminal unit to 19.0x9.0x6.6 inches (LWH), it was ensured that our actuator and PCB would fit well within the size constraints given by the control box.
Motor testing	8	By testing each motor with an analog torque wrench and verifying part numbers it can be confirmed that both motors have identical outputs. By verifying identical part numbers and matching torque output values of 1.0 in*lbs, it can be concluded that the two motors are identical.
Current limiting resistor verification and current testing	9	The chosen motor drivers come equipped with an on-board potentiometer for current regulation to each motor. This can be adjusted as the final current is set to ensure optimum operating conditions for the motors.
Reset button functionality testing	10	By utilizing a factory reset button on our microprocessor, both dampers will return to the home position when pressed. This functionality has been verified during testing.
Feedback and Real Time tracking tests	11	For the single damper actuator, real time angle data will be tracked by the potentiometer and incorporated as conditional feedback for auto-step correction. This item will be discussed at length later in the Results section.

During Phase two of testing, the items from Table 3 'Optional Specifications and Specifications that will change over time' were tested. Table 12 contains the results with a brief discussion of each of the specifications.

Table 12: Optional and Changing Specification Results

Test Description	Corresponding Specification Number	Results
IoT reporting to the cloud	12	The IoT connectivity was left as a provision for this project. The choice of the ESP32 microprocessor with wireless connectivity will allow for seamless implementation in a future generation of this prototype.
Adaptability for use in a single damper application	13	Our current co-axial actuator prototype has the ability to be easily adapted for single damper applications with the removal of nine screws.
Amount of torque created by the motor	14	The final value of the motor torque (before gear train adaption) has been measured with a digital torque wrench as 1.02 in*lbs.
Motor step testing	15	Motor step testing was conducted to ensure 0.9-degree step size. By using step intervals of 50 steps (45 degrees), it was confirmed by a protractor that our motor did move 45 degrees per every 50 steps.
Verification of motor dimensions	16	Using digital calipers, motor size was verified to match the dimensions represented in the CAD model provided by STEPPERONLINE.
Test fitting actuator into enclosure	17	Using measuring tools, CAD dimensions were verified to ensure proper fitment in control enclosure. Permanent mounting commenced upon measurement verification.
Damper speed testing	18	To verify damper speed, a stopwatch was used to monitor the amount of time for the damper blade (both move at the same speed) from the home position to 90 degrees. This operation took approximately 25 seconds.
Gear ratio verification	19	The exact ratio of the gears was estimated by creating a test program to rotate the input gear 180 times. This allowed for one-degree movements at the output gear, which was confirmed with a digital protractor.
Gear train reliability and wear testing	20	Gear train reliability and wear testing was performed by running the gear train, connected to the HVAC terminal unit, for 45 consecutive minutes. Upon inspection of the gears, there was no visible damage or wearing.
IoT Cloud tracking intervals	21	IoT integration was left as a provision for this version of the prototype.
0-10VDC input testing	22	By applying all 100 different input voltages between 0V and 10V functionality is able to be observed. This test was verified by observing each distinct position of the damper blade corresponding to each individual voltage value.

Phase 3 of testing, detailed testing, produced the most interesting results. Due to time constraints placed on the team due to the global pandemic (COVID-19), the detailed testing period was shortened to 4 days. This process, as listed in the Team's Gantt chart, was expected to take place over the course of 4 weeks. Due to this, the number of tests and completeness of testing methods have been reduced significantly. This testing phase included three separate tests. Each test was conducted on the 12in round dual blade terminal unit by HVAC Manufacturing. The first test, Test 1, consisted of using the dual blade unit as a single blade (inner blade) unit for verification of programming and accuracy. This test was a 90 incremental step test, incrementing the input voltage by 0.1V from 0V to 9V and taking angular readings at every step. Though the actuator is capable of making movements of 0.5 degrees corresponding to changes of 50mV from the input signal, due to time constraints, no testing data was reported on this feature. There was no potentiometer feedback during this test, but there was a potentiometer connected and experimental data was recorded for each step. For this test the potentiometer was used with the wiper attached to the inner damper shaft, and the body held as a reference mounted via a wing to the control box. The testing data for Test 1, in its entirety, is listed as Table 25 in Appendix V. Table 13 is a snippet of the table.

Table 13: Experimental Results for Test 1 (Snippet)

Input Voltage (V)	Theoretical Angle (deg)	Measured Angle (deg)	Difference (deg)
2.0	20	18.90	-1.10
2.1	21	19.90	-1.10
2.2	22	20.90	-1.10
2.3	23	21.90	-1.10
2.4	24	22.90	-1.10
2.5	25	23.90	-1.10
2.6	26	24.90	-1.10
2.7	27	25.90	-1.10
2.8	28	26.80	-1.20
2.9	29	27.80	-1.20

The data from this test showed several very positive trends. The actuator proved to output angles that correlated strongly with the theoretical angles. It also exhibited consistent step sizes of close to 1 degree with an average of 0.99 degrees per step as the input signal varied by 0.1V. This can be visualized with by the graphs represented in figures 4 and 5. During this process, the potentiometer voltage reading was recorded at each of the 90 steps. This data was averaged, and it was found that each 0.1V step corresponds to a 0.01442 V voltage change from our potentiometer. In the larger scope, over the 90 steps, the average error between the measured and theoretical values was 1.44 degrees. There are many reasons for this error. One possible source of error is the initial rotational flex of the shaft of the damper. With this rotational flex unaccounted for by our program, it is fair to assume that it has contributed to the error in our measured angular values. Another possible source of error could be the digital protractor. The digital protractor used in this experiment has a tolerance of +-0.15 degrees, this is another possible contributor to the error received in the experimental measurements. One more source that could introduce error is the physical limitation of the digital protractor. The digital protractor could not properly fit on the surface of the damper blade from the approximate range of 77 – 90

degrees to get a consistent measurement. This improper fitment over the last approximate 13 degrees is believed to be a significant cause of error over this region. Though there are many possible sources of error in this experiment, one statistical measurement tends to filter out most of the error and produce a more accurate representation to the accuracy of our system. The standard deviation, which can be viewed as a representation of the average distance away from the mean, revealed that our actuator performed better than initially believed to. With a standard deviation of 0.16 degrees, it can be interpreted that our actuator, on average, will create steps that are within 0.16 degrees of the 0.99-degrees average calculated during this test.

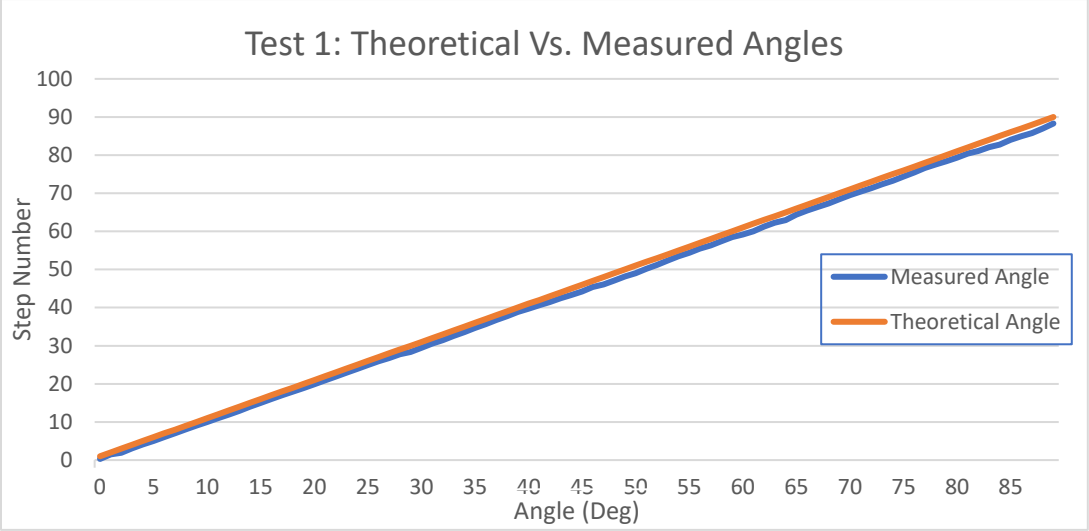


Figure 4: Test 1 angle comparison graph.

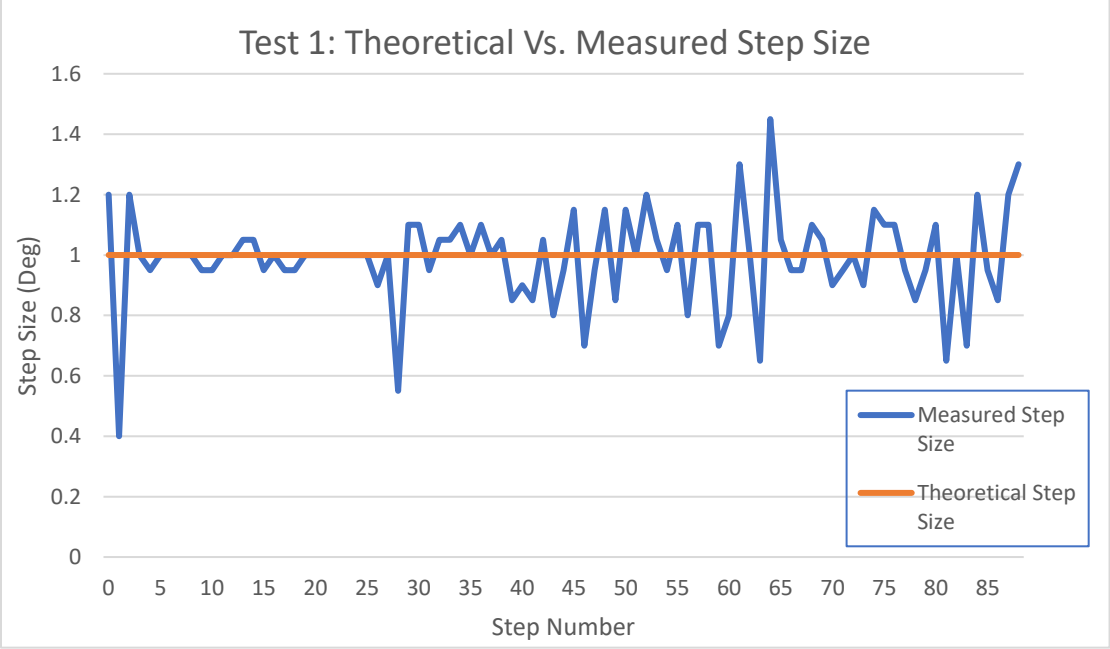


Figure 5: Test 1 step size comparison graph.

The second detailed test consisted of the same experimental setup as the first detailed test, with the addition of potentiometer feedback in the program. Again, the outer damper was held at the home position throughout this test, and the inner damper was sent through the 90 incremental step test. With our newly found potentiometer angular voltage change of 0.01442V corresponding to 1 degree, we were able to successfully implement the conditional feedback to the PCB via an additional function to the program; See the Feedback Function for Single Damper Terminal Unit in Appendix VIII.

Table 14 is a snippet of the experimental data gathered during the 90 incremental step test with potentiometer feedback. The entirety of the experimental data for Test 2 is listed in Table 26 in Appendix V.

Table 14: Experimental Results for Test 2 (Snippet)

Input Voltage (V)	Theoretical Angle (deg)	Measured Adjusted Angle (deg)	Adjusted Angle Difference (deg)	Improvement with Pot. Feedback (deg)
4.2	42	42.40	0.40	1.00
4.3	43	43.35	0.35	1.20
4.4	44	44.35	0.35	1.15
4.5	45	45.55	0.55	1.15
4.6	46	46.50	0.50	1.25
4.7	47	47.60	0.60	1.00
4.8	48	48.75	0.75	1.15
4.9	49	49.85	0.85	1.10
5.0	50	50.95	0.95	0.85
5.1	51	51.95	0.95	1.00

The data from this test showed a properly functioning feedback system with a substantial improvement in accuracy over the experimental data gathered from Test 1 with no feedback. Over the 90 steps, on average, the feedback system produced an angle that was only 0.49 degrees away from the targeted angle. This is 0.95 degrees more accurate, on average, than the actuator operating with no feedback. The entirety of the data (measured versus theoretical angles) is visualized below in Figure 6. While being more accurate overall with the introduction of feedback, our average step size changed slightly to 1.01 degrees. The introduction of feedback also improved the standard deviation of the measured step size to 0.14 degrees. A visual representation of the measured step size is shown below as Figure 7. This test did introduce new possible sources of error. With the same possible sources of error as discussed with Test 1, the possibility of flexing of the potentiometer wing has been introduced. The ever so slight flexing of the potentiometer wing, even if the angular flex is less than 0.2 degrees, it will have a large impact on the feedback loop within the program causing a much larger error. Also, after the 90-step test concluded, while the small damper blade was returning to the home position, there were several instances of gear slippage. The source of this was thought to be mechanical friction. The solution proposed and enacted by the Team was the application of a powered graphite lubricant to the gear train. During subsequent testing, this appeared to fully resolve the issue.

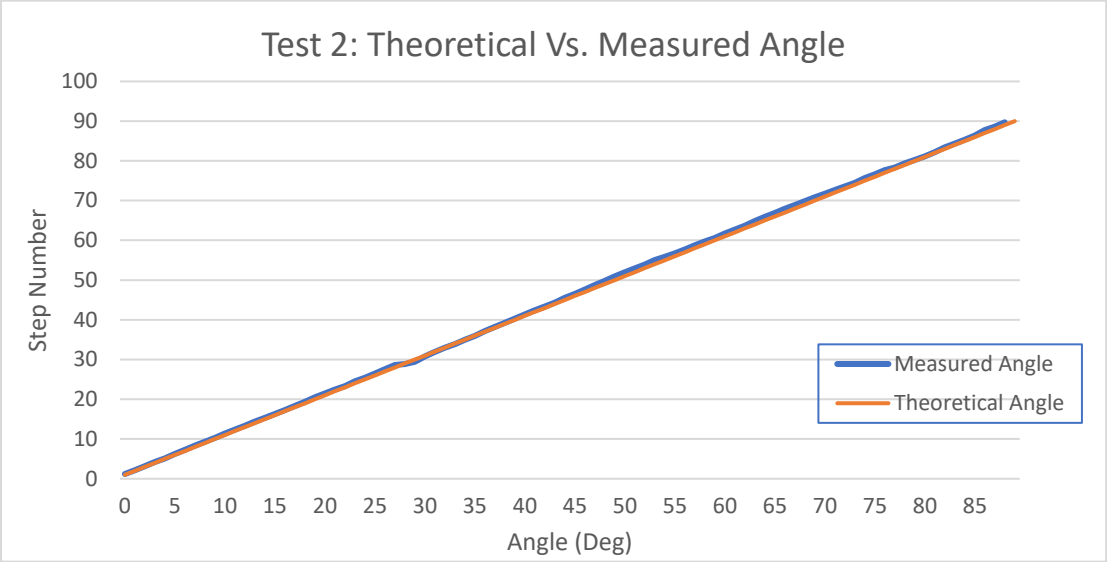


Figure 6: Test 2 angular comparison graph.

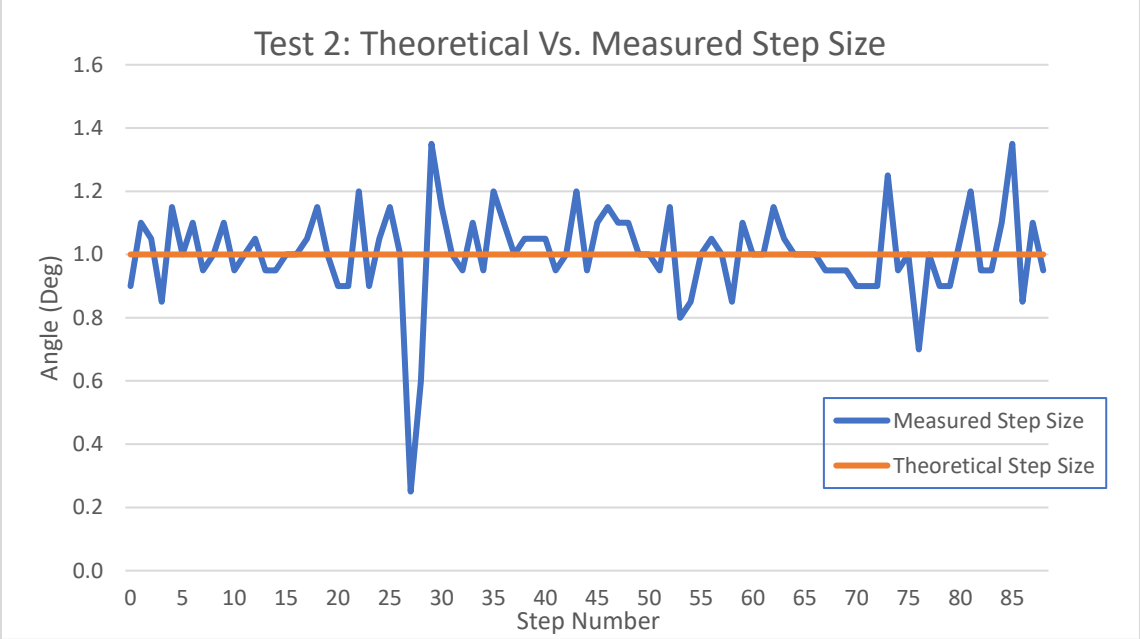


Figure 7: Test 2 step size comparison graph.

This led to the final test performed on the actuator. The final test, Test 3, is a co-axial effort. The setup for this experiment is identical to Test 1 with the removal of the potentiometer. For this test, a 0V – 9V signal is applied to both the large and small damper blade, individually, in increments of 0.1V. Experimental readings are taken for both the large and small damper blade at each of the 90 different voltage levels. This is a modified version of the 90 incremental step test to accommodate both damper blades. There is no feedback incorporated in this version of the program. Table 15is a snippet of the

experimental data gathered during this experiment. The entirety of the experimental data for Test 3 is listed in Table 27 in Appendix V.

Table 15: Experimental Results for Test 3 (Snippet)

Input Voltage (V)	Theoretical Angle (deg)	Inner Measured Angle (deg)	Difference from Theoretical (Inner) (deg)	Outer Measured Angle (deg)	Difference from Theoretical (outer) (deg)
1.5	15	15.30	0.30	13.20	-1.80
1.6	16	16.30	0.30	14.15	-1.85
1.7	17	17.20	0.20	15.15	-1.85
1.8	18	18.20	0.20	16.20	-1.80
1.9	19	19.25	0.25	17.20	-1.80
2.0	20	20.25	0.25	18.20	-1.80
2.1	21	21.25	0.25	19.25	-1.75
2.2	22	22.25	0.25	20.30	-1.70
2.3	23	23.20	0.20	21.30	-1.70
2.4	24	24.25	0.25	22.40	-1.60
2.5	25	25.25	0.25	23.35	-1.65
2.6	26	26.25	0.25	24.40	-1.60

The data from this test had some very interesting characteristics, which are represented visually in Figures 8 and 9. The inner damper exhibited a standard deviation of 0.14 degrees, which is on par with the other two tests. The inner damper also showed incredible accuracy with an average difference from the theoretical angle of 0.18 degrees and an average step size of 1.00 degrees. This is an average improvement of 0.31 degrees over Test 2, which was conducted with feedback from the potentiometer. This improved accuracy can be narrowed down to one specific factor. The only logical factor that could possibly contribute to the overall improved accuracy is the logic used in the program. Though in theory, the potentiometer feedback will be able to adjust for all error, it does severely increase the complexity of the logic in the program. With the code used in Test 2, a much simpler logic was used to create a very linear, predictable output. While with proper time and adjustments, the code that includes the feedback could be refined to be more accurate that the code used in Test 3, it does highlight the accuracy and repeatability of the system at hand. The data recorded from the large damper blade revealed an interesting nuance in the system. It was noted, during testing, that the range between 0 and 15 degrees is heavily affected by the large gasket surrounding the large damper blade. This gasket led to, what appeared to be, non-linear movement during this affected range spanning 15 degrees. The behavior of this gasket accounted for large amounts of error in our angular measurements during that range. The actuator preformed as expected once leaving the range affected by the gasket, giving repeated steps of 1.01 degrees. Including the range of degrees affected by the gasket, our data revealed that the large damper blade is an average of 1.62 degrees away from the targeted angle. Excluding the range affected by the gasket, the large damper blade is an average of 1.24 degrees away from the targeted angle. This 'affected' range caused an average error of 0.38 degrees, which is rather large, yet not very significant. The most significant aspect of the difference is represented in the standard deviation calculations. The

standard deviation of the large damper, including the 'gasket' range, 0 – 90 degrees, is 0.34 degrees, which is more than double the standard deviation of the previous tests. But, considering only the range of movement that does not include the 'gasket', 15 – 90 degrees, the standard deviation is 0.07 degrees. This is by far the best standard deviation value achieved from our testing, and an improvement of by a factor of 4.86 from the standard deviation which included the 'gasket' range. The small standard deviation value, in comparison to the rest of the tests, is believed to be attributed to the ease and repeatability of making the physical angular measurement on the large damper versus the small damper. Being that this was the only test performed on the large damper, this is unable to be verified as a probable source of error.

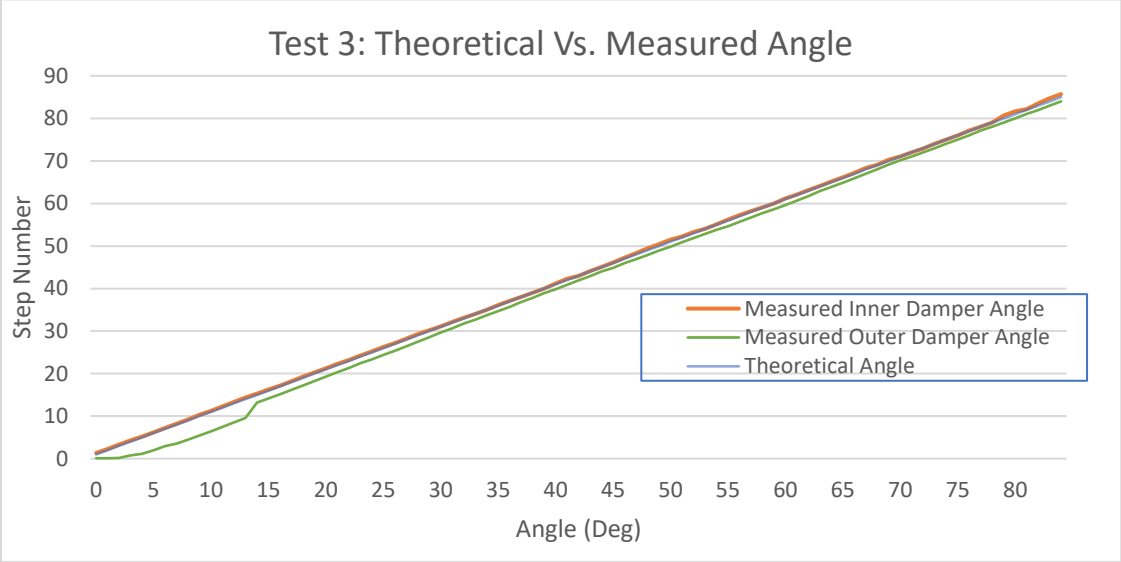


Figure 8: Test 3 angular comparison graph

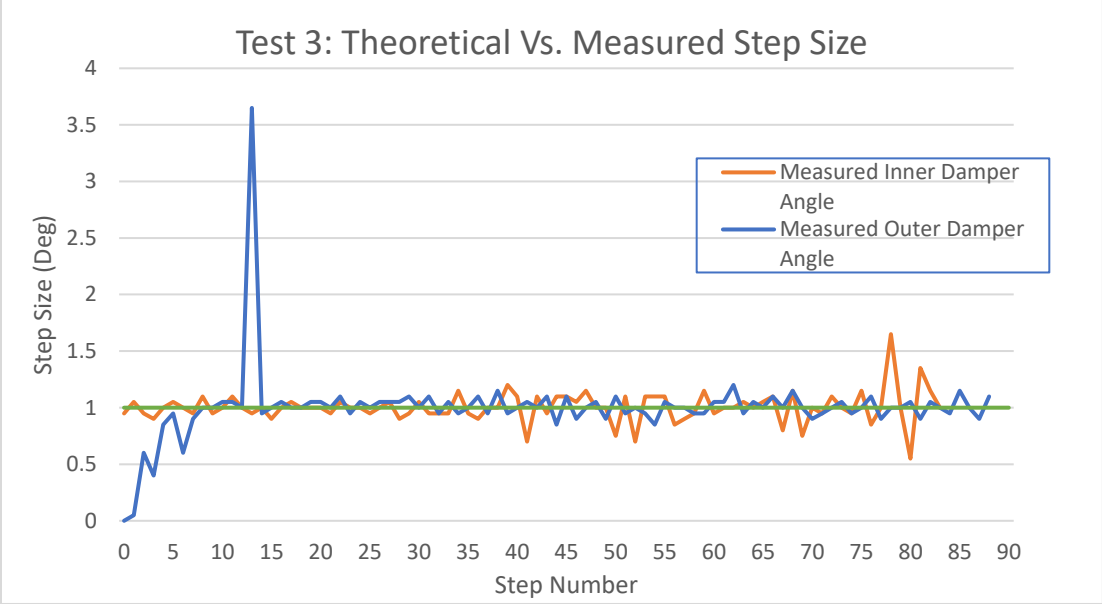


Figure 9: Test 3 step size comparison graph

Testing done by HVAC Manufacturing

HVAC Manufacturing conducted tests on the actuator during the week of 4/20/2020. Two tests were performed. Each of these tests took place on their Flow stand, which is an apparatus that simulates controlled airflow through an air duct. The first test had two iterations and consisted of inputting an analog signal beginning at 0vdc and increasing by 0.1vdc to 9vdc. Each 0.1vdc increase corresponds to a 1 degree increase in damper angle; This linear relationship holds true for the entirety of the 0 – 9vdc range. Testing data was recorded during this period. This testing data is listed in Table 35 in Appendix V. A graph showing this data is represented by Figure 10.

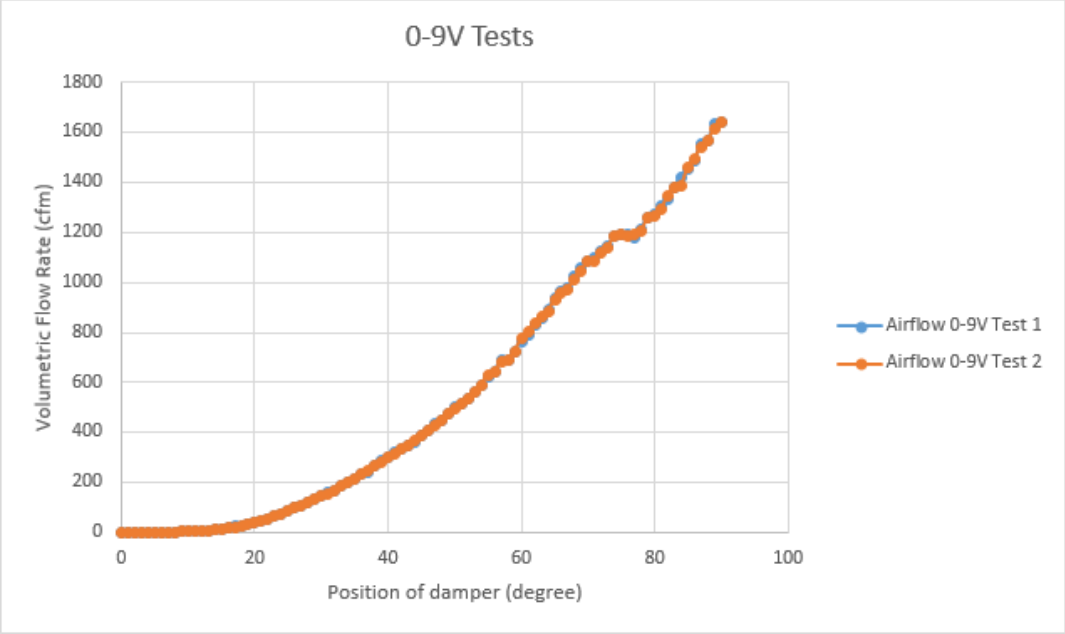


Figure 10: Comparison of the iterations of Test 1.

The second test performed by HVAC Manufacturing consisted of an identical testing set up as Test 1, except the input signal voltage began at 0vdc and increased by 0.1vdc to 9vdc, then was returned back down to 0vdc in the same manner. Each 0.1vdc increase corresponds to a 1 degree increase in damper angle; Each 0.1vdc decrease corresponds to a 1 degree decrease in damper angle. This linear relationship holds true for the entirety of the 0 – 9vdc range. Testing data was recorded during this period. This testing data is listed in Table 34 in Appendix V. A graph of this data is represented by Figure 11.

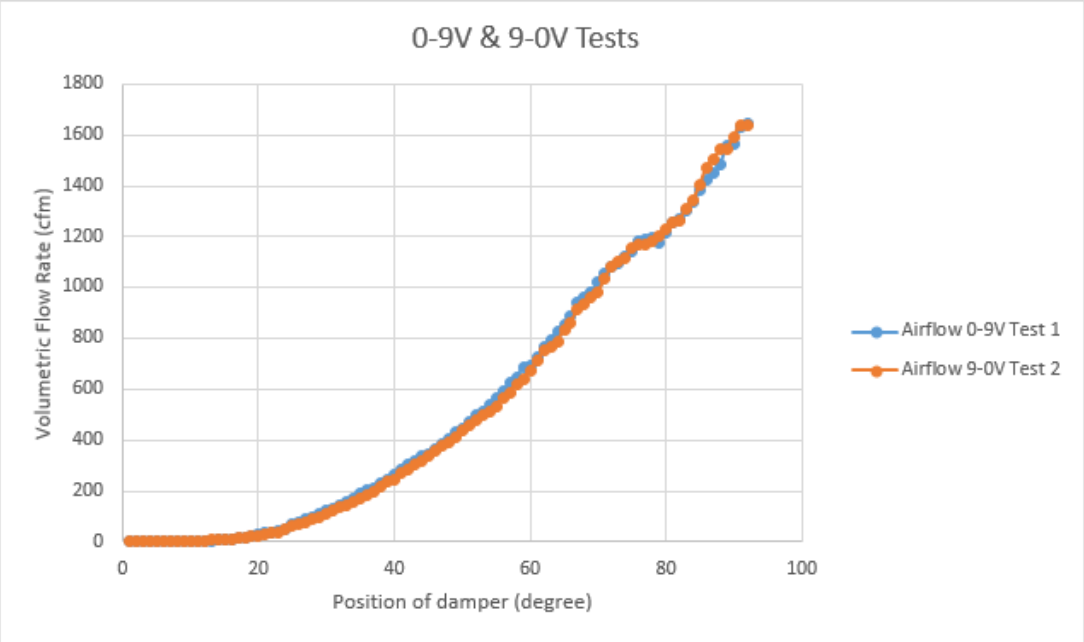


Figure 11. Comparison of Test 2 voltage increase and decrease.

BOM and detailed Budget

Table 16, shown below, shows the budget that includes the total amount of money spent over the course of the last two semesters. Table 17 and Table 18, shown below, are the bill of materials for the laser cut prototype and the bill of materials for injection molding, respectively.

Table 16: Budget of the money spent both by the team and by HVAC Mfg.

Description	Qty	Price per unit	Total Price	P/N	Manufacturer
1/4" Acrylic Sheet	2	25	50		Grainger
3/8" Keyed Shaft	2	13.11	26.22	3/8 GKS-1045-6	Various
Voltage Regulator	2	2	4	LM7805CT	Texas Instruments
ESP32 Microprocessor Dev Board	2	10	20	ESP32-DevKitC-S1	Espressif Systems
ESP32 Microprocessor Dev Board	1	11.8	11.8	ESP32-DEVkitC-V4	Espressif Systems
DRV88258 Stepper Driver Dev Board	2	8.95	17.9	Pololu item #: 2133	Pololu
Precision Potentiometer	1	20.38	20.38	6639s-301-103	Bourns
1/4 inch clamp	1	8.7	8.7	H2C-025-S	Climax Metals
3/8 inch clamp	1	12.05	12.05	H2C-037-S	Climax Metals
Stepper Motors	2	8.11	16.22	17HS08-1004S	StepperOnline
		Total Spent:	187.27		

Table 17: Prototype Bill of Materials break down

Description	Part Number	Qty	Price per unit ($)	Lead Time (days)	Company
Keyed Shafts	30F554	2	13.11	10	Grainger
Acrylic Sheet	1AG2123A	1	29.98	1	Lowe's
Standoffs	92377A211	2	9.01	7	McMaster Carr
Bolts	67675	2	4.24	1	Harbor Freight
Stepper Motor	17HS08-1004S	2	8.11	5	Stepper Online
ESP32 Microprocessor	ESP32 – DevkitC-V4	1	10.00	7	Espressif
DRV8825 Dev Board	2133	2	8.95	7	Pololu
ADS1115 Dev Board	1085	1	14.95	7	Adafruit
5.1k Resistor	MBB02070C5101FCT00	4	0.29	7	Vishay BC Components
5vdc Voltage Regulator	LM7805CT/NOPB	1	1.54	7	Texas Instruments
100uF capacitor	EEU-FR1H101B	3	0.50	7	Panasonic
.1uF capacitor	C315C104M5U5TA7303	1	0.24	7	KEMET
.22uF capacitor	C410C224M5U5TA7200	1	.31	7	KEMET
Screw Terminal – 2 Port	282837-2	3	1.04	7	TE Connectivity
Screw Terminal – 4 Port	282837-4	2	1.58	7	TE Connectivity
Screw Terminal – 3 Port	282837-3	1	1.18	7	TE Connectivity
Potentiometer	6637S-1-102	1	41.09	20	Bourns
¼ inch Shaft Coupling	H2C-025-S	1	8.70	13	Climax Metal
3/8 inch shaft coupling	H2C-037-S	1	12.05	13	Climax Metal
Shaft Adapter	985-004	2	18.18	10	Black Hawk Supply

The Injection molding BOM, shown below, shows a total cost of $351.17 for first unit produced. The reason for listing this as the first unit cost and not the cost per unit is due to the fact that some of the products listed, such as the polycarbonate sheets, would be used in the making of multiple actuators. So, while the sheet would initially cost $253.84, it would be used in making approximately 12 actuators. This alone would bring the cost down to $82.48 per actuator.

Table 18: Injection Molding B.O.M Breakdown

Description	Part Number	Manufacturer	Qty needed per unit	Min Qty	Price per unit ($)	Price per lot ($)
12” 1/4 Unthreaded Spacer	92377A211	McMaster Carr	1	11,667	7.21	84,119.07
Gear 1	N/A	Custompart.net	2	20,000	1.21	24,200.00
Gear 2	N/A	Custompart.net	2	20,000	2.91	58,200.00
Gear 3	N/A	Custompart.net	2	20,000	3.93	78,600.00
Gear 4	N/A	Custompart.net	2	20,000	3.36	67,200.00
Polycarbonate sheets 72”x96”	PUV1WR9M	ACME Plastics	1	138	253.84	35,029.92
Shaft Adapter	985-004	Black Hawk Supply	2	20,000	8.24	164,800.00
Stepper Motor	17HS08-1004S	Stepper Online	2	20,000	6.57	131,400.00
Potentiometer	6639S-301-103	Bourns	1	5,000	10.90	54,500.00
Screw Terminal	282837-2	TE Connectivity	3	1	1.04	1.04
Screw Terminal	282837-4	TE Connectivity	2	1	1.58	1.58
Screw Terminal	282837-3	TE Connectivity	1	1	1.18	1.18
ESP32 Microprocessor	ESP32-WROOM-32D	Espressif Systems	1	650	3.80	2470.00
Stepper motor driver	DRV8825PWPR	Texas Instruments	2	2,000	4.24	8480.00
Voltage Regulator	LM7805MPX/NOPB	Texas Instruments	1	2,000	.53	1060.00
LDO voltage regulator	LM1117MPX-3.3/NOPB	Texas Instruments	1	2,000	.44	880.00
Analog to Digital Converter	ADS1115IDGS	Texas Instruments	1	2,500	2.59	6475.00
.22uF 35V Ceramic Capacitor	CGA2B1X7R1V224K050BC	TDK Corporation	3	10,000	.025	250.00
.1uF 10V Ceramic Capacitor	GRM033R61A104ME15D	Murata Electronics	2	15,000	.002	30.00
1uF 10V Ceramic Capacitor	CL10A105KP8NNNC	Samsung ElectroMechanics	2	4,000	.006	24.00

Table 18: Injection Molding B.O.M Breakdown Continued

22uF 10V Ceramic Capacitor	GRM21BR61A226ME51L	Murata Electronics	1	3,000	.055	165.00
.47uF 50V Ceramic Capacitor	GRM155R61H474KE11D	Murata Electronics	2	10,000	.028	280.00
10nF 16V Ceramic Capacitor	C0402C103K4RECAUTO	KEMET	2	10,000	.023	230.00
.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D	Murata Electronics	9	15,000	.008	120.00
100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS	Nichicon	4	500	.15	75.00
4.7 uF 35V Ceramic Capacitor	GRM219R6YA475KA73D	Murata Electronics	2	4,000	.046	184.00
5.1k 1% Resistor	MBB02070C5101FCT00	Vishay BC Components	4	5,000	.03	150.00
10k 5% Resistor	RC0603JR-0710KL	Yageo	7	5,000	.0022	11.00
1.5k .1% Resistor	ERA-2AEB152X	Panasonic Electronic Components	2	10,000	.043	430.00
100m 5% Resistor	CHV2512-JW-107ELF	Bourns Inc.	4	12,000	.108	1296.00
10k Potentiometer	23BR10KLFTR	TT Electronics/Bl	2	4,000	.068	272.00
SPST .3A 12V Switch	50-0014-00	Judco Manufacturing Inc.	1	1	1.64	1.64
1.5k Ferrite Bead	MMZ2012Y152BT000	TDK Corporation	2	4,000	.024	96.00
	Total Price for First Unit:	$351.17				

Economic feasibility

Mass Production:

For mass production, as mentioned previously, the injection molding method would be used for the gears and plates, while the housing would use the thermoforming method due to its large size. The parts that cannot be thermoformed or injection molded must be outsourced. Those parts will include, but not limited to, the standoffs that help mount the plates together and the shaft adapters that attach the last gear to the damper shaft. A detailed summary of the mass production cost is summarized in the tables, assuming a total of 10000 units will be produced, shown in Appendix IX. A comparison can be made to similar products on the market that are priced around $200. With an overall estimated cost of $82.48, the product seems feasible to bring to the market and be immediately competitive.

Cost of prototype

The prototype cost includes the laser cutting method which was used in manufacturing acrylic plates, gears and housing. The parts that cannot be laser cut must also be outsourced as it would be in mass production. These parts include standoffs that are used in mounting the plates together, the shaft adapters that attach the last gear to the damper shaft, and the Implemented keyways and keyed shafts that form the compound gears. A summary of the cost of prototype is summarized in the table, assuming a total of 10000 units will be produce, in Appendix IX.

To determine the economic feasibility of mass producing the actuator with injection molding or laser cut gears, a cost break down was established. As shown above in the above BOM section, Table 17 shows the break down with laser cut gears and Table 18 shows the breakdown of the injection molding method. It is shown that with the laser cut prototype, the keyed shaft is a major contributing factor to cost so it makes the injection method more economically feasible.

Flow charts of software

The flow chart included below is the basic concept behind the idea of the programming listed in its entirety in Appendix VIII. The program reads the two analog 0-10VDC signals, moves the dampers to the desired position, and makes angle adjustments, as necessary.

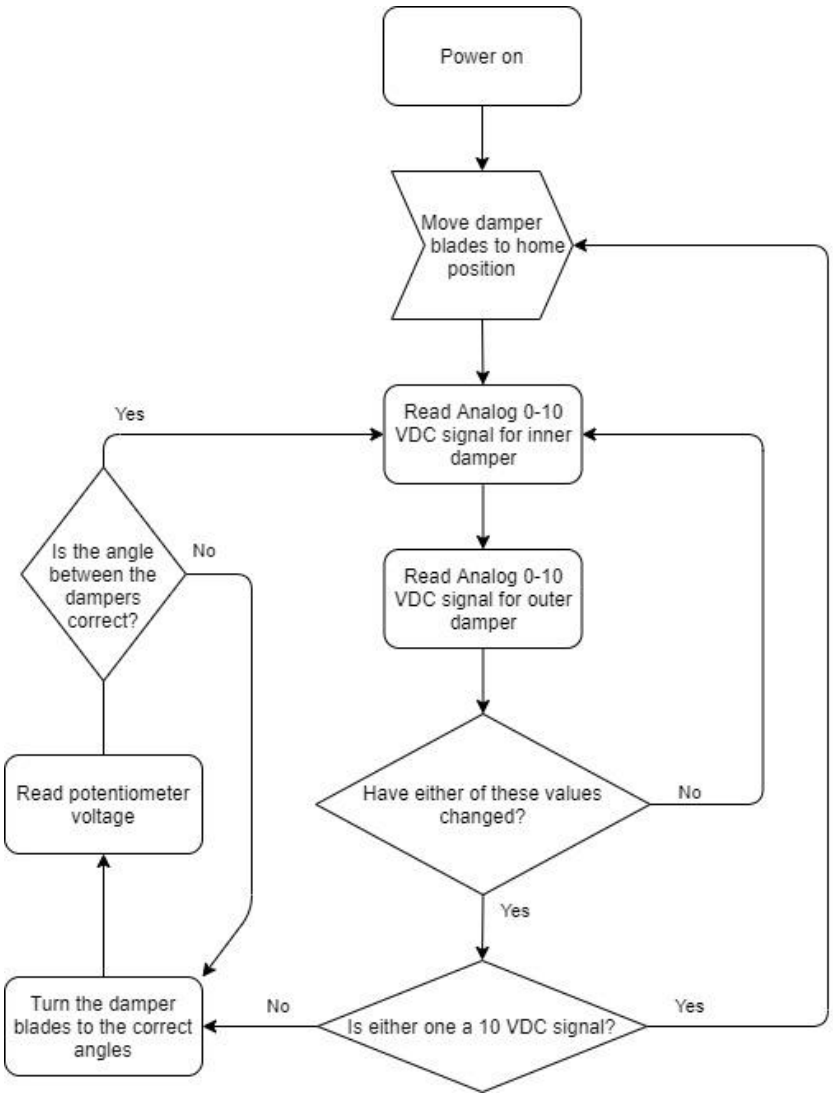


Figure 12: Programming flowchart for ESP32 MPU

Discussion

During this semester, the team was able accommodate and adapt to the changing conditions of these unprecedented times to accomplish many tasks, most of which are shown and discussed in the above sections. This section will include a discussion of the initial plans for the semester and how the team had to modify the plans to compensate issues that arose in order to successfully complete the project. The original timeline for the project as well as the milestone table is included in Appendix X, and the ARCI table showing which team member was responsible which task is included in Appendix XI.

At the start of the semester, the team had to redesign the gear train for the actuator by switching from helical gears to spur. This redesign was warranted by a push to pursue off the shelf gears. The team had to communicate with different vendors in order to find a similar system of gears to what had been previously designed. As mentioned in the Gear and Housing Design section, our investigation revealed that custom gears were more beneficial than off the shelf gears for our application. One

consideration that was brought to the attention of the Team by vendors and faculty members, that when designing a custom gear that is to be manufactured is how they attach to the shaft of rotation. It was quickly understood that the most common and the most affordable way would be to do this was through the use of keyways cut through the center of the gears. This was the best way to ensure the smaller gear will rotate at the same speed as the larger gear that it is attached to.
The team also had to design a mounting system that would position the potentiometers directly on the damper shafts. This would allow for maximum accuracy while measuring the position of the dampers.

Once the new gear design was chosen, the team planned to quickly 3D print and assemble a functioning prototype, as well as develop plans for a full prototype out of acrylic. The reasoning behind the development of the 3D printed prototype was that it would allow ample time for testing, and failure analysis of components, as well as any modification that may be required for our final acrylic design. This was found to be ideal, because changes could be made and implemented in a matter of minutes via the 3D printer and this allowed for seamless integration from design schematics to physical implementation of the final acrylic prototype.

During testing, the team identified an issue with the startup sequence of the programming. The programming was made so that the inner damper shaft would move back 91 degrees and the outer damper shaft would move back 90 degrees during each startup or when the reset button was pressed so that the person controlling the actuator knows the system is at zero degrees before sending the analog control signal. If the dampers were not opened to the full amount before startup, the motors would then 'jump' the number of steps not needed to close the dampers and thus create additional wear on both the gearing and on the damper shafts.

To remedy this issue, the team used the on-board non-volatile memory of the ESP32 microprocessor to store both damper positions throughout the program. By doing this, the motors would then only step the necessary number of steps to reach zero and not be forced to jump steps at startup. However, another possible issue was raised; The possibility of the motors skipping a step or a tooth on the gearing being skipped during movement. This would then cause the motors to be off by at least a full step and therefore would not put the damper back to the zero-degree home position during startup. The solution to this was to add a full reset to the program that is activated when either 0-10vdc analog control signal is set to 10vdc. Sending the 10vdc control signal will activate the original function that moved the damper shafts the full 91 and 90 degrees back to home and should only be used when needed. This helps to eliminate additional wear on the actuator and will create a longer lasting product.

A sign off sheet and final status sheet is included in Appendix I indicating a completion of this project.

Recommendations

While the customer specifications were met, the team feels that some aspects of the design should be considered or can be improved from the customer's original specifications.

Though the "off-the-shelf" gear idea was dismissed due to the issue of finding compounded gears with the correct tooth count and size, it is found that an injection molding method could also be considered "off-the-shelf" in a way. Once the initial cost of getting molds made for each gear, the ability to reproduce the gear assembly vastly increases, which in turn drives down cost of manufacturing. The ability to have the gear cog abundantly available, by definition, makes the process an "off-the-shelf" design.

During the initial PCB design process, HVAC Manufacturing had given the team a PCB that was already in use at their facility on other units. The team quickly found the PCB was not capable of achieving the 0.5 degree of resolution desired, nor was it capable of accepting an additional input from the potentiometer. Though it was not necessary, HVAC's PCB did not have provisions to integrate IoT or provide a user with real-time information on the system. It is recommended to use Espressif Systems ESP-32 microprocessor paired with ADS1115 ADC. The microprocessor has enough I/O ports to accept additional measurement devices. The ADS1115 provides the ability to micro-step the motors to achieve the accuracy desired. The ESP32 has provisions to connect to the cloud and upload information to allow a user to read real-time data.

HVAC manufacturing required the ability to read the difference of angle between both the inner damper and outer damper. In order to correctly read the difference with a high level of accuracy, it is recommended to use a precision potentiometer. The resolution of this style of potentiometers is virtually infinite. These are considered an "off-the-shelf" item, which will eliminate the need to design and build a custom potentiometer that would be less accurate. While the microprocessor can tell the user the angle difference between the two shafts, it would also need an additional potentiometer mounted to one of the shafts to help give the microprocessor reference data. For example, If the microprocessor wanted to move both dampers to 30 degrees, and both motors missed six steps, the actual angle of the dampers would be 27 degrees. Since the potentiometer reads an angle difference of the two shafts as zero, the microprocessor would assume the damper is in the correct position. However, if an additional precision potentiometer is connected to one shaft and used as an angle reference, the microprocessor could process this as feedback and adjust the necessary number of steps to move to the correct angle required.

The team feels that the above-mentioned recommendations should be considered while bringing the design to its final stages. These recommendations were found to be of significance while performing investigations and various tests.

Conclusion

While many milestones have been achieved over the course of the semester, it was not without difficulty. The team had to remain fluid so that they could modify the design as necessary when a challenge arose. This semester brought a new set of challenges, both known and unknown. For examples, the position and mounting system of the potentiometers proved to be a hill to climb as well as making the keyway fitted enough for the gear to slot directly to the shaft without hesitation. Not to mention, redesigning the wing to withstand higher stress. The team worked closely with the faculty and the sponsor to ensure the project remained on track throughout the testing and final design stages to have a functional prototype.

Appendix I

Sign-off Sheet

Included below is the sign-off sheet signed by Mr. Chauhan, Dr. Barakat, and Mr. Adams.

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Senior Design Project II

MENG 4216 / EENG 4315

Project Co-axial Rotary Actuator Delivery and Acceptance

Senior design team 7, Cross Discipline Engineering from UT-Tyler College of Engineering, has worked with a sponsor HVAC Manufacturing Inc to design, build, and test a rotary style co-axial damper actuator as part of the senior students' academic work during the academic year of 2019-2020. This document includes the sign-off list and HVAC Manufacturing Inc final approval of the outcome of co-axial rotary actuator delivered by Cross Discipline Engineering, based on the previously set and mutually-approved scope and specifications of the project. An authorized signature indicates this approval.

Table 1: Sponsor Sign OFF list for Deliverables of the Senior Project Co-Axial Rotary Actuator

Item No.	Description of Deliverable	Comments:	Sponsor Sign Off: Authorized Initials
Co-Axial Rotary Actuator	Rotary actuator capable of turning two damper blades		
Universal	Ability to adapt to single damper unit		
Torque	Capable of 55 in*lbs of torque to turn damper blade	Estimated maximum torque to turn largest rectangular damper with added mechanical loss	
Gears	"Off-the-shelf" spur gear design to minimize cost	Team change with customer approval. "off-the shelf" not feasible for compound gears. Gears will be custom designed.	
Fitment	Must fit within actuator enclosure (19"x9"x6.6")		
Lubrication	Lubrication is required only once and can last lifespan of unit		
Housing	Gear enclosure for noise reduction	Housing is designed, but not implemented due to time constraints.	

Item No.	Description of Deliverable	Comments:	Sponsor Sign Off: Authorized Initials
Electrical	Accept 24VAC power		
Input Signal	Accepts 0-10VDC signal		
Accuracy	Capable of 0.5 degree of accuracy	Accommodated by 200 motor steps	
Resolution	Potentiometer capable of 0.1 degrees of resolution	High precision potentiometer has virtually infinite resolution as per Bourne	
Damper Tracking	Ability to track angle difference of inner and outer damper blades		
Reset	Ability to reset system to bring dampers to "home" position	Reset provided by ESP-32 microprocessor	
Home	When powering on, damper blades must return to home position		
IoT	IoT capability	Customer Change: Not required Has provisions to implement	
Production Model Documentation	Technical Documentation		
B.O.M.	Bill of Materials		
I.O.M.	Installation and Operations Manual		
Actuator Design	CAD files for complete actuator assembly		
Electrical Schematic	Electrical Layout		
Testing	Testing performed at HVAC facility	Customer Change: Customer will test actuators due to time constraints	

The following signatures indicate that HVAC Manufacturing Inc approves of the completion of this project and deliverables stated above which included all sponsor changes from original design and any consequent changes in the project, as mutually approved by all signing parties. Also indicated is the acknowledgement by HVAC Manufacturing Inc of reception of the final product of the project.

Dr. Nael Barakat *Team Advisor* *U.T. Tyler Engineering Department Faculty*	Apr. 28, 20 Date
Abhay Chauhan *Product Manager* *HVAC Manufacturing Inc*	4/24/2020 Date
Jacob Adams *Team Captain* *Cross Discipline Engineering* *U.T. Tyler Engineering Student*	4/24/2020 Date

Final Status Sheet

Included below is the final status sheet showing the project completion status.

The University of Texas at TYLER COLLEGE OF ENGINEERING

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SENIOR DESIGN II _ FINAL STATUS SHEET

TEAM: ___7_____	**Date:** ___4/28/2020_____
Project final status: **COMPLETED:** _____	**NOT COMPLETED:** __X__ **ESTIMATED % Completion** _95_ **%**
Location on OneDrive where team project folder can be downloaded - See instructions after this table: https://www.dropbox.com/sh/94dzynwnk6p036r/AAAssCPh9GkqJEAnx8IdeAmva?dl=0	
PENDING ITEMS: - Double Damper Feedback programming	
OUTSTANDING ITEMS ORDERED (BUT NOT RECEIVED)	
OUTSTANDING ITEMS NOT ORDERED	
FINAL COMMENTS: - The system is fully functional, and the sign-off sheet has been completed by the sponsor.	
SIGNATURE: **1.- Name: Robert Adams**	**Signature:** Robert Adams
2.- Name: Andrew Aiken	**Signature:**
3.- Name: Michael Fults	**Signature:**
4.- Name: Cameron Timbes	**Signature:** Cameron Timbes
5.- Name: Lam Trinh	**Signature:** Lam Trihn
6.- Name: Marcelo Zavala	**Signature:** Marcelo Zavala

The University of Texas at TYLER

TYR 7: CROSS DISCIPLINE ENGINEERING

Electrical & Mechanical Engineering

CO-AXIAL ROTARY ACTUATOR

Team Members: Jacob Adams, Andrew Aiken, Michael Fults, Cameron Timbes, Lam Trinh, Marcelo Zavala
Department of Mechanical and Electrical Engineering, UT-Tyler, Senior Projects 2019 - 2020
Sponsor: HVAC Manufacturing, Inc
Advisors: Dr. Barakat, Dr. Sundaravadivel

Abstract

The purpose of this project is to design and build a manufacturing ready system for remote control of air outlets in commercial Heat, Ventilation, and Air Conditioning (HVAC) units. This system is capable of collecting and communicating data related to HVAC, wirelessly to the cloud, through IoT. This applied research project is sponsored by an industrial partner – HVAC Manufacturing in Athens, TX. A team of undergraduate students carried out this project as their senior engineering year design project.

Concept

To design and build a rotary coaxial actuator that will have the ability to control a dual or single damping HVAC terminal unit, allowing for a greater overall control of air flow. In addition, a secondary focus will be to integrate IoT (Internet of Things) connectivity to allow for wireless monitoring.

Background

Currently there are no rotary co-axial actuators available for this type of HVAC dual damper

However, on the market the following does exist:

- Rotary actuator
  - Applicable for single blade damper design **only**
  - Incremental movements are not accurate
  - No IoT integration
- Linear coaxial actuator
  - Available for a dual damper design
  - Linear motion to rotary motion is problematic
  - Incremental movements are not accurate
  - No IoT integration

Customer Initial Requirements

Mechanical requirements
- Motor assembly must be universal to single and dual damper applications
- Fits within a L19"xW9.0"xH6.6" enclosure
- Minimal noise generation
- Minimum output torque value of 55 lbs·in
- Gear lubricant must last lifetime of gear train

Electrical Requirements
- System to be powered by existing 24VAC system
- Must accept 0-10VDC input signal
- Real time tracking of dampers for feedback
- Reset button to bring motors to "home" position

Final Specifications

- Actuator dimensions – L9.50"xW5.00"xH4.98"
- Gear ratio – 1:180
- Compounded spur gears
- PCB dimensions – L6.00"xW3.50"
- Electrically driven by stepper motors.
- Resolution of damper shaft – 0.5 °
- Electrical step size - 0.05 volts (200 steps)
- IoT capable

Figure 1: Damper Unit

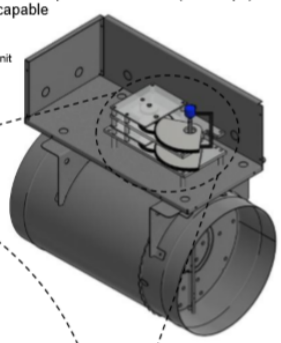


Figure 2: Isometric and Orthographic Views of Actuator Assembly

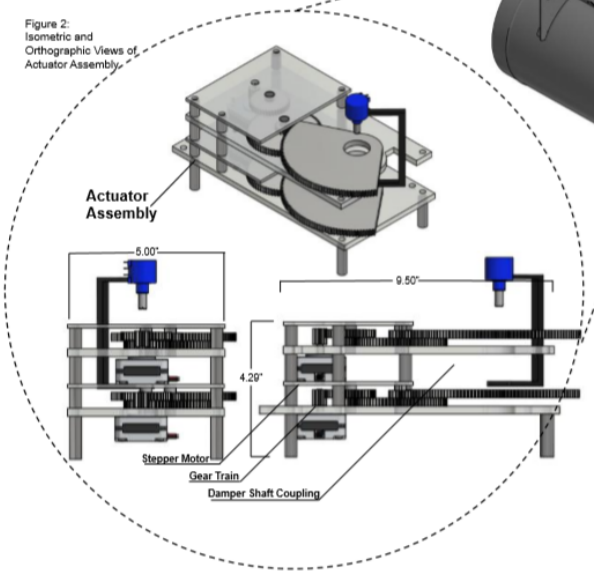
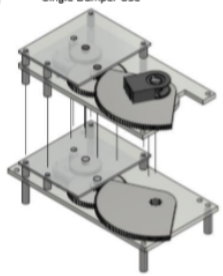


Figure 3: Breakdown Showing Removable Assembly for Single Damper Use



Electrical Design Selection

Figure 4: ESP-32



Espressif ESP-32
- Operating temperature -40°C - 85°C
- Low power consumption 3.3VDC
- WiFi capable 802.11b/g/n
  - Security – IEEE 802.11 WFA/WPA/WPA2/WAPI
- Multi-programming language capable
- 34 I/O ports

Figure 5: Stepper Motor



NEMA 17 stepper motor (stand alone)
- 1.8° step angle
- Maximum Holding toque - 1.15 lbs·in
- Maximum Pull-out torque – 1.05 lbs·in

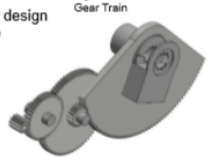
NEMA 17 stepper motor (adapted to gear train)
- 0.2° step angle
- Maximum Holding toque – 96.6 lbs·in
- Maximum Pull-out torque – 88.2 lbs·in

Meets desired specifications

Mechanical Gear Selection

Spur gears
- Reliable operation
- Simple and compact design
- Easy to manufacture
- Economical

Figure 6: Gear Train



Design Specs
- 105° Final gear
- 0.25" gear thickness

Material Selection
- Polylactic acid (PLA)
  - Used in prototyping gear train via 3D printing
- Acrylic Plastic (Plexiglass)
  - Used in Gear and motor housing

Acknowledgements

We would like to express our gratitude to Dr. Barakat, Dr. Fumo, Dr. Goh, Dr. Indic, Dr. Shirvaiker, and Dr. Sundaravadivel, at U.T. Tyler, for their guidance and assistance throughout various areas of our project.
We also would like to thank HVAC Manufacturing for their guidance and for allowing us to use their flow stand for testing.
Lastly, We would like to thank Edward Farina who helped with manufacturing items in the U.T. Tyler Fabrication Lab.

Appendix II

Standards Referenced During Design

Excerpt of IEEE 802.11 (2016)

4. General description

4.1 General description of the architecture

This clause presents the concepts and terminology used within this standard. Specific terms are defined in Clause 3. Illustrations convey key IEEE 802.11 concepts and the interrelationships of the architectural components. IEEE Std 802.11 uses an architecture to describe functional components of an IEEE 802.11 LAN. The architectural descriptions are not intended to represent any specific physical implementation of IEEE Std 802.11.

4.2 How wireless local area networks (WLANs) are different

4.2.1 Introduction

Wireless networks have fundamental characteristics that make them significantly different from traditional wired LANs.

4.2.2 Wireless station (STA)

In the design of wired LANs it is implicitly assumed that an address is equivalent to a physical location. In wireless networks, this is not always the case. In IEEE Std 802.11, the addressable unit is a station (STA). Physical and operational characteristics are defined by modifiers that are placed in front of the term STA. For example, in the case of location and mobility, the addressable units are the fixed STA, the portable STA, and the mobile STA. The STA is an addressable destination, but not (in general) a fixed location.

A STA might take on multiple distinct characteristics, each of which shape its function. For example, a single addressable unit might simultaneously be a portable STA, a quality-of-service (QoS) STA, a dependent STA, and a hidden STA.

4.2.3 Media impact on design and performance

The PHYs used in IEEE Std 802.11 are fundamentally different from wired media. Thus IEEE 802.11 PHYs:

a) Use a medium that has neither absolute nor readily observable boundaries outside of which STAs with PHY transceivers are known to be unable to receive network frames
b) Are unprotected from other signals that are sharing the medium
c) Communicate over a medium significantly less reliable than wired PHYs
d) Have dynamic topologies
e) Lack full connectivity, and therefore the assumption normally made that every STA can hear every other STA is invalid (i.e., STAs might be “hidden” from each other)
f) Have time-varying and asymmetric propagation properties
g) Might experience interference from logically disjoint IEEE 802.11 networks operating in overlapping areas

Because of limitations on wireless PHY ranges, WLANs intended to cover reasonable geographic distances can be built from basic coverage building blocks. When providing QoS services, the MAC endeavors to provide QoS “service guarantees” within the limitations of the medium properties identified above. In other words, particularly in unlicensed spectrum, true guarantees are often not possible. However, gradations of service are always possible; and in sufficiently controlled environments, QoS guarantees are possible.

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4.2.4 The impact of handling mobile STAs

One of the requirements of IEEE Std 802.11 is to handle *mobile* as well as *portable* STAs. A *portable* STA is one that is moved from location to location, but that is used only while at a fixed location. *Mobile* STAs actually access the LAN while in motion.

For technical reasons, it is not sufficient to handle only portable STAs. Propagation effects blur the distinction between portable and mobile STAs; stationary STAs often appear to be mobile due to propagation effects.

Mobile STAs typically are battery powered. Hence power management is an important consideration. For example, it cannot be presumed that a STA's receiver is always powered on.

4.2.5 Interaction with other IEEE 802® layers

IEEE Std 802.11 is required to appear to higher layers [logical link control (LLC)] as a general-purpose IEEE 802 LAN. This requires that the IEEE 802.11 network handle STA mobility within the MAC sublayer. To meet reliability assumptions (that LLC makes about lower layers), it is necessary for IEEE Std 802.11 to incorporate functionality that is untraditional for MAC sublayers.

In a robust security network association (RSNA), IEEE Std 802.11 provides functions to protect Data frames, IEEE Std 802.1X-2010 provides authentication and a Controlled Port, and IEEE Std 802.11 and IEEE Std 802.1X-2010 collaborate to provide key management. All STAs in an RSNA have a corresponding IEEE 802.1X™ entity that handles these services. This standard defines how an RSNA utilizes IEEE Std 802.1X-2010 to access these services. Within IEEE Std 802.11, EAPOL PDUs are carried as MSDUs within one or more Data frames, as described in IEEE Std 802.1X-2010, Clause 12. Within this standard, Data frames used for this purpose are generally referred to as *EAPOL-Key frames*, *EAPOL-Key request frames*, and *EAPOL-Start frames*.

When used to support applications that have QoS requirements, each IEEE 802.11 LAN provides a link within an end-to-end QoS environment that can be established between, and managed by, higher layer entities. To handle QoS traffic in a manner comparable to other IEEE 802 LANs, the IEEE 802.11 QoS facility requires the IEEE 802.11 MAC sublayers to incorporate functionality that is not traditional for MAC sublayers. In addition, it might be necessary for certain higher layer management entities to be "WLAN aware" at least to the extent of understanding that the available bandwidth and other QoS characteristics of a WLAN are subject to frequent, and sometimes substantial, dynamic changes due to causes other than traffic load and are outside the direct control of network management entities.

4.2.6 Interaction with non-IEEE-802 protocols

An RSNA utilizes non-IEEE-802 protocols for its authentication and key management (AKM) services. Some of these protocols are defined by other standards organizations, such as the Internet Engineering Task Force (IETF).

4.3 Components of the IEEE 802.11 architecture

4.3.1 General

The IEEE 802.11 architecture consists of several components that interact to provide a WLAN that supports STA mobility transparently to upper layers.

The basic service set (BSS) is the basic building block of an IEEE 802.11 LAN. Figure 4-1 shows two BSSs, each of which has two STAs that are members of the BSS.

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It is useful to think of each oval depicting a BSS as the coverage area within which the member STAs of the BSS can remain in communication. In the case of transmissions such as in a directional multi-gigabit (DMG) BSS, the individual coverage area of a transmission from one member STA to another can be thought of as a cone and hence is referred to as a *directional transmission*. The collection of all possible directional transmissions by a member STA defines the coverage area. (The concept of area, while not precise, is often good enough.) This area is called the *Basic Service Area (BSA)*. If a STA moves out of its BSA, it can no longer directly communicate with other STAs present in the BSA.

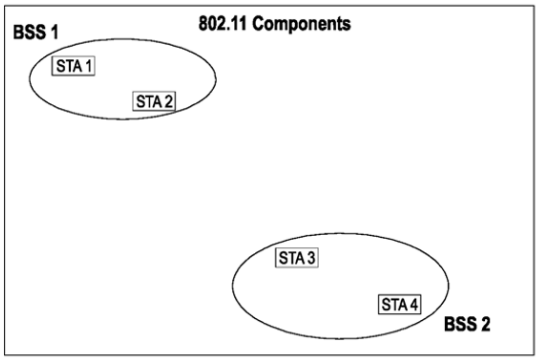


Figure 4-1—BSSs

4.3.2 The independent BSS (IBSS)

The IBSS is the most basic type of IEEE 802.11 LAN. Since the BSSs shown in Figure 4-1 are simple and lack other components (contrast this with Figure 4-2), the two can be taken to be representative of two IBSSs.

This mode of operation is possible when IEEE 802.11 STAs are able to communicate directly. Because this type of IEEE 802.11 LAN is often formed without preplanning, for only as long as the LAN is needed.

4.3.3 The personal BSS (PBSS)

Similar to the IBSS, the PBSS is a type of IEEE 802.11 LAN in which STAs communicate directly with each other.

In contrast to the IBSS, in the PBSS one STA assumes the role of the PBSS control point (PCP). The PCP provides the basic timing for the PBSS through DMG Beacon and Announce frames as well as allocation of service periods and contention based access periods.

A PBSS can be established only by DMG STAs. Not every DMG BSS is a PBSS. A DMG BSS can be a PBSS, an infrastructure BSS, or an IBSS.

4.3.4 STA membership in a BSS is dynamic

A STA's membership in a BSS is dynamic (STAs turn on, turn off, come within range, and go out of range). To become a member of an infrastructure BSS or an IBSS, a STA joins the BSS using the synchronization procedure described in 11.1.4.5. To start a new mesh BSS or to become a member of a mesh BSS, a STA starts the transmission of Beacons and performs the synchronization maintenance procedure described in 14.13. To access all of the services of an infrastructure BSS, a STA becomes "associated." These

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5. General description

5.1 Introduction

A low-rate wireless personal area network (LR-WPAN) is a simple, low-cost communication network that allows wireless connectivity in applications with limited power and relaxed throughput requirements. The main objectives of an LR-WPAN are ease of installation, reliable data transfer, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol.

This standard defines multiple PHYs operating in a variety of frequency bands, as described in 10.1.1.

Two different device types can participate in an IEEE 802.15.4 network: a full-function device (FFD) and a reduced-function device (RFD). An FFD is a device that is capable of serving as a personal area network (PAN) coordinator or a coordinator, as defined in 6.1. An RFD is a device that is not capable of serving as either a PAN coordinator or a coordinator. An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor; it does not have the need to send large amounts of data and only associates with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity.

Supplemental information for different industrial domains is described in "Applications of IEEE Std 802.15.4" [B3].[9]

5.2 Special application spaces

Although this standard is intended address many diverse application spaces, some application spaces have unique requirements which required specific elements added to this standard. These elements are described in this subclause.

5.2.1 Smart utility network (SUN)

SUNs enable multiple applications to operate over shared network resources, providing monitoring and control of a utility system. SUN devices are designed to operate in very large-scale, low-power wireless applications and often require using the maximum transmit power available under applicable regulations, in order to provide long-range, point-to-point connections. Frequently, SUNs are required to cover geographically widespread areas containing a large number of outdoor devices. In these cases, SUN devices are able to employ mesh or peer-to-peer multihop techniques to communicate with an access point.

5.2.2 Rail communications and control (RCC)

RCC refers to a wireless information exchange and sensor or control communications deployed in areas such as the following:

- A wireless link between trains, locomotives, or other mobile rolling stock to fixed trackside or network infrastructure
- A link between connected fixed, remote trackside infrastructure and fixed network infrastructure
- A link between vehicles in the same train or between two or more trains

RCC devices are intended to support mobile rail vehicle communications at high speeds with data rates that enable connections at distances of over 50 km. The RCC PHYs are designed to take advantage of relatively small amounts of spectrum where spectrum is costly or scarce.

[9]The numbers in brackets correspond to the numbers of the bibliography in Annex A.

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5.2.3 Television white space (TVWS)

TVWS operation has the requirement to determine which TVWS frequency allocations are available for use at a given time and geographic location. TVWS devices need to have have access to TVWS channel availability information, for example, via a central database that is accessed over the Internet. A TVWS device that has no connection to the Internet must depend upon another TVWS device that has access to the TVWS database via the Internet to acquire channel availability information.

5.2.4 Radio frequency identification (RFID)

Active RFID devices are used to identify and often locate people or objects in industrial or commercial environments. Typical applications include asset management, inventory management, process control and automation, safety and accountability.

In its simplest form an active RFID system comprises a number of transmit-only tags that periodically transmit a packet containing a unique ID and a small amount of data. The packet is received by one or more readers that may simply register the tag as present, may employ further processing to determine the location of the tag, or forward data to an application server. More complex active RFID systems might employ two-way communications with the tag for control, communication, and coordination.

5.2.5 Low-energy, critical infrastructure monitoring (LECIM)

The LECIM portions of this standard are designed to implement a minimal network infrastructure that enables the collection of scheduled and event data from a large number of non-mains powered end points that are widely dispersed, or are in challenging propagation environments. To facilitate low energy operation necessary for multi-year battery life, MAC protocols that minimize network maintenance traffic and device wake durations have been defined.

5.2.6 Medical body area network (MBAN) services

Some countries have allocated spectrum for MBAN services on a secondary basis such that MBAN devices are required to protect all primary users and accept possible interference from those users. MBAN devices operating within this allocated spectrum conform to a set of rules which restrict use of the band to only medical, non-voice use under direction of a healthcare practitioner, among other requirements. When a primary user is making use of a portion of the band, MBAN devices vacate that portion of the band. Use of the band by the primary user is, in general, scheduled well in advance allowing MBAN users to share the band in an orderly manner.

5.3 Components of the IEEE 802.15.4 WPAN

A system conforming to this standard consists of several components. The most basic is the device. A device has a single radio interface that implements an IEEE Std 802.15.4 MAC and PHY. Two or more devices communicating on the same physical channel constitute a wireless personal area network (WPAN). A WPAN includes at least one FFD, operating as the PAN coordinator.

5.4 Multi-PHY management (MPM) of the SUN WPAN

Multiple, different SUN PHYs can operate in the same location and within the same frequency band. In order to mitigate interference, an MPM scheme is specified for SUNs to facilitate inter-PHY coexistence. For this purpose, the MPM scheme facilitates interoperability and negotiation among potential coordinators with different PHYs by permitting a potential coordinator to detect an operating network during its discovery phase using the common signaling mode (CSM) appropriate to the band being used. The MPM

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procedure can be used in conjunction with the clear channel assessment (CCA) mechanism to provide coexistence.

5.5 Network topologies

Depending on the application requirements, an IEEE 802.15.4 LR-WPAN operates in either of two topologies: the star topology or the peer-to-peer topology. Both are shown in Figure 5-1. In the star topology, the communication is established between devices and a single central controller, called the PAN coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communications. The PAN coordinator is the primary controller of the PAN. All devices operating on a network of either topology have unique addresses, referred to as extended addresses. In addition, a device can be assigned a short address during the association process. A device will use either the extended address or the short address for communication within the PAN. The transmission of the extended and short address fields is optional for RFD-TX devices. The PAN coordinator will often be mains powered, while the devices will likely be battery powered. Applications that benefit from a star topology include home automation, personal computer (PC) peripherals, games, and personal health care.

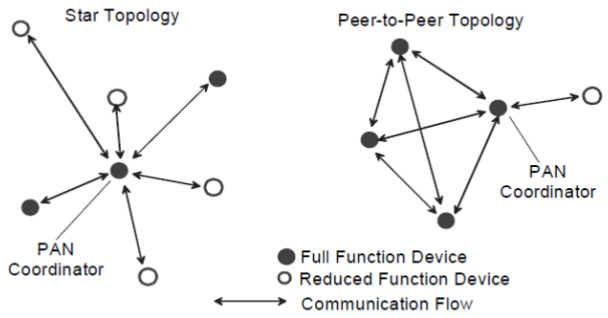


Figure 5-1—Star and peer-to-peer topology examples

The peer-to-peer topology also has a PAN coordinator; however, it differs from the star topology in that any device is able to communicate with any other device as long as they are in range of one another. Peer-to-peer topology allows more complex network formations to be implemented, such as mesh networking topology. Applications such as industrial control and monitoring, wireless sensor networks, asset and inventory tracking, intelligent agriculture, and security would benefit from such a network topology. A peer-to-peer network allows multiple hops to route messages from any device to any other device on the network. Such functions can be added at the higher layer, but they are not part of this standard.

Each independent PAN selects a unique identifier. This PAN identifier (ID) allows communication between devices within a network using short addresses and enables transmissions between devices across independent networks. The mechanism by which identifiers are chosen is outside the scope of this standard.

The network formation is performed by the higher layer, which is not part of this standard.

5.5.1 Star network formation

The basic structure of a star network is illustrated in Figure 5-1. After an FFD is activated, it can establish its own network and become the PAN coordinator. All star networks operate independently from all other star networks currently in operation. This is achieved by choosing a PAN ID that is not currently used by any other network within the radio communications range. Once the PAN ID is chosen, the PAN coordinator

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allows other devices, potentially both FFDs and RFDs, to join its network. The higher layer can use the procedures described in 6.3 and 6.4 to form a star network. An RFD-RX can also serve as a PAN coordinator termination point for RFD-TXs.

Timeslotted channel hopping (TSCH) PANs are topology independent and can be used in star topologies as well as partial or full mesh topologies.

LECIM networks primarily operate in a star topology. LECIM networks are typically asymmetric in energy supply and capability, having a PAN coordinator that is mains powered (or otherwise provided a substantial power source) and energy and/or cost constrained devices. The PAN coordinator typically monitors the channel more often than a device. A device sleeps unless it has a Data frame to send.

5.5.2 Peer-to-peer network formation

In a peer-to-peer topology, each device is capable of communicating with any other device within its radio communications range. One device is nominated as the PAN coordinator, for instance, by virtue of being the first device to communicate on the channel. Further network structures are constructed out of the peer-to-peer topology, and it is possible to impose topological restrictions on the formation of the network.

An example of the use of the peer-to-peer communications topology is the cluster tree. The cluster tree network is a special case of a peer-to-peer network in which most devices are FFDs. An RFD connects to a cluster tree network as a leaf device at the end of a branch because RFDs do not allow other devices to associate. Any FFD is able to act as a coordinator and provide synchronization services to other devices or other coordinators. Only one of these coordinators is the overall PAN coordinator, potentially because it has greater computational resources than any other device in the PAN. The PAN coordinator forms the first cluster by choosing an unused PAN ID and broadcasting beacon frames to neighboring devices. A contention resolution mechanism is required if two or more FFDs simultaneously attempt to establish themselves as PAN coordinators; however, such a mechanism is outside the scope of this standard. A candidate device receiving a beacon frame is able to request to join the network at the PAN coordinator. If the PAN coordinator permits the device to join, it adds the new device as a child device in its neighbor list. Then the newly joined device adds the PAN coordinator as its parent in its neighbor list and begins transmitting periodic beacons; other candidate devices are able to then join the network at that device. If the original candidate device is not able to join the network at the PAN coordinator, it will search for another parent device. The detailed procedures describing how a PAN is started and how devices join a PAN are found in 6.3 and 6.4.

The simplest form of a cluster tree network is a single cluster network, but larger networks are possible by forming a mesh of multiple neighboring clusters. Once predetermined application or network requirements are met, the first PAN coordinator instructs a device to become the PAN coordinator of a new cluster adjacent to the first one. Other devices gradually connect and form a multicluster network structure, such as the one seen in Figure 5-2. The lines in Figure 5-2 represent the parent-child relationships of the devices and not the communication flow. The advantage of a multicluster structure is increased coverage area, while the disadvantage is an increase in message latency.

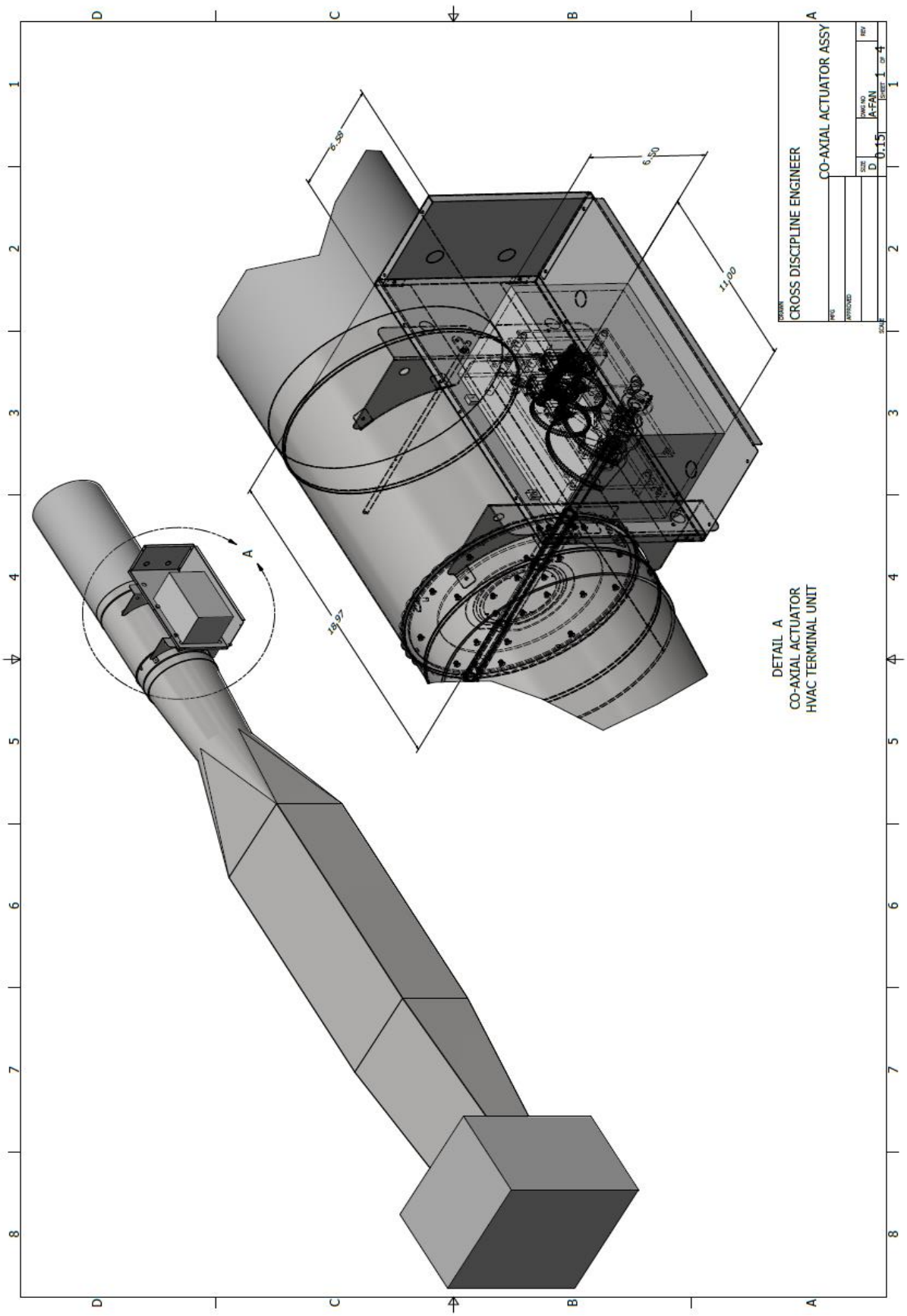
A TMCTP is a form of cluster tree network where the SPC is the overall PAN coordinator providing synchronization services to other PAN coordinators in the cluster. The SPC also has access to the geolocation database (GDB) server to provide TVWS channel availability information to other PAN coordinators. An example is shown in Figure 5-3. In the TMCTP, collisions between clusters can be reduced because each cluster uses its own channel; in addition, the coverage area is increased through the TMCTP parent-child structure. Each TMCTP-parent PAN coordinator, including the SPC, communicates with its TMCTP-child PAN coordinators during the CAP or CFP of the TMCTP-parent PAN coordinator superframe and receives beacon frames of its TMCTP-child PAN coordinators on a dedicated channel during the dedicated beacon slots (DBS) assigned to them in the BOP, as shown with an asterisk (*) in Figure 5-3.

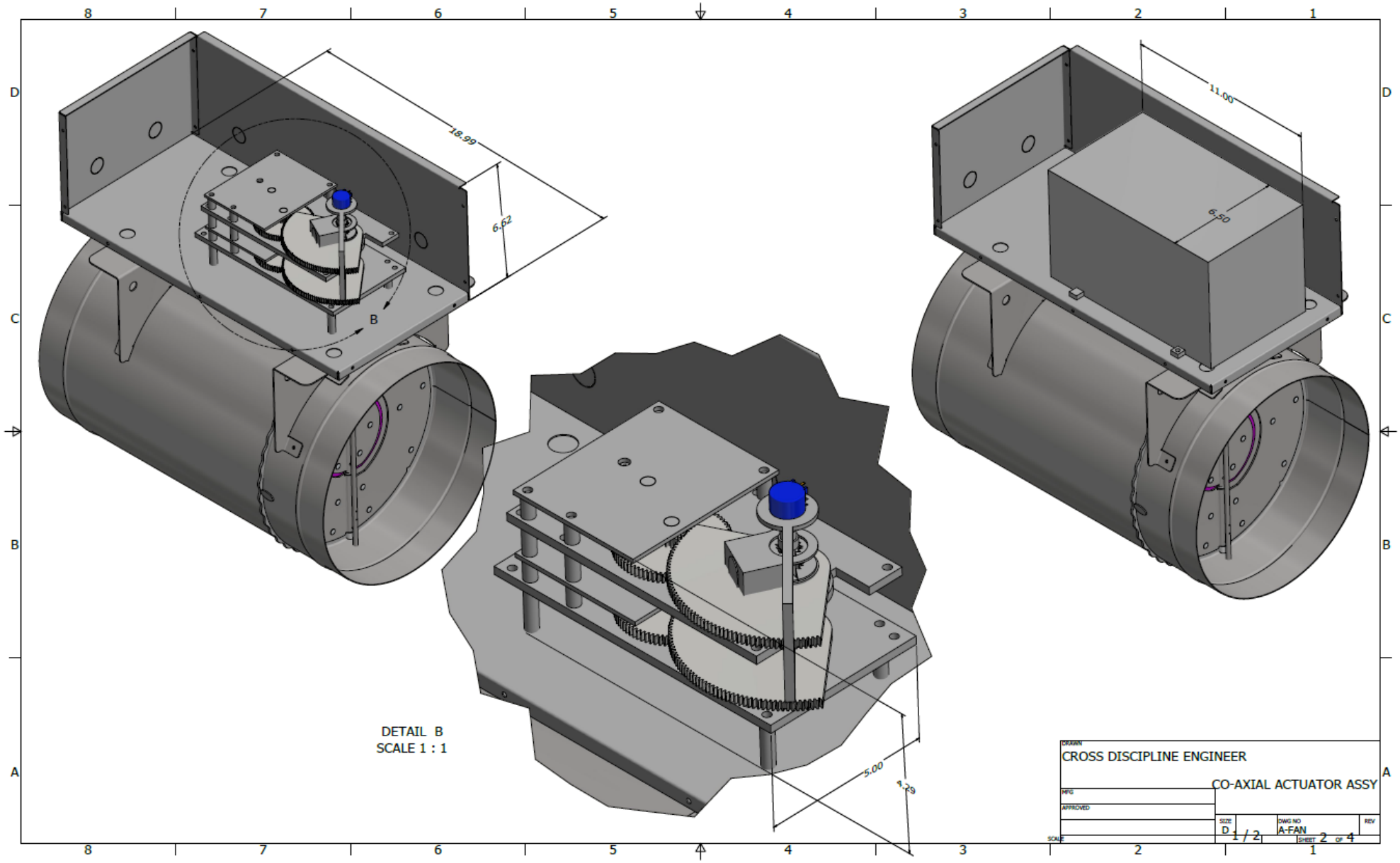
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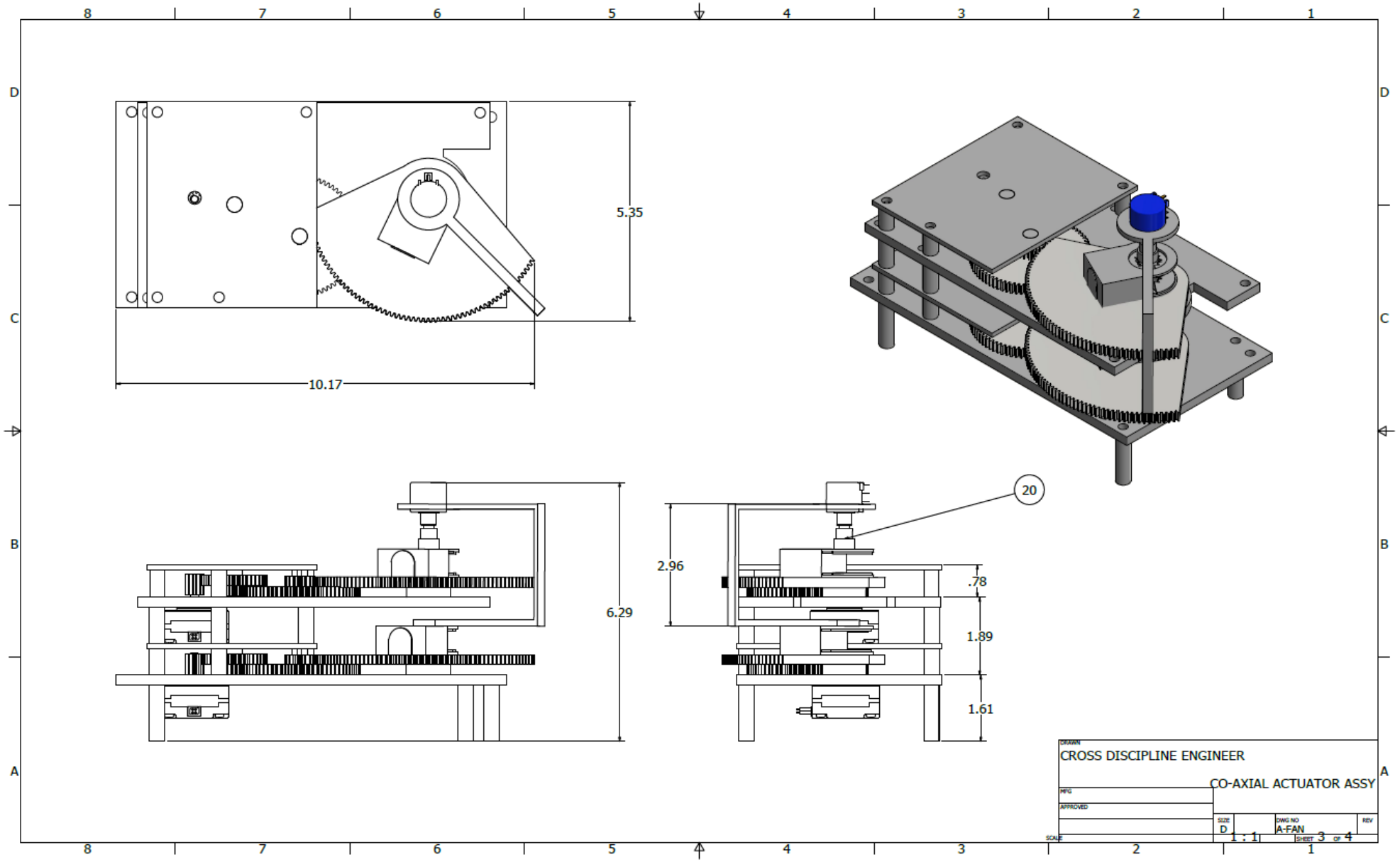
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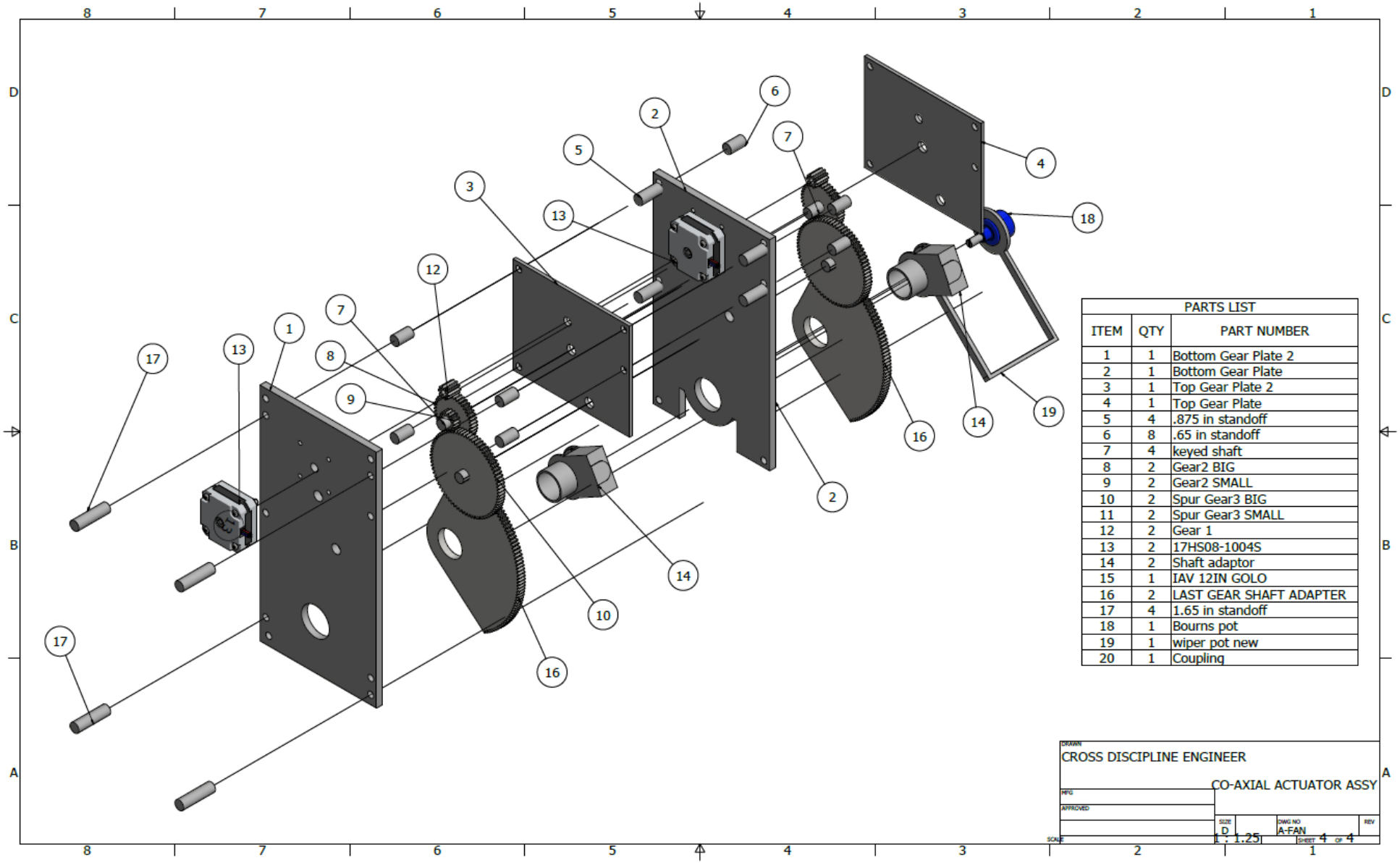
Appendix III

Mechanical drawings




18.99
6.62
B
11.00
6.50
5.00
1.79
DETAIL B
SCALE 1 : 1
CROSS DISCIPLINE ENGINEER
CO-AXIAL ACTUATOR ASSY
A-FAN
D
1 / 2
2 OF 4


8
7
6
5
4
3
2
1
D
C
B
A
5.35
10.17
6.29
2.96
20
.78
1.89
1.61
DRAWN
CROSS DISCIPLINE ENGINEER
CO-AXIAL ACTUATOR ASSY
MFG
APPROVED
SIZE
D
DWG NO
A-FAN
REV
SCALE
1 : 1
SHEET 3 OF 4



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Bottom Gear Plate 2
2	1	Bottom Gear Plate
3	1	Top Gear Plate 2
4	1	Top Gear Plate
5	4	.875 in standoff
6	8	.65 in standoff
7	4	keyed shaft
8	2	Gear2 BIG
9	2	Gear2 SMALL
10	2	Spur Gear3 BIG
11	2	Spur Gear3 SMALL
12	2	Gear 1
13	2	17HS08-1004S
14	2	Shaft adaptor
15	1	IAV 12IN GOLO
16	2	LAST GEAR SHAFT ADAPTER
17	4	1.65 in standoff
18	1	Bourns pot
19	1	wiper pot new
20	1	Coupling

DRAWN: CROSS DISCIPLINE ENGINEER

CO-AXIAL ACTUATOR ASSY

MFG

APPROVED

SIZE D | DWG NO A-FAN | REV

SCALE 1 : 1.25 | SHEET 4 OF 4

Appendix IV

Electrical circuits diagrams

Included below are the electrical circuit diagrams and their respective tables explaining what each component is.

Prototype breadboard Layout:

The prototype breadboard was created to allow the for testing of the prototype actuator assembly without the team having to have a printed circuit board manufactured. While the team would have preferred to manufacture a PCB, due to time constraints this wasn't possible.

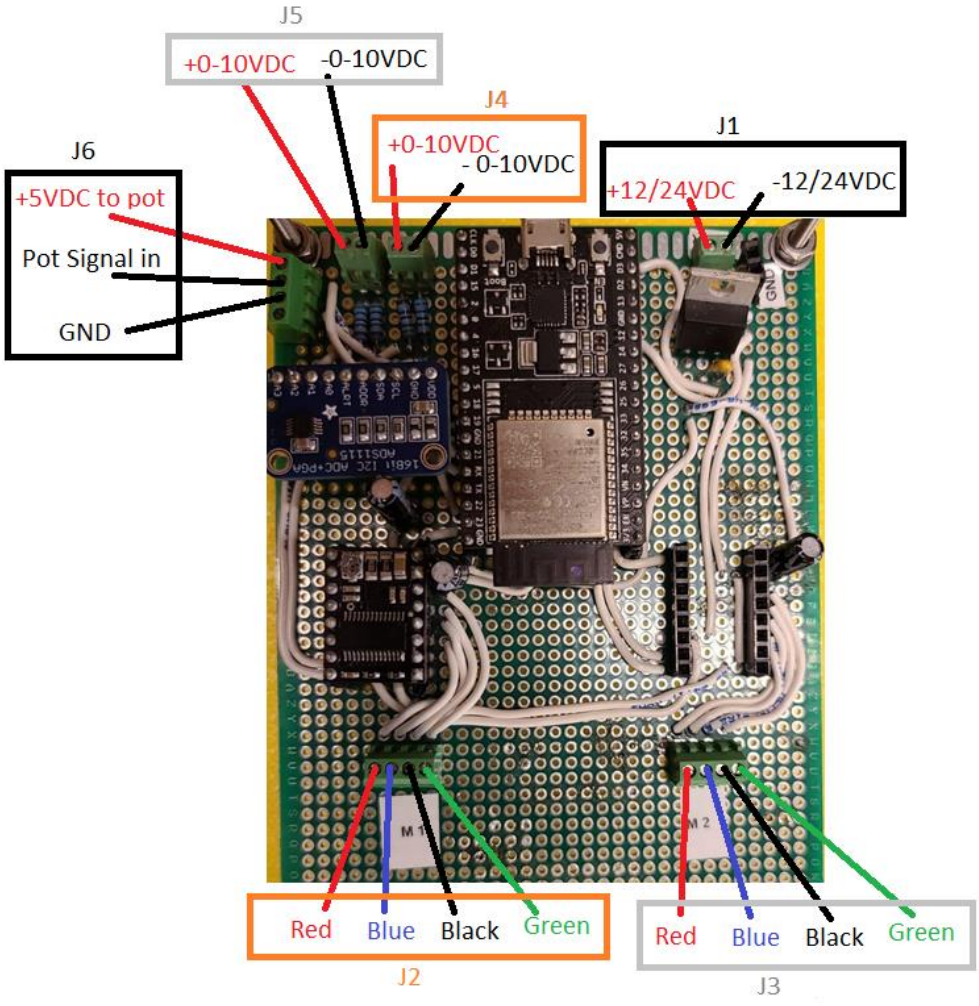
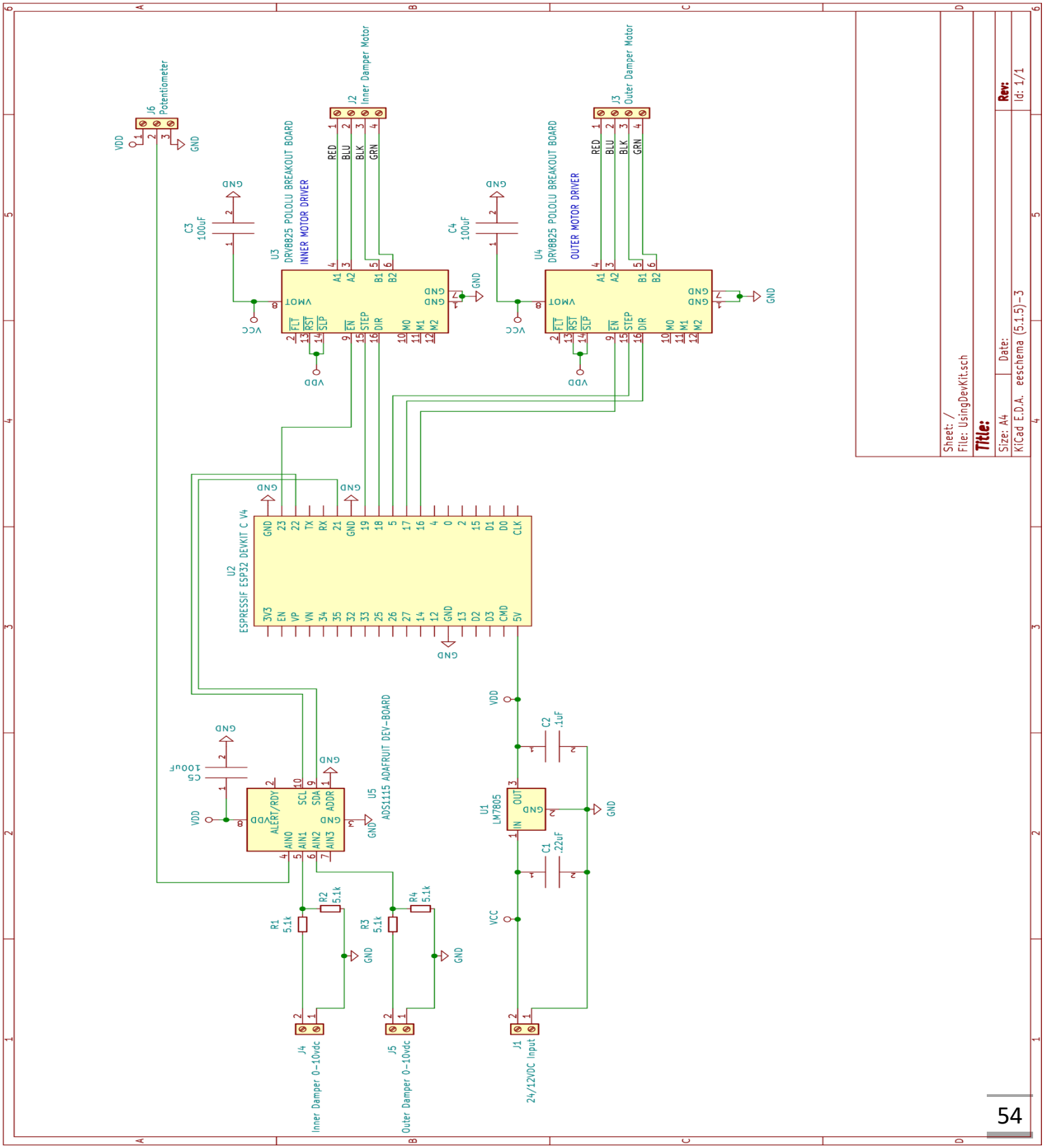


Figure 13: Prototype Breadboard Layout and explanation

Prototype breadboard Schematic

The schematic used in the making of the prototype breadboard is included below, the components are included the table that follows.



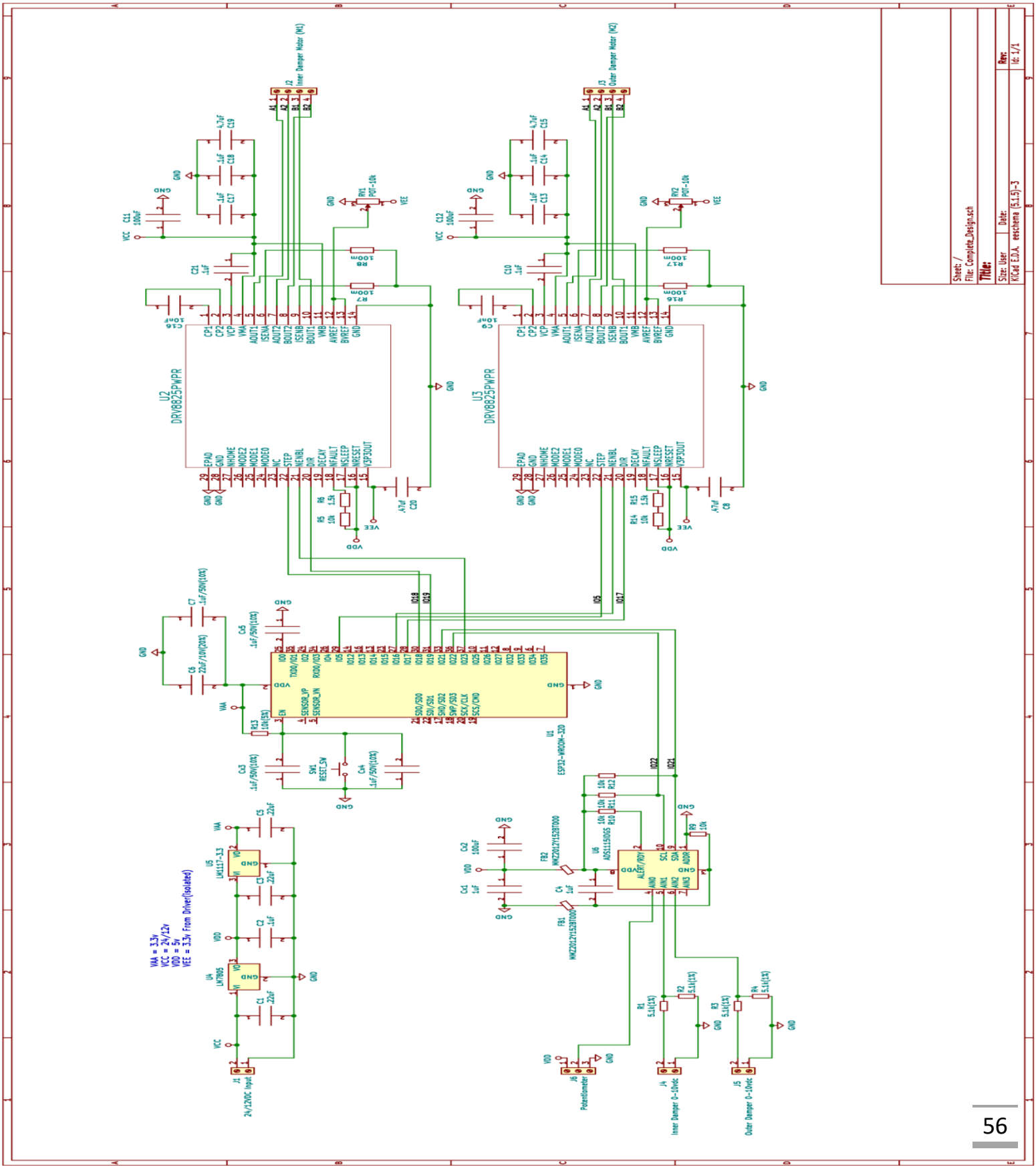
Electronic Components Table for Prototype Breadboard

Table 19: Components list for prototype breadboard included in the schematic above

Ref Des	Description	P/N
C1	.22uF 50V Ceramic Capacitor	C410C224M5U5TA7200
C2	.1uF 50V Ceramic Capacitor	C315C104M5U5TA7303
C3	100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS
C4	100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS
C5	100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS
J1	Screw Terminal	282837-2
J2	Screw Terminal	282837-4
J3	Screw Terminal	282837-4
J4	Screw Terminal	282837-2
J5	Screw Terminal	282837-2
J6	Screw Terminal	282837-3
R1	5.1k 1% Resistor	MBB02070C5101FCT00
R2	5.1k 1% Resistor	MBB02070C5101FCT00
R3	5.1k 1% Resistor	MBB02070C5101FCT00
R4	5.1k 1% Resistor	MBB02070C5101FCT00
U1	Voltage Regulator	LM7805
U2	ESP32 Microprocessor	ESP32-DevKitC-V4
U3	DRV8825 Pololu Dev Board	Pololu ID: 2133
U4	DRV8825 Pololu Dev Board	Pololu ID: 2133
U5	ADS1115 Adafruit Breakout Board	Adafruit ID: 1085

Complete PCB Schematic

The schematic used in the making of the printed circuit board is included below, the components are included the table that follows.



Electronic Components Table for Complete PCB

Table 20: Components list for complete PCB schematic included above

Ref Des	Description	P/N
C1	.22uF 35V Ceramic Capacitor	CGA2B1X7R1V224K050BC
C2	.1uF 10V Ceramic Capacitor	GRM033R61A104ME15D
C3	.22uF 35V Ceramic Capacitor	CGA2B1X7R1V224K050BC
C4	1uF 10V Ceramic Capacitor	CL10A105KP8NNNC
C5	.22uF 35V Ceramic Capacitor	CGA2B1X7R1V224K050BC
C6	22uF 10V Ceramic Capacitor	GRM21BR61A226ME51L
C7	.1uF 10V Ceramic Capacitor	GRM033R61A104ME15D
C8	.47uF 50V Ceramic Capacitor	GRM155R61H474KE11D
C9	10nF 16V Ceramic Capacitor	C0402C103K4RECAUTO
C10	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C11	100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS
C12	100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS
C13	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C14	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C15	4.7 uF 35V Ceramic Capacitor	GRM219R6YA475KA73D
C16	10nF 16V Ceramic Capacitor	C0402C103K4RECAUTO
C17	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C18	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C19	4.7 uF 35V Ceramic Capacitor	GRM219R6YA475KA73D
C20	.47uF 50V Ceramic Capacitor	GRM155R61H474KE11D
C21	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C22	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C23	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C24	.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D
C25	1uF 10V Ceramic Capacitor	CL10A105KP8NNNC
C26	100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS
FB1	1.5k Ferrite Bead	MMZ2012Y152BT000
FB2	1.5k Ferrite Bead	MMZ2012Y152BT000
J1	Screw Terminal	282837-2
J2	Screw Terminal	282837-4
J3	Screw Terminal	282837-4
J4	Screw Terminal	282837-2
J5	Screw Terminal	282837-2
J6	Screw Terminal	282837-3
R1	5.1k 1% Resistor	MBB02070C5101FCT00
R2	5.1k 1% Resistor	MBB02070C5101FCT00

Table 20: Components list for complete PCB schematic included above Continued

Ref Des	Description	P/N
R3	5.1k 1% Resistor	MBB02070C5101FCT00
R4	5.1k 1% Resistor	MBB02070C5101FCT00
R5	10k 5% Resistor	RC0603JR-0710KL
R6	1.5k .1% Resistor	ERA-2AEB152X
R7	100m 5% Resistor	CHV2512-JW-107ELF
R8	100m 5% Resistor	CHV2512-JW-107ELF
R9	10k 5% Resistor	RC0603JR-0710KL
R10	10k 5% Resistor	RC0603JR-0710KL
R11	10k 5% Resistor	RC0603JR-0710KL
R12	10k 5% Resistor	RC0603JR-0710KL
R13	10k 5% Resistor	RC0603JR-0710KL
R14	10k 5% Resistor	RC0603JR-0710KL
R15	1.5k .1% Resistor	ERA-2AEB152X
R16	100m 5% Resistor	CHV2512-JW-107ELF
R17	100m 5% Resistor	CHV2512-JW-107ELF
RV1	10k Potentiometer	23BR10KLFTR
RV2	10k Potentiometer	23BR10KLFTR
SW1	SPST .3A 12V Switch	50-0014-00
U1	ESP32 Microprocessor	ESP32-WROOM-32D
U2	Stepper motor driver	DRV8825PPWR
U3	Stepper motor driver	DRV8825PPWR
U4	Voltage Regulator	LM7805
U5	LDO voltage regulator	LM1117-3.3
U6	Analog to Digital Converter	ADS1115IDGS

PCB & Prototype Breadboard Connection Definitions:

The following table is the pin definition for both the breadboard and PCB schematics:

Table 21: Breadboard & PCB schematic connection definitions

Pin	Definition
J1	The power input to the breadboard
J2	The connection to M1, which is the motor for the inner damper shaft on a double damper terminal unit. This will also act as the connection to the stepper motor on a single damper terminal unit.
J3	The connection to M2, which is the motor for the outer damper shaft on a double damper terminal unit. This will NOT be connected when using the breadboard on a single damper terminal unit.
J4	The analog 0-10vdc signal input for the inner stepper motor, M1. This also controls the stepper motor on a single damper terminal unit.

Table 21: Breadboard & PCB schematic connection definitions Continued

Pin	Definition
J5	The analog 0-10vdc signal input for the outer stepper motor, M2. This connection will NOT be used when working with a single damper terminal unit.
J6	The potentiometer connections

The prototype and PCB shown above have all of the same and use very similar components. The main difference between the PCB and breadboard are as follows:

- The PCB uses surface mount resistors and capacitors to make the overall size smaller while the breadboard uses through hole components that are easier to solder.
- The breadboard uses Devkit boards to achieve the same results as the PCB
- The PCB has all unecessary components that are included on the dev boards removed; This includes the programming USB and USB controller.

Motor Specifications & Torque Graph

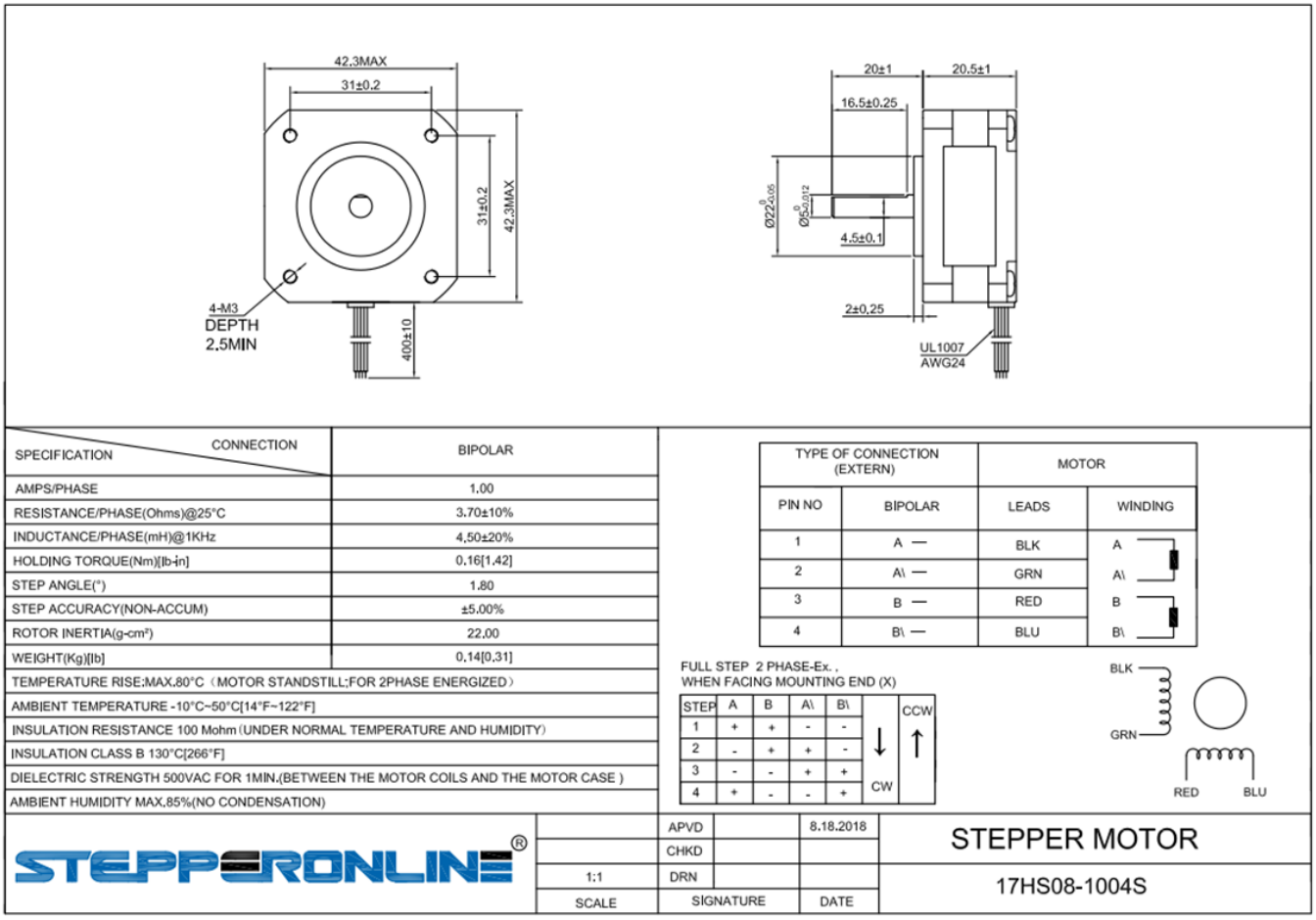


Figure 14: Specifications and dimensions of the 17HS08-1004S stepper motor

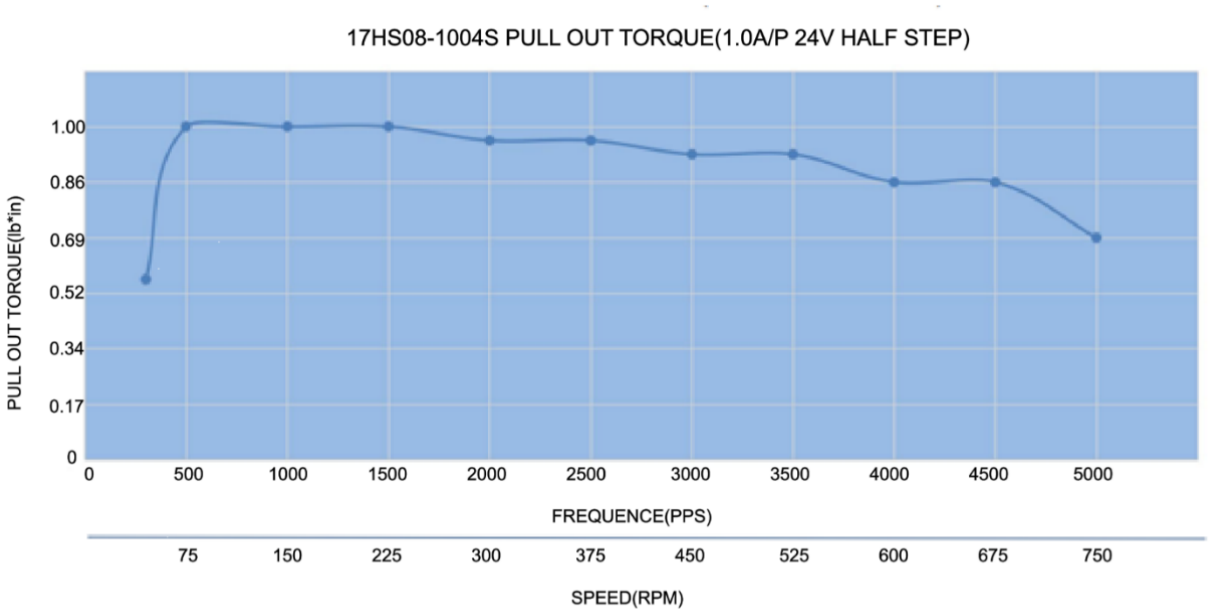


Figure 15: Pull out torque curve for the 17HS08-1004S stepper motor



Features

- Essentially infinite resolution
- Excellent rotational life
- High quality, rugged construction
- General purpose applications
- Non-standard features available
- Cost and space saving

6539/6639 - Precision Potentiometer

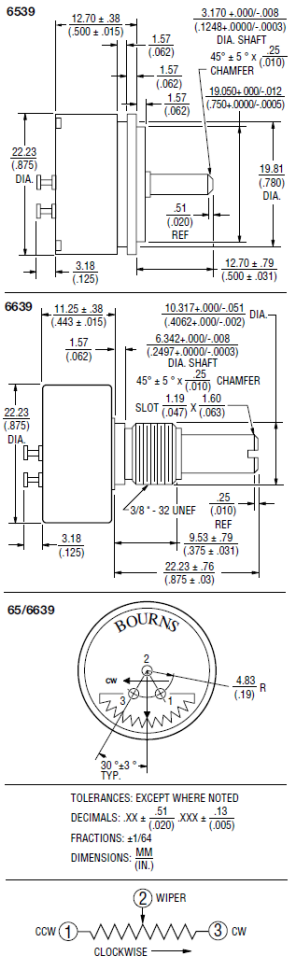
Electrical Characteristics[1]	6539 Servo Mount	6639 Bushing Mount
Standard Resistance Range	1 K to 100 K ohms	1 K to 100 K ohms
Total Resistance Tolerance	±15 %	±15 %
Independent Linearity	±2.0 %	±2.0 %
Effective Electrical Angle	340 ° +3 °	340 ° +3 °
End Voltage	0.5 % maximum	0.5 % maximum
Output Smoothness	0.1 %	0.1 %
Dielectric Withstanding Voltage (MIL-STD-202, Method 301)		
Sea Level	750 VAC minimum	750 VAC minimum
Power Rating (Voltage Limited By Power Dissipation or 300 VAC, Whichever is Less)		
+70 °C	1.0 watt	1.0 watt
+125 °C	0 watt	0 watt
Insulation Resistance (500 VDC)	500 megohms minimum	500 megohms minimum
Resolution	Essentially infinite	Essentially infinite

Environmental Characteristics[1]		
Operating Temperature Range	+1 °C to +125 °C	-40 °C to +125 °C
Storage Temperature Range	-65 °C to +125 °C	-65 °C to +125 °C
Temperature Coefficient		
Over Storage Temperature Range	±500 ppm/°C maximum	±500 ppm/°C maximum
Vibration	15 G	15 G
Wiper Bounce	0.1 millisecond maximum	0.1 millisecond maximum
Total Resistance Shift	±10 %	±10 %
Voltage Ratio Shift	±0.5 %	±0.5 %
Shock	50 G	50 G
Wiper Bounce	0.1 millisecond maximum	0.1 millisecond maximum
Total Resistance Shift	±5 %	±5 %
Voltage Ratio Shift	±0.5 %	±0.5 %
Load Life	1,000 hours, 1 watt	1,000 hours, 1 watt
Total Resistance Shift	±10 %	±10 %
Rotational Life (No Load)	10,000,000 shaft revolutions	10,000,000 shaft revolutions
Total Resistance Shift	±10 % maximum	±10 % maximum
Moisture Resistance (MIL-STD-202, Method 106)		
Total Resistance Shift	±15 %	±15 %
IP Rating	IP 40	IP 40

Mechanical Characteristics[1]	
Mechanical Angle	Continuous, Stops (340 ° +8 °, -0 °) available
Stop Strength (applies to -301 with mechanical stops only)	22.6 N-cm (2 lb.-in.)
Torque (Starting & Running)[2]	0.40 N-cm (0.5 oz.-in.) max.
Mounting	170-200 N-cm (15-18 lb.-in.) maximum
Shaft Runout	0.13 mm (0.005 in.) T.I.R.
Lateral Runout	0.08 mm (0.003 in.) T.I.R.
Shaft End Play	0.13 mm (0.005 in.) T.I.R.
Shaft Radial Play	0.13 mm (0.005 in.) T.I.R.
Pilot Diameter Runout	0.06 mm (0.0025 in.) T.I.R.
Backlash	0.1 ° maximum
Weight	18 gm (6539 Servo Mount), 24 gm (6639 Bushing Mount)
Terminals	Rear Turret Type
Soldering Condition	
Manual Soldering	96.5Sn/3.0Ag/0.5Cu solid wire or no-clean rosin cored wire 370 °C (700 °F) max. for 3 seconds
Wave Soldering	96.5Sn/3.0Ag/0.5Cu solder with no-clean flux 260 °C (500 °F) max. for 5 seconds
Wash processes	Not recommended
Marking	Manufacturer's name and part number, resistance value and tolerance, linearity tolerance, wiring diagram, and date code.
Ganging (Multiple Section Pots)	1 cup maximum
Hardware (6639 only)	One lockwasher (H-37-2) and one mounting nut (H-38-2) is shipped with potentiometer.

[1]At room ambient: +25 °C nominal and 50 % relative humidity nominal, except as noted.
[2]2.82 N-cm (4.0 oz.-in.) max. at -40 °C.

Product Dimensions



WARNING Cancer and Reproductive Harm - www.P65Warnings.ca.gov

*RoHS Directive 2015/863, Mar 31, 2015 and Annex.
Specifications are subject to change without notice.
Users should verify actual device performance in their specific applications.
The products described herein and this document are subject to specific legal disclaimers as set forth on the last page of this document, and at www.bourns.com/docs/legal/disclaimer.pdf.

Figure 16: Bourns potentiometer specifications sheet

6539/6639 - Precision Potentiometer

BOURNS®

Recommended Part Numbers

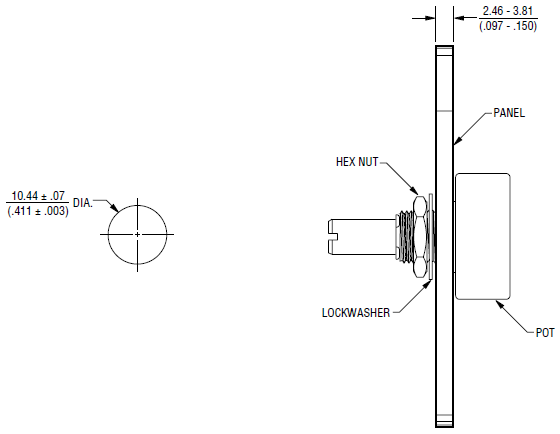
Part Number	Resistance (Ω)
6539S-1-102	1,000
6539S-1-502	5,000
6539S-1-103	10,000

BOLDFACE LISTINGS ARE IN STOCK AND READILY AVAILABLE THROUGH DISTRIBUTION.
FOR OTHER OPTIONS CONSULT FACTORY.

Part Number	Mechanical Stop	A/R Lug	Shaft
6639S-1-RC	No	No	Slotted
6639S-2-RC	No	No	Flatted
6639S-3-RC	No	Yes	Slotted
6639S-4-RC	No	Yes	Flatted
6639S-5-RC	Yes	Yes	Slotted
6639S-6-RC	Yes	Yes	Flatted
6639S-7-RC	Yes	No	Slotted
6639S-8-RC	Yes	No	Flatted

Panel Thickness Dimensions

(For Bushing Mount Only)



Panel thickness and hole diameters are recommended for best fit. However, customers may adjust the dimensions to suit their specific application.

DIMENSIONS: MM / (INCHES) TOLERANCES: ± 0.127 / (.005)

REV. 10/19
Specifications are subject to change without notice.
Users should verify actual device performance in their specific applications.
The products described herein and this document are subject to specific legal disclaimers as set forth on the last page of this document, and at www.bourns.com/docs/legal/disclaimer.pdf.

Figure 17: Bourns potentiometer specifications sheet continued

Appendix V

Design of experiments, experimental procedures, and results

User manual

Setup

1. Attach the actuator using the standoffs to the HVAC terminal unit. Make sure to tighten the clamps tightly to the damper shafts to ensure no slipping will occur.

Single Damper Operation

1. Power on the board by applying a 12/24VDC input to connector J1
2. Apply a 0-10VDC signal to the input J4 to move the damper. The value corresponds to the angle of the shaft, divided by 10. For example, 1.8volts at the connector J4 is equivalent to 18 degrees at the damper shaft and 9 volts is equivalent to 90 degrees.The resolution of the damper shaft is .5 degrees, meaning every 50mV adjustments at J4 will cause the system to move.

Double Damper Operation

1. Power on the board by applying a 12/24VDC input to connector J1
2. Apply a 0-10VDC signal to the input J4 to move the inner damper and apply a 0-10VDC signal to J5 to move the outer damper. The value corresponds to the angle of the shaft, divided by 10. For example, 1.8volts at the connector J5/J4 is equivalent to 18 degrees at the damper shaft and 9 volts is equivalent to 90 degrees. The resolution of the damper shaft is .5 degrees, meaning every 50mV adjustments at J5 or J4 will cause the system to move.
3. Due to the design of the terminal unit, the program will not allow the outer damper to move further than the inner damper, however, they the dampers are allowed to be at the same angle.

Safety

1. When making connections to the PCB board, ensure the board is not connected to power.
2. Ensure the actuator housing is properly installed before powering the board and moving the dampers.

Equipment setup for testing

The following table lists the laboratory equipment used during testing.

Table 22: Bench laboratory equipment used in this laboratory experiment.

Manufacturer	Model No.	Description
KeySight	E36600	DC Power Supply
Neiko	03727A	Analog Torque Wrench
GenRed	82413	Digital Protractor
HVAC MFG.	N/A	12in Dual Blade Round Terminal Unit

ESP32 On-Board Analog to Digital Converter Test

The original design for the circuit board of the actuator was to use the on-board ESP32 analog to digital converter (ADC) to read the 0-10vdc signal that adjusts the damper position. During testing, the team was able to identify this as an issue due to the accuracy of the on-board ADC. See the following table and figure below for the results of the testing done on the on-board ESP32 analog to digital converter.

Table 23: ESP32 on-board Analog to digital converter readings found during testing

Test No.	0-10vdc value	Voltage Reading at ESP32 On-Board ADC	Calculated value by program
1	0.10	0.02	0.06
2	0.50	0.13	0.41
3	1.00	0.29	0.91
4	2.00	0.52	1.63
5	3.00	0.82	2.56
6	5.00	1.45	4.53
7	6.00	1.79	5.59
8	7.00	2.14	6.69
9	9.00	2.80	8.75
10	10.00	3.14	9.81

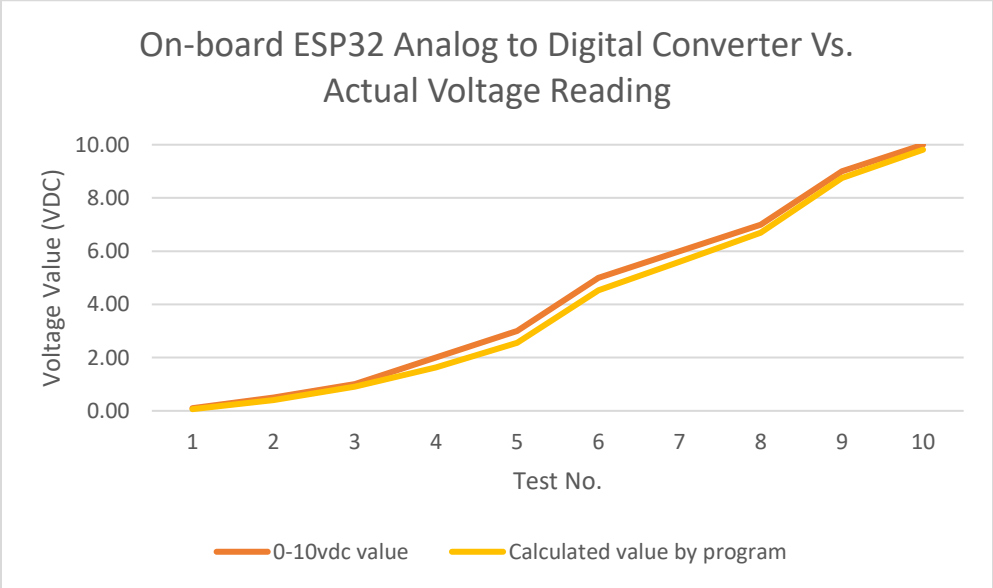


Figure 18: ESP32 ADC Vs. Actual Voltage reading

This issue seems to be generated due to the non-linear aspects and calibration needed for the on-board ADC, as well as the use of a voltage divider to adjust the voltage down to less than 3.3 volts. Given that the team needs 50mV step sizes, accuracy needs to be at the bare minimum no greater than +-25mV so the program can correctly interpret the electrical steps. After discussing this issue as a team and doing research, the use of an external ADC with greater accuracy, a linear digital response, and the ability to read higher voltages was the solution. The table and figure below show the data found by the

team during testing for the ADS1115 external ADC; Note that the differences are so minimal that they can barely be seen on the graph.

ADS1115 Analog to Digital Converter Test

Table 24: ADS1115 External Analog to Digital converter readings found during testing

Test No.	0-10vdc Set value	Actual 0-10vdc value read by multimeter	Voltage Reading at ADS1115 External ADC (after voltage divider)	Calculated value by program
1	0.10	0.09	0.048	0.096
2	0.50	0.51	0.247	0.494
3	1.00	0.99	0.501	1.002
4	2.00	1.99	0.997	1.994
5	3.00	3.01	1.502	3.004
6	5.00	4.99	2.498	4.996
7	6.00	5.99	2.999	5.998
8	7.00	6.99	3.499	6.998
9	9.00	9.01	4.503	9.006
10	10.00	9.99	5.001	10.002

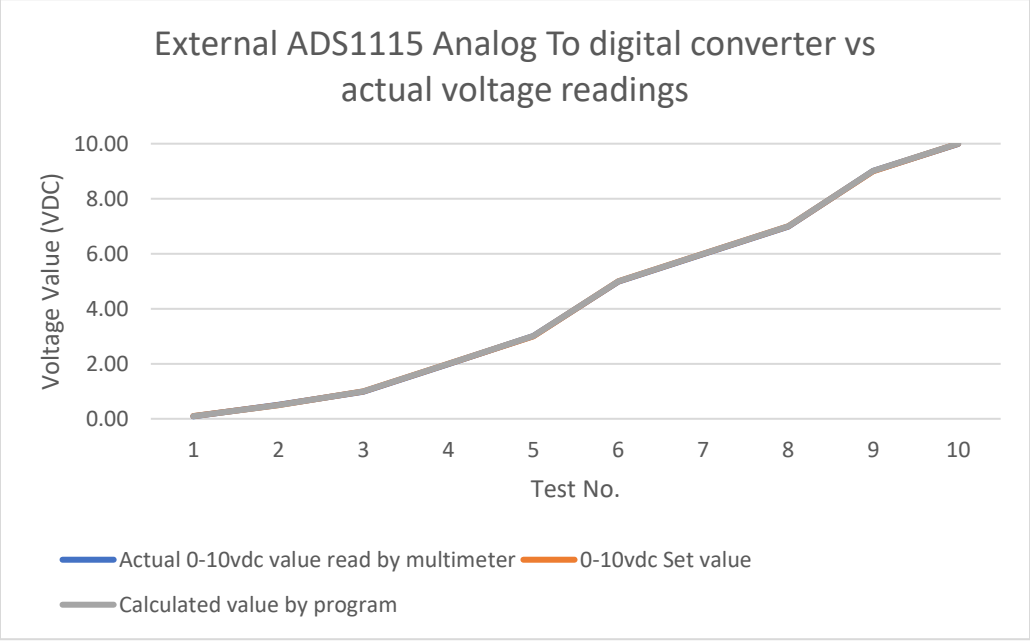


Figure 19: Graph showing the difference between the external ADC readings, and the actual measured voltage

When looking at the table and figure above, the values read by the external ADC were always within +- 6mV of the set 0-10VDC signal on the DC power supply. Given the need for a 0.5 degree of resolution, the team used a 50mV electrical step size which gives 200 individual steps between 0-10V. This allows for the first 180 steps to move the damper shafts from 0-90 degrees, and leaves the last 20 steps for other functions, such as a reset. Since the electrical step size is 50mV, having an inaccuracy of

+-6mV is not an issue, and can easily be adjusted for by the programming of the ESP32 Microprocessor. The accuracy of the 0-10vdc signal is also shown in above mentioned table and graph and shows that the signal is accurate down to the 10mV range. This leaves the possibility that the inaccuracy is simply due to the power supply. In either case, as long as the power supply and external ADC are accurate to the +-25mV, the program will be able to distinguish between each electrical step.

Detailed Testing Data

Table 25: Test 1 Experimental Data

Theoretical Input Voltage (V)	Theoretical Theoretical Angle (deg)	Measured Measured Angle (deg)	Calculated Difference (deg)	Calculated Potentiometer Reading Difference (V)
0.1	1	0.30	-0.70	0.01509
0.2	2	1.50	-0.50	0.01341
0.3	3	1.90	-1.10	0.01444
0.4	4	3.10	-0.90	0.01462
0.5	5	4.10	-0.90	0.00901
0.6	6	5.05	-0.95	0.02193
0.7	7	6.05	-0.95	0.01069
0.8	8	7.05	-0.95	0.01931
0.9	9	8.05	-0.95	0.01107
1.0	10	9.05	-0.95	0.01181
1.1	11	10.00	-1.00	0.01594
1.2	12	10.95	-1.05	0.01106
1.3	13	11.95	-1.05	0.01312
1.4	14	12.95	-1.05	0.01744
1.5	15	14.00	-1.00	0.01406
1.6	16	15.05	-0.95	0.01088
1.7	17	16.00	-1.00	0.01443
1.8	18	17.00	-1.00	0.01688
1.9	19	17.95	-1.05	0.0105
2.0	20	18.90	-1.10	0.01744
2.1	21	19.90	-1.10	0.01331
2.2	22	20.90	-1.10	0.01312
2.3	23	21.90	-1.10	0.01275
2.4	24	22.90	-1.10	0.0165
2.5	25	23.90	-1.10	0.01482
2.6	26	24.90	-1.10	0.01575
2.7	27	25.90	-1.10	0.01162
2.8	28	26.80	-1.20	0.01444
2.9	29	27.80	-1.20	0.021
3.0	30	28.35	-1.65	0.01181

Table 25: Test 1 Experimental Data Continued

Theoretical Input Voltage (V)	Theoretical Theoretical Angle (deg)	Measured Measured Angle (deg)	Calculated Difference (deg)	Calculated Potentiometer Reading Difference (V)
3.1	31	29.45	-1.55	0.01519
3.2	32	30.55	-1.45	0.01163
3.3	33	31.50	-1.50	0.01181
3.4	34	32.55	-1.45	0.01706
3.5	35	33.60	-1.40	0.01931
3.6	36	34.70	-1.30	0.00469
3.7	37	35.70	-1.30	0.01931
3.8	38	36.80	-1.20	0.01069
3.9	39	37.80	-1.20	0.01594
4.0	40	38.85	-1.15	0.0135
4.1	41	39.70	-1.30	0.01762
4.2	42	40.60	-1.40	0.01013
4.3	43	41.45	-1.55	0.018
4.4	44	42.50	-1.50	0.01144
4.5	45	43.30	-1.70	0.01556
4.6	46	44.25	-1.75	0.01481
4.7	47	45.40	-1.60	0.01462
4.8	48	46.10	-1.90	0.0135
4.9	49	47.05	-1.95	0.01594
5.0	50	48.20	-1.80	0.01331
5.1	51	49.05	-1.95	0.01426
5.2	52	50.20	-1.80	0.01443
5.3	53	51.20	-1.80	0.012
5.4	54	52.40	-1.60	0.01838
5.5	55	53.45	-1.55	0.01256
5.6	56	54.40	-1.60	0.01931
5.7	57	55.50	-1.50	0.01069
5.8	58	56.30	-1.70	0.01519
5.9	59	57.40	-1.60	0.01519
6.0	60	58.50	-1.50	0.0135
6.1	61	59.20	-1.80	0.0135
6.2	62	60.00	-2.00	0.01537
6.3	63	61.30	-1.70	0.015
6.4	64	62.30	-1.70	0.01444
6.5	65	62.95	-2.05	0.01369
6.6	66	64.40	-1.60	0.01724
6.7	67	65.45	-1.55	0.01275
6.8	68	66.40	-1.60	0.01219

Table 25: Test 1 Experimental Data Continued

Theoretical	Theoretical	Measured	Calculated	Calculated
Input Voltage (V)	Theoretical Angle (deg)	Measured Angle (deg)	Difference (deg)	Potentiometer Reading Difference (V)
6.9	69	67.35	-1.65	0.01388
7.0	70	68.45	-1.55	0.01593
7.1	71	69.50	-1.50	0.01519
7.2	72	70.40	-1.60	0.01557
7.3	73	71.35	-1.65	0.01349
7.4	74	72.35	-1.65	0.01482
7.5	75	73.25	-1.75	0.01144
7.6	76	74.40	-1.60	0.01631
7.7	77	75.50	-1.50	0.01669
7.8	78	76.60	-1.40	0.01162
7.9	79	77.55	-1.45	0.01031
8.0	80	78.40	-1.60	0.02381
8.1	81	79.35	-1.65	0.00863
8.2	82	80.45	-1.55	0.018
8.3	83	81.10	-1.90	0.01238
8.4	84	82.10	-1.90	0.01762
8.5	85	82.80	-2.20	0.01275
8.6	86	84.00	-2.00	0.01894
8.7	87	84.95	-2.05	0.01181
8.8	88	85.80	-2.20	0.01594
8.9	89	87.00	-2.00	0.01612
9.0	90	88.30	-1.70	N/A
		avg step size (deg)	avg error (deg)	average pot difference per degree (V)
		0.99	1.44	0.014418539
		standard deviation		
		0.16		

Table 26: Test 2 Experimental Data

Theoretical Input Voltage (V)	Theoretical Theoretical Angle (deg)	Measured Measured Adjusted Angle (deg)	Calculated Adjusted Angle Difference (deg)	Calculated Improvement with Pot Feedback (deg)
0.1	1	1.20	0.20	0.50
0.2	2	2.10	0.10	0.40
0.3	3	3.20	0.20	0.90
0.4	4	4.25	0.25	0.65
0.5	5	5.10	0.10	0.80
0.6	6	6.25	0.25	0.70
0.7	7	7.25	0.25	0.70
0.8	8	8.35	0.35	0.60
0.9	9	9.30	0.30	0.65
1.0	10	10.30	0.30	0.65
1.1	11	11.40	0.40	0.60
1.2	12	12.35	0.35	0.70
1.3	13	13.35	0.35	0.70
1.4	14	14.40	0.40	0.65
1.5	15	15.35	0.35	0.65
1.6	16	16.30	0.30	0.65
1.7	17	17.30	0.30	0.70
1.8	18	18.30	0.30	0.70
1.9	19	19.35	0.35	0.70
2.0	20	20.50	0.50	0.60
2.1	21	21.50	0.50	0.60
2.2	22	22.40	0.40	0.70
2.3	23	23.30	0.30	0.80
2.4	24	24.50	0.50	0.60
2.5	25	25.40	0.40	0.70
2.6	26	26.45	0.45	0.65
2.7	27	27.60	0.60	0.50
2.8	28	28.60	0.60	0.60
2.9	29	28.85	-0.15	1.05
3.0	30	29.45	-0.55	1.10
3.1	31	30.80	-0.20	1.35
3.2	32	31.95	-0.05	1.40
3.3	33	32.95	-0.05	1.45
3.4	34	33.90	-0.10	1.35
3.5	35	35.00	0.00	1.40
3.6	36	35.95	-0.05	1.25

Table 26: Test 2 Experimental Data Continued

Theoretical Input Voltage (V)	Theoretical Theoretical Angle (deg)	Measured Measured Adjusted Angle (deg)	Calculated Adjusted Angle Difference (deg)	Calculated Improvement with Pot Feedback (deg)
3.7	37	37.15	0.15	1.15
3.8	38	38.25	0.25	0.95
3.9	39	39.25	0.25	0.95
4.0	40	40.30	0.30	0.85
4.1	41	41.35	0.35	0.95
4.2	42	42.40	0.40	1.00
4.3	43	43.35	0.35	1.20
4.4	44	44.35	0.35	1.15
4.5	45	45.55	0.55	1.15
4.6	46	46.50	0.50	1.25
4.7	47	47.60	0.60	1.00
4.8	48	48.75	0.75	1.15
4.9	49	49.85	0.85	1.10
5.0	50	50.95	0.95	0.85
5.1	51	51.95	0.95	1.00
5.2	52	52.95	0.95	0.85
5.3	53	53.90	0.90	0.90
5.4	54	55.05	1.05	0.55
5.5	55	55.85	0.85	0.70
5.6	56	56.70	0.70	0.90
5.7	57	57.70	0.70	0.80
5.8	58	58.75	0.75	0.95
5.9	59	59.75	0.75	0.85
6.0	60	60.60	0.60	0.90
6.1	61	61.70	0.70	1.10
6.2	62	62.70	0.70	1.30
6.3	63	63.70	0.70	1.00
6.4	64	64.85	0.85	0.85
6.5	65	65.90	0.90	1.15
6.6	66	66.90	0.90	0.70
6.7	67	67.90	0.90	0.65
6.8	68	68.90	0.90	0.70
6.9	69	69.85	0.85	0.80
7.0	70	70.80	0.80	0.75
7.1	71	71.75	0.75	0.75
7.2	72	72.65	0.65	0.95

Table 26: Test 2 Experimental Data Continued

Theoretical	Theoretical	Measured	Calculated	Calculated
Input Voltage (V)	Theoretical Angle (deg)	Measured Adjusted Angle (deg)	Adjusted Angle Difference (deg)	Improvement with Pot Feedback (deg)
7.3	73	73.55	0.55	1.10
7.4	74	74.45	0.45	1.20
7.5	75	75.70	0.70	1.05
7.6	76	76.65	0.65	0.95
7.7	77	77.65	0.65	0.85
7.8	78	78.35	0.35	1.05
7.9	79	79.35	0.35	1.10
8.0	80	80.25	0.25	1.35
8.1	81	81.15	0.15	1.50
8.2	82	82.20	0.20	1.35
8.3	83	83.40	0.40	1.50
8.4	84	84.35	0.35	1.55
8.5	85	85.30	0.30	1.90
8.6	86	86.40	0.40	1.60
8.7	87	87.75	0.75	1.30
8.8	88	88.60	0.60	1.60
8.9	89	89.70	0.70	1.30
9.0	90	90.65	0.65	1.05
		avg step size (deg)	avg error (deg)	avg improvement (deg)
		1.01	0.485	0.953333333
		standard deviation		
		0.14		

Table 27: Test 3 Experimental Data

Theoretical Input Voltage (V)	Theoretical Theoretical Angle (deg)	Measured Inner Measured Angle (deg)	Calculated Inner difference from Theoretical (deg)	Measured Outer Measured Angle (deg)	Calculated Outer difference from Theoretical (deg)
0.1	1	1.35	0.35	0.10	-0.90
0.2	2	2.30	0.30	0.10	-1.90
0.3	3	3.35	0.35	0.15	-2.85
0.4	4	4.30	0.30	0.75	-3.25
0.5	5	5.20	0.20	1.15	-3.85
0.6	6	6.20	0.20	2.00	-4.00
0.7	7	7.25	0.25	2.95	-4.05
0.8	8	8.25	0.25	3.55	-4.45
0.9	9	9.20	0.20	4.45	-4.55
1.0	10	10.30	0.30	5.45	-4.55
1.1	11	11.25	0.25	6.45	-4.55
1.2	12	12.25	0.25	7.50	-4.50
1.3	13	13.35	0.35	8.55	-4.45
1.4	14	14.35	0.35	9.55	-4.45
1.5	15	15.30	0.30	13.20	-1.80
1.6	16	16.30	0.30	14.15	-1.85
1.7	17	17.20	0.20	15.15	-1.85
1.8	18	18.20	0.20	16.20	-1.80
1.9	19	19.25	0.25	17.20	-1.80
2.0	20	20.25	0.25	18.20	-1.80
2.1	21	21.25	0.25	19.25	-1.75
2.2	22	22.25	0.25	20.30	-1.70
2.3	23	23.20	0.20	21.30	-1.70
2.4	24	24.25	0.25	22.40	-1.60
2.5	25	25.25	0.25	23.35	-1.65
2.6	26	26.25	0.25	24.40	-1.60
2.7	27	27.20	0.20	25.40	-1.60
2.8	28	28.20	0.20	26.45	-1.55
2.9	29	29.25	0.25	27.50	-1.50
3.0	30	30.15	0.15	28.55	-1.45
3.1	31	31.10	0.10	29.65	-1.35
3.2	32	32.15	0.15	30.65	-1.35
3.3	33	33.10	0.10	31.75	-1.25
3.4	34	34.05	0.05	32.70	-1.30
3.5	35	35.00	0.00	33.75	-1.25

Table 27: Test 3 Experimental Data Continued

Theoretical	Theoretical	Measured	Calculated	Measured	Calculated
Input Voltage (V)	Theoretical Angle (deg)	Inner Measured Angle (deg)	Inner difference from Theoretical (deg)	Outer Measured Angle (deg)	Outer difference from Theoretical (deg)
3.6	36	36.15	0.15	34.70	-1.30
3.7	37	37.10	0.10	35.70	-1.30
3.8	38	38.00	0.00	36.80	-1.20
3.9	39	39.00	0.00	37.75	-1.25
4.0	40	40.00	0.00	38.90	-1.10
4.1	41	41.20	0.20	39.85	-1.15
4.2	42	42.30	0.30	40.85	-1.15
4.3	43	43.00	0.00	41.90	-1.10
4.4	44	44.10	0.10	42.90	-1.10
4.5	45	45.05	0.05	44.00	-1.00
4.6	46	46.15	0.15	44.85	-1.15
4.7	47	47.25	0.25	45.95	-1.05
4.8	48	48.30	0.30	46.85	-1.15
4.9	49	49.45	0.45	47.85	-1.15
5.0	50	50.45	0.45	48.90	-1.10
5.1	51	51.45	0.45	49.80	-1.20
5.2	52	52.20	0.20	50.90	-1.10
5.3	53	53.30	0.30	51.85	-1.15
5.4	54	54.00	0.00	52.85	-1.15
5.5	55	55.10	0.10	53.80	-1.20
5.6	56	56.20	0.20	54.65	-1.35
5.7	57	57.30	0.30	55.70	-1.30
5.8	58	58.15	0.15	56.70	-1.30
5.9	59	59.05	0.05	57.70	-1.30
6.0	60	60.00	0.00	58.65	-1.35
6.1	61	61.15	0.15	59.60	-1.40
6.2	62	62.10	0.10	60.65	-1.35
6.3	63	63.10	0.10	61.70	-1.30
6.4	64	64.10	0.10	62.90	-1.10
6.5	65	65.15	0.15	63.85	-1.15
6.6	66	66.15	0.15	64.90	-1.10
6.7	67	67.20	0.20	65.90	-1.10
6.8	68	68.30	0.30	67.00	-1.00
6.9	69	69.10	0.10	68.00	-1.00
7.0	70	70.25	0.25	69.15	-0.85
7.1	71	71.00	0.00	70.15	-0.85

Table 27: Test 3 Experimental Data Continued

Theoretical	Theoretical	Measured	Calculated	Measured	Calculated
Input Voltage (V)	Theoretical Angle (deg)	Inner Measured Angle (deg)	Inner difference from Theoretical (deg)	Outer Measured Angle (deg)	Outer difference from Theoretical (deg)
7.2	72	72.00	0.00	71.05	-0.95
7.3	73	72.95	-0.05	72.00	-1.00
7.4	74	74.05	0.05	73.00	-1.00
7.5	75	75.05	0.05	74.05	-0.95
7.6	76	76.00	0.00	75.00	-1.00
7.7	77	77.15	0.15	76.00	-1.00
7.8	78	78.00	0.00	77.10	-0.90
7.9	79	79.00	0.00	78.00	-1.00
8.0	80	80.65	0.65	79.00	-1.00
8.1	81	81.65	0.65	80.00	-1.00
8.2	82	82.20	0.20	81.05	-0.95
8.3	83	83.55	0.55	81.95	-1.05
8.4	84	84.70	0.70	83.00	-1.00
8.5	85	85.70	0.70	84.00	-1.00
8.6	86	N/A	N/A	84.95	-1.05
8.7	87	N/A	N/A	86.10	-0.90
8.8	88	N/A	N/A	87.10	-0.90
8.9	89	N/A	N/A	88.00	-1.00
9.0	90	N/A	N/A	89.10	-0.90
		avg step size (deg)	avg error	avg step size (deg)	avg error
		1.00	0.21	1.00	1.624444444
		standard deviation		standard deviation	
		0.14		0.34	
				avg step size (excluding gasket range)(deg)	
				1.01	
				sd (excluding the gasket range)	
				0.07	

HVAC Mfg. Testing Data

Included below is the testing data provided by the team from HVAC Mfg. after the company completed their initial testing.

Table 34: HVAC Mfg. Testing data for the 0-9VDC and 9-0VDC tests

Input	Reference Airflow Test 1	Reference Airflow Test 2	Calculated Airflow Test 1	Calculated Airflow Test 2	Coefficient Test 1	Coefficient Test 2	Avg Coefficient	New CFM 1	New CFM 2	% Different CFM 1	% Different CFM 2
0	0.6448	0.2372	0.0000	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1	0.8883	0.4651	0.3493	0.3479	2.5434	1.3371	1.9402	0.6776	0.6749	31.0873	31.0873
2	1.2349	0.7400	1.3938	1.3928	0.8860	0.5313	0.7086	0.9877	0.9870	25.0253	25.0253
3	1.4564	1.6322	3.1432	3.1317	0.4633	0.5212	0.4923	1.5473	1.5416	5.8778	5.8778
4	1.9964	2.2447	5.5823	5.5511	0.3576	0.4044	0.3810	2.1269	2.1150	6.1329	6.1329
5	2.1774	2.8108	8.7228	8.6432	0.2496	0.3252	0.2874	2.5071	2.4842	13.1479	13.1479
6	2.3751	3.2672	12.5548	12.4838	0.1892	0.2617	0.2254	2.8305	2.8144	16.0859	16.0859
7	3.0203	3.6570	17.3169	16.9070	0.1744	0.2163	0.1954	3.3830	3.3029	10.7213	10.7213
8	3.0686	4.1405	22.5859	22.3217	0.1359	0.1855	0.1607	3.6291	3.5866	15.4437	15.4437
9	3.8569	4.5738	28.4365	28.3273	0.1356	0.1615	0.1485	4.2241	4.2079	8.6946	8.6946
10	4.8102	5.3624	35.0118	34.7825	0.1374	0.1542	0.1458	5.1040	5.0706	5.7552	5.7552
11	6.1870	6.5357	42.0056	42.5816	0.1473	0.1535	0.1504	6.3172	6.4038	2.0599	2.0599
12	7.6579	7.6466	49.5115	50.3226	0.1547	0.1520	0.1533	7.5907	7.7150	0.8861	0.8861
13	9.4451	9.0599	58.4223	58.2632	0.1617	0.1555	0.1586	9.2649	9.2396	1.9450	1.9450
14	12.3714	10.8009	66.9157	67.8592	0.1849	0.1592	0.1720	11.5111	11.6734	7.4739	7.4739
15	15.7087	13.7148	76.5147	78.7773	0.2053	0.1741	0.1897	14.5148	14.9440	8.2253	8.2253
16	19.7459	16.8310	87.1833	89.1141	0.2265	0.1889	0.2077	18.1061	18.5071	9.0564	9.0564
17	23.8878	20.6932	98.4343	100.2814	0.2427	0.2064	0.2245	22.0999	22.5146	8.0900	8.0900
18	29.6856	24.9905	110.6328	112.9839	0.2683	0.2212	0.2448	27.0781	27.6535	9.6298	9.6298
19	33.9244	29.4789	123.0741	124.8662	0.2756	0.2361	0.2559	31.4901	31.9486	7.7303	7.7303
20	38.7491	34.4700	134.1950	138.5530	0.2888	0.2488	0.2688	36.0675	37.2387	7.4352	7.4352
21	46.4180	39.6404	150.0138	153.3264	0.3094	0.2585	0.2840	42.6010	43.5417	8.9599	8.9599
22	52.0728	47.6533	164.4830	165.2626	0.3166	0.2883	0.3025	49.7507	49.9865	4.6677	4.6677
23	69.4772	60.9229	180.2363	183.2067	0.3855	0.3325	0.3590	64.7062	65.7726	7.3734	7.3734
24	76.1806	69.5774	195.2500	198.9956	0.3902	0.3496	0.3699	72.2242	73.6097	5.4780	5.4780
25	89.0198	77.9504	213.3187	214.7679	0.4173	0.3630	0.3901	83.2221	83.7875	6.9666	6.9666
26	98.3512	88.2743	229.5809	229.6073	0.4284	0.3845	0.4064	93.3077	93.3184	5.4053	5.4053
27	109.7346	98.9102	247.7274	249.7293	0.4430	0.3961	0.4195	103.9259	104.7658	5.5892	5.5892
28	122.2882	110.2478	268.2803	270.5383	0.4558	0.4075	0.4317	115.8079	116.7826	5.5957	5.5957
29	132.1151	122.2842	281.6517	285.4577	0.4691	0.4284	0.4487	126.3845	128.0923	4.5343	4.5343
30	144.1117	137.0919	302.2863	312.9746	0.4767	0.4380	0.4574	138.2609	143.1496	4.2317	4.2317
31	159.2725	146.2778	326.7733	327.8757	0.4874	0.4461	0.4668	152.5292	153.0438	4.4210	4.4210
32	169.9727	155.5214	342.2725	348.9534	0.4966	0.4457	0.4711	161.2583	164.4060	5.4040	5.4040
33	188.2865	169.6352	368.1477	369.9462	0.5114	0.4585	0.4850	178.5485	179.4207	5.4540	5.4540
34	203.2493	186.5693	389.2590	392.0291	0.5221	0.4759	0.4990	194.2501	195.6325	4.6328	4.6328
35	213.3215	200.5795	411.5244	414.7667	0.5184	0.4836	0.5010	206.1665	207.7908	3.4705	3.4705
36	233.6085	215.0835	435.8987	439.4118	0.5359	0.4895	0.5127	223.4862	225.2874	4.5293	4.5293

Table 34: HVAC Mfg. Testing data for the 0-9VDC and 9-0VDC tests Continued

37	243.9243	236.1499	453.6965	462.7347	0.5376	0.5103	0.5240	237.7309	242.4667	2.6052	2.6052
38	266.5820	247.5915	482.7603	484.5450	0.5522	0.5110	0.5316	256.6308	257.5795	3.8776	3.8776
39	286.1823	274.4108	511.0861	518.3951	0.5599	0.5293	0.5446	278.3621	282.3429	2.8094	2.8094
40	301.4355	287.5483	534.1370	542.6240	0.5643	0.5299	0.5471	292.2432	296.8867	3.1454	3.1454
41	318.9886	302.4251	559.4093	566.9596	0.5702	0.5334	0.5518	308.6931	312.8596	3.3352	3.3352
42	335.5867	318.7332	583.1722	591.8016	0.5755	0.5386	0.5570	324.8361	329.6429	3.3095	3.3095
43	347.7694	340.8285	597.9716	622.5598	0.5816	0.5475	0.5645	337.5684	351.4490	3.0219	3.0219
42	335.5867	318.7332	583.1722	591.8016	0.5755	0.5386	0.5570	324.8361	329.6429	3.3095	3.3095
43	347.7694	340.8285	597.9716	622.5598	0.5816	0.5475	0.5645	337.5684	351.4490	3.0219	3.0219
44	364.6778	356.8542	629.9596	651.2316	0.5789	0.5480	0.5634	354.9378	366.9231	2.7441	2.7441
45	385.4302	377.9205	664.3443	673.2242	0.5802	0.5614	0.5708	379.1829	384.2513	1.6476	1.6476
46	408.3062	389.4913	693.1518	703.9377	0.5891	0.5533	0.5712	395.9148	402.0755	3.1298	3.1298
47	432.7384	415.1932	720.9484	739.7921	0.6002	0.5612	0.5807	418.6780	429.6211	3.3583	3.3583
48	448.4945	439.5817	749.4904	772.5619	0.5984	0.5690	0.5837	437.4744	450.9411	2.5190	2.5190
49	473.3589	455.6669	781.4271	795.2017	0.6058	0.5730	0.5894	460.5663	468.6850	2.7776	2.7776
50	499.9913	478.6574	817.9001	828.2327	0.6113	0.5779	0.5946	486.3386	492.4825	2.8072	2.8072
51	514.0879	498.2992	836.9274	851.5092	0.6143	0.5852	0.5997	501.9270	510.6721	2.4228	2.4228
52	537.8624	515.4397	871.4946	877.3441	0.6172	0.5875	0.6023	524.9327	528.4561	2.4631	2.4631
53	565.9514	535.4665	908.6407	904.8909	0.6229	0.5917	0.6073	551.8184	549.5412	2.5612	2.5612
54	590.5339	563.1436	928.8234	943.6613	0.6358	0.5968	0.6163	572.4114	581.5556	3.1660	3.1660
55	624.4027	588.7237	972.0093	973.9274	0.6424	0.6045	0.6234	605.9835	607.1793	3.0396	3.0396
56	645.5513	621.4644	1006.8077	1021.2707	0.6412	0.6085	0.6249	629.1073	638.1446	2.6139	2.6139
57	688.5155	641.6197	1039.7543	1048.2859	0.6622	0.6121	0.6371	662.4566	667.8923	3.9337	3.9337
58	693.0721	676.2465	1048.2413	1102.9548	0.6612	0.6131	0.6371	667.8862	702.7469	3.7710	3.7710
59	726.1325	711.4843	1090.1434	1136.7961	0.6661	0.6259	0.6460	704.2091	734.3458	3.1132	3.1132
60	767.0296	751.7887	1134.3546	1185.9701	0.6762	0.6339	0.6550	743.0496	776.8599	3.2272	3.2272
61	790.8134	765.0979	1152.9543	1204.9987	0.6859	0.6349	0.6604	761.4332	795.8043	3.8585	3.8585
62	829.5178	787.5996	1201.2460	1228.1252	0.6905	0.6413	0.6659	799.9399	817.8394	3.6975	3.6975
63	855.0568	836.0507	1235.4389	1293.1734	0.6921	0.6465	0.6693	826.8907	865.5330	3.4063	3.4063
64	890.9808	863.8533	1271.6115	1315.3697	0.7007	0.6567	0.6787	863.0482	892.7471	3.2365	3.2365
65	938.4217	911.9361	1323.9373	1375.0121	0.7088	0.6632	0.6860	908.2420	943.2801	3.3229	3.3229
66	963.5442	931.9068	1349.0654	1395.4239	0.7142	0.6678	0.6910	932.2456	964.2808	3.3573	3.3573
67	981.4823	964.8804	1373.9174	1420.6554	0.7144	0.6792	0.6968	957.3096	989.8754	2.5251	2.5251
68	1023.3719	981.8926	1417.3896	1438.9467	0.7220	0.6824	0.7022	995.2773	1010.4150	2.8228	2.8228
69	1058.2306	1035.6850	1455.8515	1480.7735	0.7269	0.6994	0.7132	1038.2420	1056.0150	1.9252	1.9252
70	1084.4952	1079.6560	1494.2964	1567.1918	0.7258	0.6889	0.7073	1056.9670	1108.5280	2.6045	2.6045
71	1095.9121	1100.9990	1524.8637	1595.5005	0.7187	0.6901	0.7044	1074.0840	1123.8390	2.0323	2.0323
72	1122.9641	1117.5220	1553.3809	1601.3086	0.7229	0.6979	0.7104	1103.5190	1137.5670	1.7621	1.7621
73	1144.3278	1155.2940	1591.2490	1611.0661	0.7191	0.7171	0.7181	1142.7050	1156.9360	0.1420	0.1420
74	1184.8957	1172.4510	1653.2621	1661.8137	0.7167	0.7055	0.7111	1175.6560	1181.7380	0.7859	0.7859
75	1192.2951	1172.6510	1705.3861	1644.4054	0.6991	0.7131	0.7061	1204.2160	1161.1560	0.9899	0.9899
76	1193.2870	1183.1280	1759.1901	1717.2355	0.6783	0.6890	0.6836	1202.6600	1173.9780	0.7794	0.7794
77	1176.7758	1201.6270	1667.9681	1729.8675	0.7055	0.6946	0.7001	1167.7030	1211.0370	0.7770	0.7770
78	1215.8426	1227.2860	1729.3709	1843.8282	0.7031	0.6656	0.6843	1183.4720	1261.7990	2.7352	2.7352

Table 34: HVAC Mfg. Testing data for the 0-9VDC and 9-0VDC tests

79	1257.2617	1254.2970	1829.5894	1860.3917	0.6872	0.6742	0.6807	1245.3960	1266.3630	0.9528	0.9528
80	1271.0525	1266.4440	1814.9644	1890.3001	0.7003	0.6700	0.6851	1243.5120	1295.1280	2.2147	2.2147
81	1304.0815	1313.0610	1927.0049	1945.4391	0.6767	0.6749	0.6758	1302.3500	1314.8090	0.1329	0.1329
82	1334.8078	1346.0600	1953.1317	1947.2466	0.6834	0.6913	0.6873	1342.4680	1338.4230	0.5706	0.5706
83	1383.0118	1403.1190	1971.3746	1965.1562	0.7015	0.7140	0.7078	1395.2850	1390.8840	0.8796	0.8796
84	1423.5571	1473.9530	2020.8641	2071.0350	0.7044	0.7117	0.7081	1430.9020	1466.4260	0.5133	0.5133
85	1453.5909	1503.6410	2038.0161	2059.7263	0.7132	0.7300	0.7216	1470.6910	1486.3580	1.1628	1.1628
86	1484.7274	1542.5580	2043.5249	2067.5836	0.7266	0.7461	0.7363	1504.6680	1522.3830	1.3253	1.3253
87	1557.2742	1547.9080	2122.7102	2112.8957	0.7336	0.7326	0.7331	1556.1860	1548.9910	0.0699	0.0699
88	1567.7681	1594.0660	2174.3194	2121.4957	0.7210	0.7514	0.7362	1600.7630	1561.8730	2.0612	2.0612
89	1632.3997	1641.7500	2228.7173	2185.1275	0.7324	0.7513	0.7419	1653.4500	1621.1110	1.2731	1.2731
90	1643.8276	1638.0390	2260.4088	2243.8217	0.7272	0.7300	0.7286	1646.9880	1634.9020	0.1919	0.1919

Table 35: HVAC Mfg. Testing data for the two 0-9VDC tests

Input	Reference Airflow Test 1	Reference Airflow Test 2	AVG Ref Airflow	Calculated Airflow Test 1	Calculated Airflow Test 2	Coefficient Test 1	Coefficient Test 2	Avg Coefficient	New CFM 1	New CFM 2	% Different CFM 1	% Different CFM 2
0	0.6448	0.4028	0.5238	0.0000	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1	0.8883	0.5334	0.7109	0.3493	0.3482	1.5272	2.0418	1.7845	0.6233	0.6213	14.4165	14.4165
2	1.2349	1.0330	1.1339	1.3938	1.3910	0.7411	0.8152	0.7782	1.0846	1.0824	4.7596	4.7596
3	1.4564	1.1072	1.2818	3.1432	3.1290	0.3523	0.4096	0.3810	1.1974	1.1920	7.5327	7.5327
4	1.9964	1.6965	1.8465	5.5823	5.5478	0.3039	0.3328	0.3184	1.7773	1.7663	4.5412	4.5412
5	2.1774	2.1879	2.1827	8.7228	8.6593	0.2508	0.2521	0.2514	2.1933	2.1773	0.2454	0.2454
6	2.3751	2.3570	2.3661	12.5548	12.4594	0.1877	0.1899	0.1888	2.3706	2.3526	0.5740	0.5740
7	3.0203	2.7943	2.9073	17.3169	17.1794	0.1614	0.1692	0.1653	2.8624	2.8397	2.3801	2.3801
8	3.0686	3.0559	3.0623	22.5859	22.4824	0.1353	0.1362	0.1358	3.0661	3.0521	0.3334	0.3334
9	3.8569	3.5312	3.6940	28.4365	28.4196	0.1242	0.1300	0.1271	3.6137	3.6116	2.2833	2.2833
10	4.8102	4.6130	4.7116	35.0118	34.9278	0.1318	0.1349	0.1333	4.6680	4.6568	1.1774	1.1774
11	6.1870	5.8781	6.0326	42.0056	41.8665	0.1399	0.1441	0.1420	5.9654	5.9456	1.4626	1.4626
12	7.6579	7.2248	7.4413	49.5115	49.3440	0.1459	0.1508	0.1484	7.3457	7.3208	1.6460	1.6460
13	9.4451	8.8285	9.1368	58.4223	58.2875	0.1511	0.1568	0.1539	8.9932	8.9724	1.8316	1.8316
14	12.3714	11.1889	11.7802	66.9157	67.1551	0.1672	0.1754	0.1713	11.4635	11.5045	2.3956	2.3956
15	15.7087	14.5646	15.1367	76.5147	77.2993	0.1904	0.1958	0.1931	14.7738	14.9253	1.4159	1.4159
16	19.7459	17.7703	18.7581	87.1833	88.6685	0.2038	0.2116	0.2077	18.1071	18.4155	1.8600	1.8600
17	23.8878	22.1984	23.0431	98.4343	99.5882	0.2255	0.2314	0.2284	22.4873	22.7509	1.2844	1.2844
18	29.6856	27.8604	28.7730	110.6328	113.5298	0.2518	0.2534	0.2526	27.9496	28.6815	0.3192	0.3192
19	33.9244	32.9598	33.4421	123.0741	123.5689	0.2678	0.2706	0.2692	33.1340	33.2672	0.5257	0.5257
20	38.7491	37.4697	38.1094	134.1950	135.0247	0.2792	0.2822	0.2807	37.6725	37.9054	0.5382	0.5382
21	46.4180	46.1750	46.2965	150.0138	147.9602	0.3078	0.3129	0.3104	46.5570	45.9197	0.8206	0.8206
22	52.0728	51.9742	52.0235	164.4830	159.5428	0.3160	0.3261	0.3210	52.8043	51.2183	1.5720	1.5720
23	69.4772	67.9636	68.7204	180.2363	179.0988	0.3771	0.3837	0.3804	68.5602	68.1276	0.8702	0.8702
24	76.1806	76.0113	76.0960	195.2500	194.4386	0.3893	0.3914	0.3903	76.2124	75.8957	0.2639	0.2639

Table 35: HVAC Mfg. Testing data for the two 0-9VDC tests Continued

Input	Reference Airflow Test 1	Reference Airflow Test 2	AVG Ref Airflow	Calculated Airflow Test 1	Calculated Airflow Test 2	Coefficient Test 1	Coefficient Test 2	Avg Coefficient	New CFM 1	New CFM 2	% Different CFM 1	% Different CFM 2
25	89.0198	88.1554	88.5876	213.3187	212.9284	0.4133	0.4160	0.4147	88.4526	88.2908	0.3361	0.3361
26	98.3512	97.0521	97.7017	229.5809	227.0744	0.4227	0.4303	0.4265	97.9161	96.8471	0.8824	0.8824
27	109.7346	109.1608	109.4477	247.7274	247.2901	0.4406	0.4426	0.4416	109.4010	109.2079	0.2196	0.2196
28	122.2882	121.9670	122.1276	268.2803	264.5398	0.4546	0.4617	0.4581	122.9107	121.1970	0.7678	0.7678
29	132.1151	131.8672	131.9912	281.6517	279.9728	0.4682	0.4714	0.4698	132.3249	131.5362	0.3459	0.3459
30	144.1117	146.9592	145.5355	302.2863	305.8891	0.4862	0.4758	0.4810	145.3903	147.1231	1.0791	1.0791
31	159.2725	157.0276	158.1500	326.7733	324.3833	0.4805	0.4875	0.4840	158.1714	157.0146	0.7232	0.7232
32	169.9727	169.5619	169.7673	342.2725	343.8404	0.4954	0.4937	0.4946	169.2775	170.0530	0.1680	0.1680
33	188.2865	185.4141	186.8503	368.1477	368.0291	0.5036	0.5077	0.5057	186.1623	186.1023	0.4019	0.4019
34	203.2493	201.2201	202.2347	389.2590	390.6602	0.5169	0.5177	0.5173	201.3647	202.0896	0.0718	0.0718
35	213.3215	213.2559	213.2887	411.5244	414.2496	0.5182	0.5149	0.5165	212.5707	213.9784	0.3223	0.3223
36	233.6085	232.2253	232.9169	435.8987	436.4788	0.5328	0.5336	0.5332	232.4163	232.7256	0.0822	0.0822
37	243.9243	245.6859	244.8051	453.6965	457.5437	0.5415	0.5350	0.5383	244.2163	246.2872	0.6018	0.6018
38	266.5820	268.1211	267.3516	482.7603	481.3482	0.5554	0.5554	0.5554	268.1285	267.3442	0.0028	0.0028
39	286.1823	278.6109	282.3966	511.0861	504.2765	0.5451	0.5600	0.5526	282.4104	278.6476	1.3454	1.3454
40	301.4355	300.9423	301.1889	534.1370	541.3910	0.5634	0.5563	0.5599	299.0478	303.1091	0.6335	0.6335
41	318.9886	318.1567	318.5727	559.4093	562.2469	0.5687	0.5666	0.5677	317.5608	319.1716	0.1877	0.1877
42	335.5867	337.2461	336.4164	583.1722	586.9709	0.5783	0.5731	0.5757	335.7426	337.9297	0.4478	0.4478
43	347.7694	347.1779	347.4737	597.9716	598.7774	0.5806	0.5803	0.5804	347.0920	347.5597	0.0248	0.0248
44	364.6778	370.2033	367.4406	629.9596	635.8357	0.5877	0.5779	0.5828	367.1241	370.5485	0.8387	0.8387
45	385.4302	388.4434	386.9368	664.3443	663.3545	0.5847	0.5833	0.5840	387.9788	387.4007	0.1198	0.1198
46	408.3062	408.0117	408.1590	693.1518	683.3559	0.5886	0.5973	0.5930	411.0108	405.2023	0.7297	0.7297
47	432.7384	431.1517	431.9450	720.9484	718.2782	0.5980	0.6014	0.5997	432.3512	430.7499	0.2774	0.2774
48	448.4945	450.5091	449.5018	749.4904	742.7679	0.6011	0.6052	0.6031	452.0396	447.9850	0.3386	0.3386
49	473.3589	476.0549	474.7069	781.4271	779.6948	0.6092	0.6088	0.6090	475.9082	474.8532	0.0308	0.0308
50	499.9913	499.0637	499.5275	817.9001	811.8989	0.6102	0.6153	0.6127	501.1417	497.4647	0.4147	0.4147
51	514.0879	513.0194	513.5536	836.9274	830.9889	0.6130	0.6180	0.6155	515.1215	511.4664	0.4081	0.4081

Table 35: HVAC Mfg. Testing data for the two 0-9VDC tests Continued

Input	Reference Airflow Test 1	Reference Airflow Test 2	AVG Ref Airflow	Calculated Airflow Test 1	Calculated Airflow Test 2	Coefficient Test 1	Coefficient Test 2	Avg Coefficient	New CFM 1	New CFM 2	% Different CFM 1	% Different CFM 2
52	537.8624	535.7342	536.7983	871.4946	859.8892	0.6147	0.6243	0.6195	539.8886	532.6992	0.7695	0.7695
53	565.9514	564.6006	565.2760	908.6407	889.2646	0.6214	0.6357	0.6285	571.0967	558.9185	1.1375	1.1375
54	590.5339	590.6909	590.6124	928.8234	924.2147	0.6360	0.6390	0.6375	592.1243	589.1862	0.2421	0.2421
55	624.4027	629.2783	626.8405	972.0093	979.9815	0.6474	0.6396	0.6435	625.5097	630.6400	0.6025	0.6025
56	645.5513	640.5751	643.0632	1006.8077	994.7099	0.6362	0.6465	0.6414	645.7297	637.9706	0.7983	0.7983
57	688.5155	683.6412	686.0783	1039.7543	1030.6684	0.6575	0.6657	0.6616	687.8838	681.8728	0.6168	0.6168
58	693.0721	692.7772	692.9246	1048.2413	1043.2938	0.6609	0.6642	0.6625	694.4939	691.2160	0.2472	0.2472
59	726.1324	720.9879	723.5602	1090.1434	1081.1169	0.6614	0.6693	0.6653	725.2946	719.2891	0.5938	0.5938
60	767.0296	774.6671	770.8483	1134.3546	1149.7570	0.6829	0.6704	0.6767	767.5945	778.0170	0.9214	0.9214
61	790.8134	802.4776	796.6455	1152.9543	1173.6534	0.6960	0.6788	0.6874	792.5365	806.7650	1.2543	1.2543
62	829.5178	834.8488	832.1833	1201.2460	1207.2747	0.6950	0.6893	0.6921	831.4382	835.6110	0.4102	0.4102
63	855.0568	864.7959	859.9263	1235.4389	1243.6903	0.7000	0.6914	0.6957	859.5085	865.2491	0.6152	0.6152
64	890.9808	884.4381	887.7094	1271.6115	1273.9519	0.6955	0.6968	0.6962	885.2584	886.8877	0.0927	0.0927
65	938.4217	928.3655	933.3936	1323.9373	1311.8578	0.7012	0.7115	0.7064	935.1768	926.6444	0.7283	0.7283
66	963.5442	956.5663	960.0552	1349.0654	1336.5856	0.7091	0.7183	0.7137	962.7928	953.8863	0.6467	0.6467
67	981.4823	974.6351	978.0587	1373.9174	1354.0405	0.7094	0.7223	0.7159	983.5257	969.2967	0.9040	0.9040
68	1023.3719	1011.8952	1017.6335	1417.3896	1407.7141	0.7139	0.7229	0.7184	1018.2615	1011.3106	0.6252	0.6252
69	1058.2306	1044.7553	1051.4930	1455.8515	1444.3564	0.7176	0.7280	0.7228	1052.3084	1043.9996	0.7178	0.7178
70	1084.4952	1085.8746	1085.1849	1494.2964	1496.9460	0.7267	0.7249	0.7258	1084.5694	1086.4925	0.1203	0.1203
71	1095.9121	1085.4232	1090.6677	1524.8637	1492.7677	0.7118	0.7306	0.7212	1099.7707	1076.6222	1.3046	1.3046
72	1122.9641	1122.3269	1122.6455	1553.3809	1566.7255	0.7225	0.7166	0.7195	1117.7051	1127.3069	0.4135	0.4135
73	1144.3278	1140.5780	1142.4529	1591.2490	1615.2270	0.7168	0.7073	0.7120	1133.0356	1150.1089	0.6657	0.6657
74	1184.8957	1185.6576	1185.2766	1653.2621	1695.4138	0.7172	0.6991	0.7081	1170.7328	1200.5819	1.2748	1.2748
75	1192.2951	1190.2465	1191.2708	1705.3861	1681.5253	0.6979	0.7084	0.7032	1199.2107	1182.4320	0.7475	0.7475
76	1193.2870	1183.7200	1188.5035	1759.1901	1679.1623	0.6729	0.7078	0.6903	1214.4334	1159.1873	2.5290	2.5290
77	1176.7758	1195.3120	1186.0439	1667.9681	1740.2532	0.7166	0.6815	0.6991	1166.0455	1216.5787	2.5099	2.5099

Table 35: HVAC Mfg. Testing data for the two 0-9VDC tests Continued

78	1215.8426	1205.6467	1210.7447	1729.3709	1728.5886	0.6972	0.7004	0.6988	1208.4696	1207.9230	0.2336	0.2336
79	1257.2617	1257.1937	1257.2277	1829.5894	1806.3856	0.6871	0.6960	0.6916	1265.2855	1249.2385	0.6395	0.6395
80	1271.0525	1270.0028	1270.5276	1814.9644	1819.3280	0.6997	0.6983	0.6990	1268.7416	1271.7919	0.0994	0.0994
81	1304.0815	1292.6271	1298.3543	1927.0049	1859.8716	0.6708	0.6981	0.6844	1318.9231	1272.9743	1.9938	1.9938
82	1334.8078	1345.1467	1339.9773	1953.1317	1922.2380	0.6887	0.6971	0.6929	1353.3298	1331.9236	0.6047	0.6047
83	1383.0118	1377.6870	1380.3494	1971.3746	1958.4662	0.6988	0.7048	0.7018	1383.5672	1374.5077	0.4250	0.4250
84	1423.5571	1386.4413	1404.9992	2020.8641	1971.0409	0.6861	0.7128	0.6994	1413.4778	1378.6293	1.9128	1.9128
85	1453.5909	1459.0225	1456.3067	2038.0161	2059.2824	0.7159	0.7072	0.7115	1450.1449	1465.2769	0.6122	0.6122
86	1484.7274	1494.0416	1489.3845	2043.5249	2076.7200	0.7311	0.7172	0.7241	1479.8096	1503.8477	0.9617	0.9617
87	1557.2742	1544.2062	1550.7402	2122.7102	2142.8491	0.7275	0.7237	0.7256	1540.1861	1554.7984	0.2610	0.2610
88	1567.7681	1568.0013	1567.8847	2174.3194	2185.3367	0.7211	0.7175	0.7193	1563.9908	1571.9155	0.2564	0.2564
89	1632.3997	1617.5206	1624.9602	2228.7173	2236.8617	0.7258	0.7264	0.7261	1618.2822	1624.1958	0.0471	0.0471
90	1643.8276	1642.9385	1643.3831	2260.4088	2271.9229	0.7268	0.7233	0.7251	1638.9964	1647.3452	0.2405	0.2405

Appendix VI

Detailed design calculations, formulae derivations, and software extra analysis output (e.g. FEA pictures)

Gear Train Material Analysis

Included in the figures below are the FEA analysis of the gear train designed for use in the co-axial actuator.

Von Mises Stress

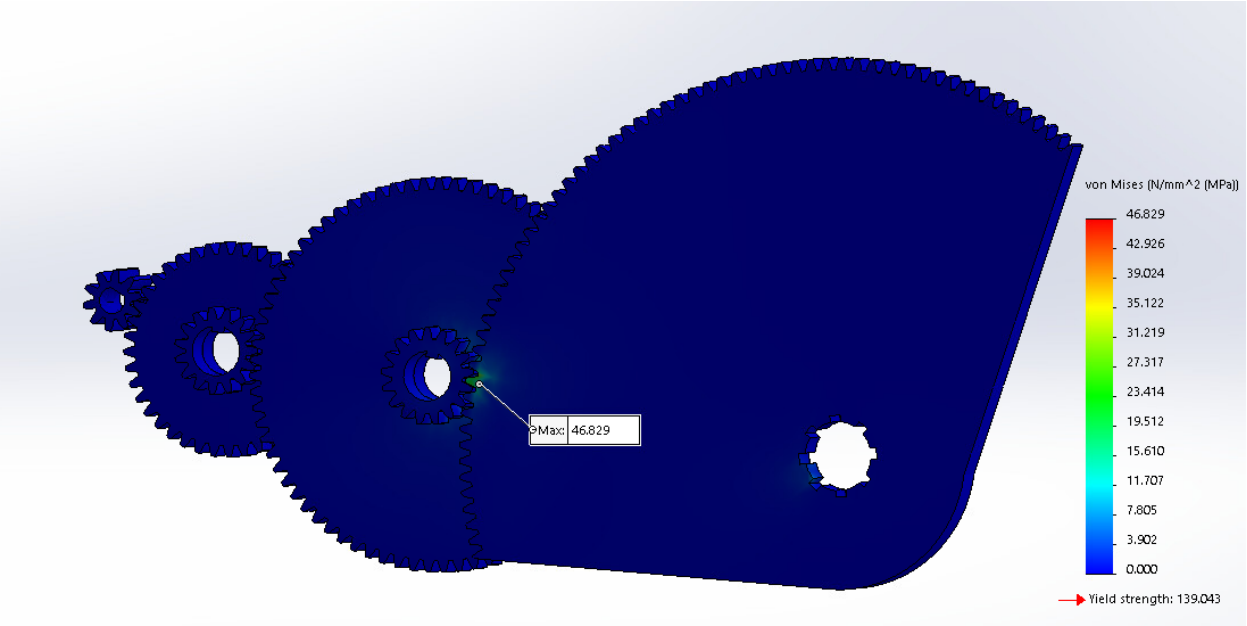


Figure 20: Von Mises stress simulation for Nylon 6,10

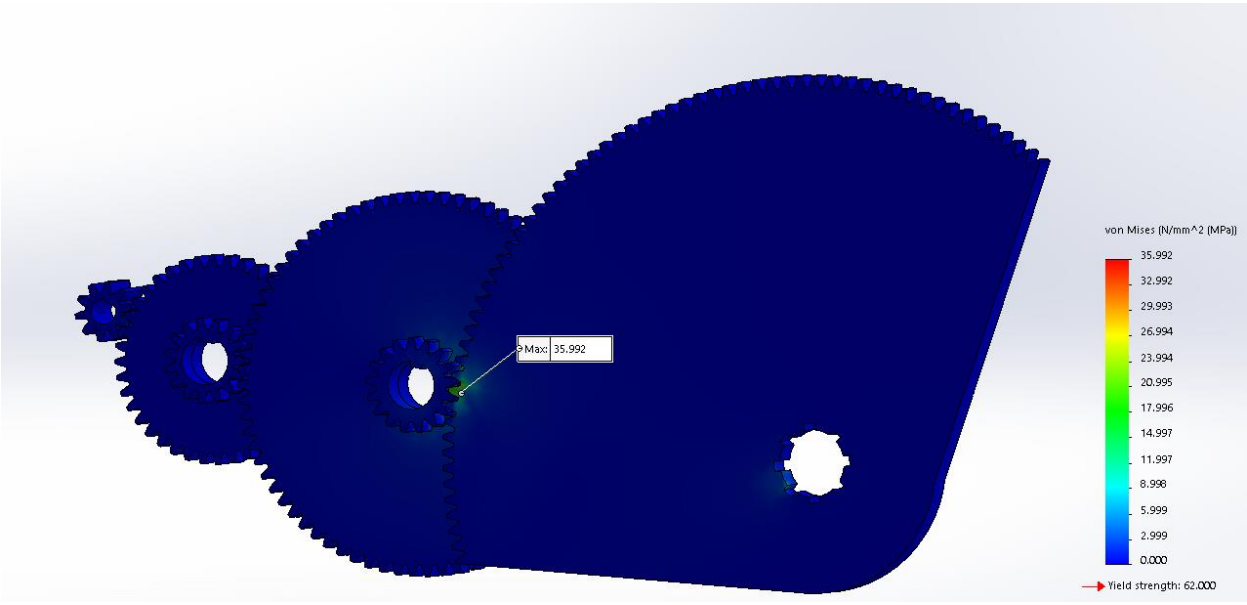


Figure 21: Von Mises stress simulation for ABS Polycarbonate.

Bending Stress Deformation

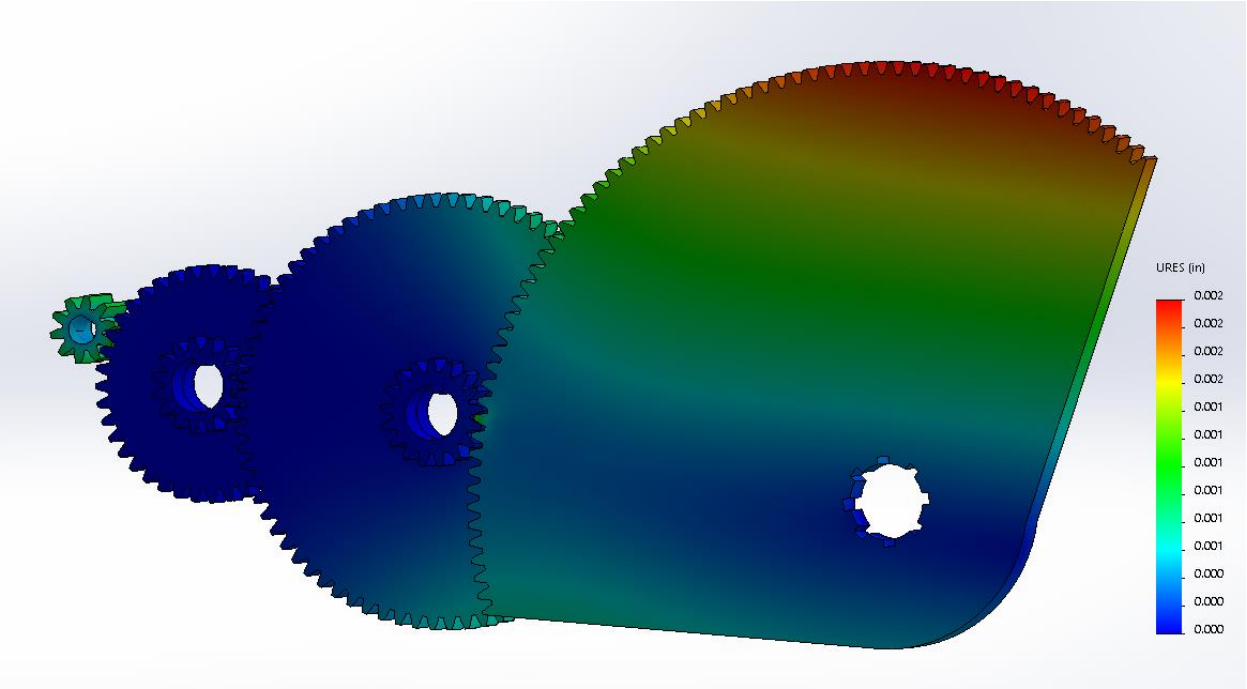


Figure 22: Bending stress deformation simulation for Nylon 6,10.

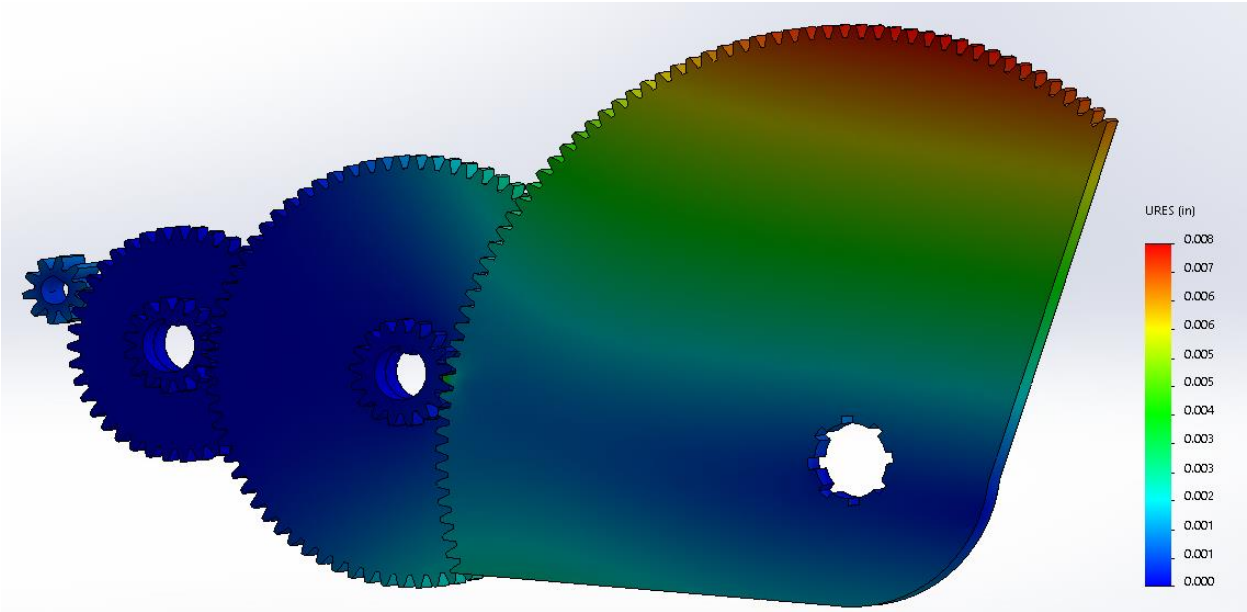


Figure 23: Bending stress deformation simulation for ABS Polycarbonate.

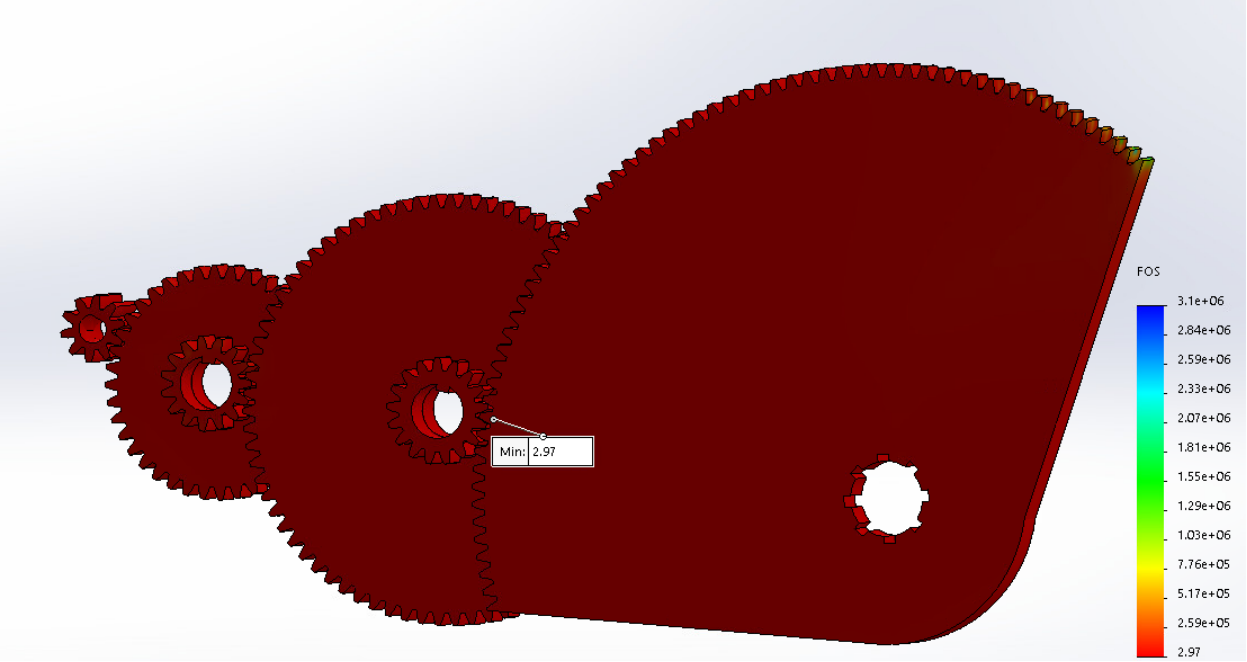


Figure 24: Factor of safety simulation for Nylon 6,10.

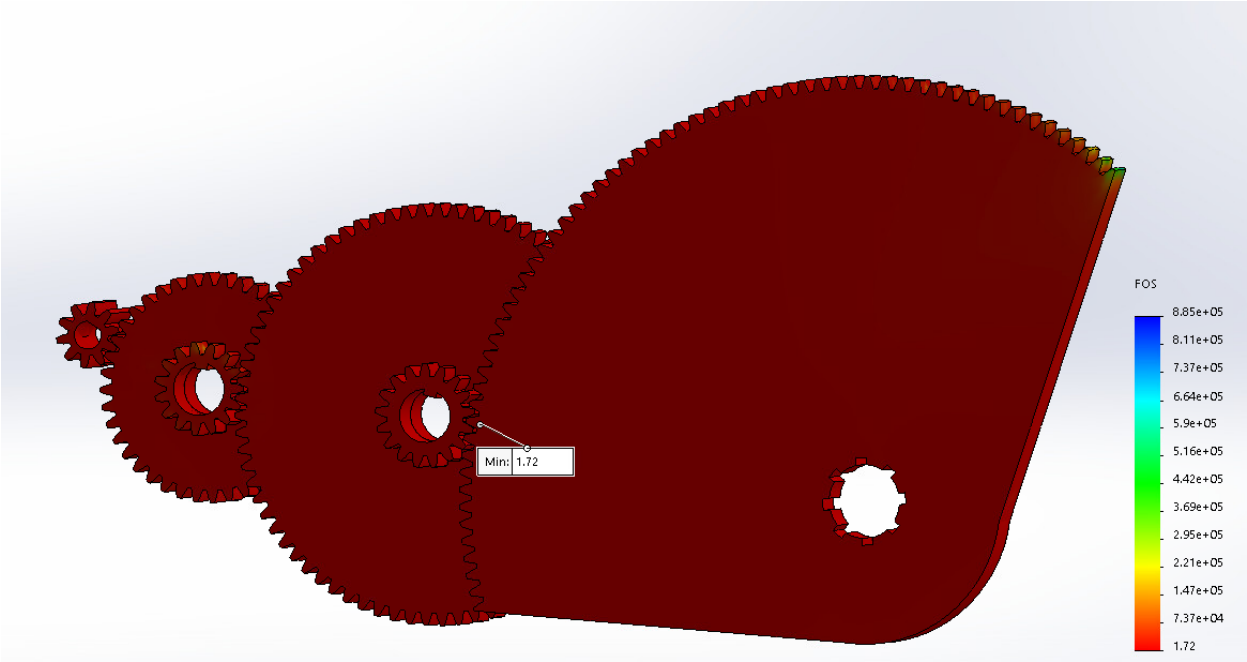


Figure 25: Factor of safety simulation for ABS Polycarbonate.

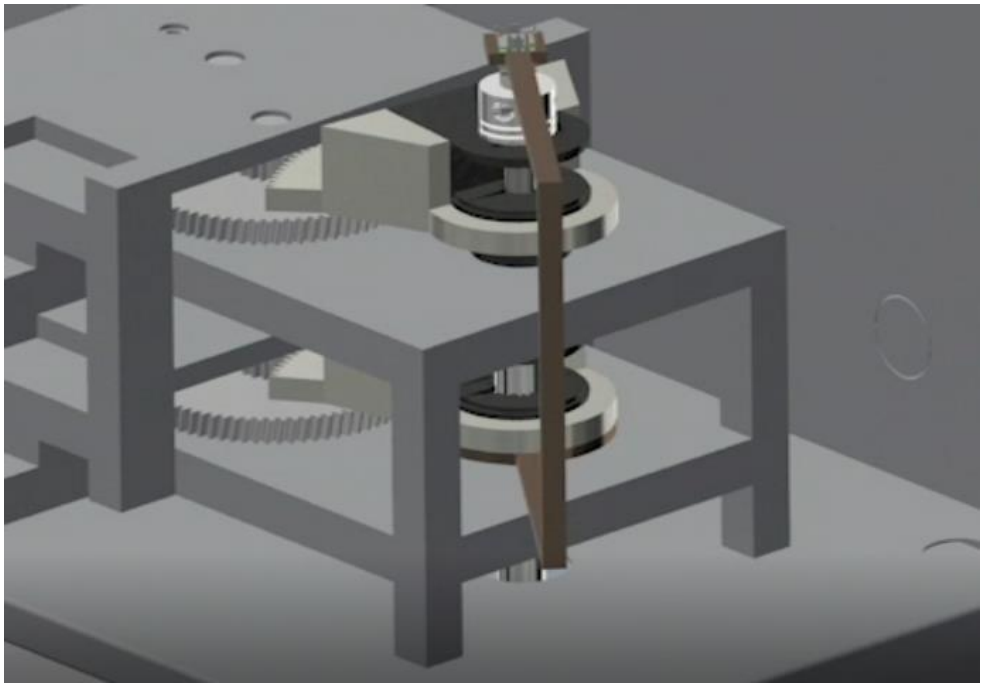


Figure 26: PLA gear train simulation with potentiometer wing

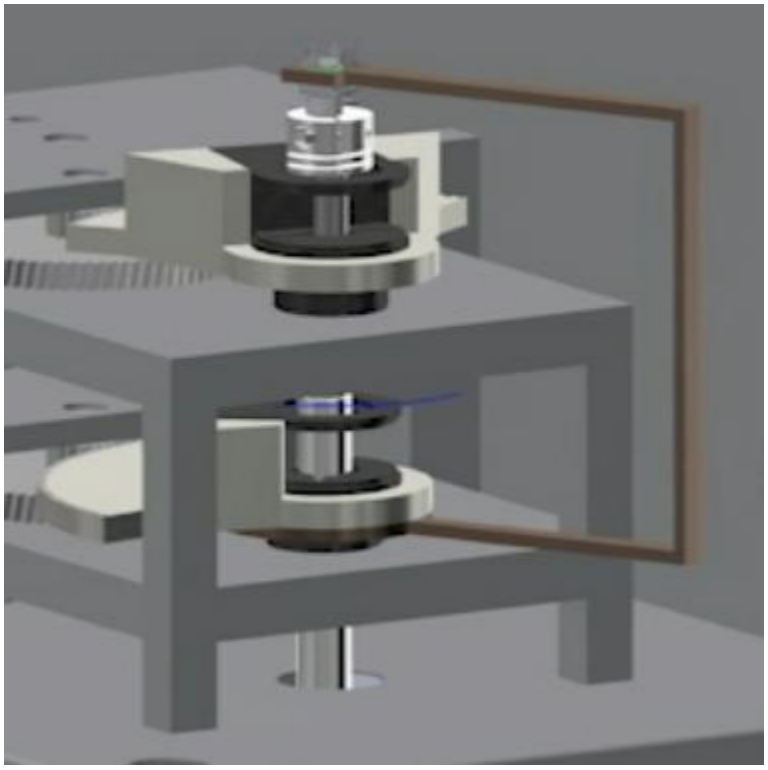


Figure 27: Another view of the PLA gear train simulation with potentiometer wing

Types of backlash

During the backlash analysis of the gear train, the team calculated the following types of backlash using the equations shown further on:

- Circumferential backlash
- Normal Backlash
- Angular Backlash
- Radial Backlash

Circumferential backlash is the distance of the arc on the pitch circle. This distance is measure when the gear is rotated until the interlock tooth flank engage contact while the other interlocking gear is stationary. Normal backlash is the distance between the interlocking tooth flank within the pair of gears when the tooth surfaces are in contact. Angular backlash is the angle that enable movement in the gear while the mating gear is at rest. Radial backlash is the shrinkage of movement in the stated center distance when it is fix so that the interlocking tooth flanks of the mating gears come to contact of each other.

Equations for backlash

Circumferential backlash:

$$\frac{Normal\ Backlash}{Cos\alpha * Cos\beta}$$

(Eq. 2)

Normal backlash:

Circumferential backlash * Cosα * Cosβ

(Eq. 3)

Angular backlash:

$$\frac{360^{\circ} * \text{Circumferential backlash}}{\pi * Reference\ Diameter}$$

(Eq. 4)

Radial backlash:

$$\frac{Normal\ Backlash}{2Sin(\alpha)}$$

(Eq. 5)

Appendix VII

Detailed Testing Plans with Expected Outcomes:

The following tables include the testing plans and expected outcomes for each of the required and optional specifications.

Table 28: Tests and expected outcome for the required specifications

Required Specifications		
Test description	Corresponding Specification Number	Testing Plan & Expected Outcome
Actuator torque test for round damper	1	Test: Connect actuator assembly to largest round HVAC terminal unit (12”). Put power to the actuator and turn the actuator on. Apply a signal to the 0-10VDC input to allow the actuator to function. Expected Outcome: The actuator should be able to open the damper blade on the largest round HVAC terminal unit when fully closed with the gasket compressed.
Actuator Torque test for rectangular damper	2	Test: Connect actuator assembly to largest rectangular HVAC terminal unit (14” x 24”). Put power to the actuator and turn the actuator on. Apply a signal to the 0-10VDC input to allow the actuator to function. Expected Outcome: The actuator should be able to open the damper blade on the largest rectangular HVAC terminal unit when fully closed with the gasket compressed.
Maximum torque output	3	Test: Powering on the actuator and applying a signal to the 0-10VDC input with the actuator not connected to a HVAC terminal unit. Use an adaptor to connect a torque wrench to the output of the actuator assembly and measure the torque. Expected Outcome: The amount of torque should be greater than 55 in*lbs. This will allow for the actuator to properly turn the damper shafts with no issues.
Basic power on and functionality test	4	Test: Apply 24VAC to the actuator power input. The actuator should power on successfully. Once powered on, apply a signal to the 0-10VDC input. The Actuator should be power the motors and turn the damper blades. Expected Outcome: The Actuator should be able to be powered from the 24VAC, and function as intended when powered on. This means the actuator should turn the damper blades to the desired angles as the 0-10VDC signal changes voltages, as well as output a feedback to the main controller.

Table 28: Tests and expected outcome for the required specifications Continued

Test description	Corresponding Specification Number	Testing Plan & Expected Outcome
Verification of measurements and diameters of the inner damper shaft and corresponding gear	5	Test: Attach calipers to the output shaft of the inner damper blade. Measure the diameter of the shaft, report these findings, and verify these measurements with the CAD files provided. Measure the inner diameter of the output gear that attaches to the inner damper shaft and record these values. Expected outcome: The values found in the above test should be identical to those in the CAD files. Verify all measurements with the CAD files.
Verification of measurements and diameters of the outer damper shaft and corresponding gear	6	Test: Attach calipers to the output shaft of the outer damper blade. Measure the diameter of the shaft, report these findings, and verify these measurements with the CAD files provided. Measure the inner diameter of the output gear that attaches to the inner damper shaft and record these values. Expected outcome: The values found in the above test should be identical to those in the CAD files. Verify all measurements with the CAD files. The output gear should fit tightly over the output shaft as to not create any play in the gear train.
Verification of actuator fitment and enclosure measurements	7	Test: The actuator assembly must fit within the dimensions of the sheet metal enclosure on the HVAC terminal unit. Once the actuator is fully assembled, test fit the assembly into the metal enclosure of the terminal unit. Expected Outcome: The Actuator should fit properly into the enclosure.
Motor testing	8	Test: Inspect visually to verify the same motor is used in both locations. Fit the motor into the actuator assembly. The motor should fit and function as intended and turn the damper shafts. Expected Outcome: Identical motors should be used in both locations and be able to turn both dampers independently of each other.

Table 28: Tests and expected outcome for the required specifications Continued

Test description	Corresponding Specification Number	Testing Plan & Expected Outcome
Current limiting resistor verification and current testing	9	Test: Visually inspection of the PCB should be able to verify that there is a current limiting resistor on 24VAC input. Measurement the amount of current used by the PCB board and verify that the power being used does not exceed 100 Watts or 4.16 amps at 24VAC as this is the limit of the transformer. Expected outcome: Current limiting resistor should be appropriately placed on the PCB board and limit the current to a value that keeps the PCB functioning properly. The expected amount of power being used by the PCB board is estimated to be around 60 watts under full load.
Reset button functionality testing	10	Test: Inspect visually for a reset button on the actuator assembly. Press the reset button and Expected Outcome: When pressed, the reset button should turn both inner and outer damper blades back to the 0-degree (Home) position.
Feedback and Real Time tracking tests	11	Test: After assembly the actuator assembly, and connecting to a HVAC terminal unit, power on the actuator. Apply a signal to the 0-10VDC input. Once the actuator has stopped moving, measure the voltage coming out of the PCB on the feedback connection to the controller. Expected Outcome: The voltage feedback sent to the main controller of the terminal unit should be the same as the voltage sent through the 0-10VDC signal input.

Table 29: Tests and expected outcomes for optional specifications

Optional Specifications & Specifications that will change over time		
Test Description	Corresponding Specification Number	Testing plan & Expected Outcome
IoT reporting to the cloud	12	Test: Power on the actuator and apply a voltage to the 0-10VDC input. Allow the actuator appropriate time to open the damper blades and stop moving. The IoT portion of the actuator will report the position of the damper to a cloud service. Expected Outcome: Check the cloud service used for the report of the position of the damper blades.
Adaptability for use in a single damper application	13	Test: After the actuator is fully assembled, remove the screws and clamps holding the two halves of the actuator assembly together. One half of the actuator assembly should be able to separate from the other half to allow for use in a single damper blade application. Expected Outcome: The actuator should be able to separate easily and function as intended afterwards on single damper terminal unit.
Amount of torque created by the motor	14	Test: Connect the motor to a motor driver and Arduino for external testing. This will give us the ability to power the motor on and test for function without placing the motor in the actuator. Once the motor is powered on, step the motor to test for functionality. If the motor is stepping correctly, attach a torque wrench with a 3D printed adapter to measure the amount of torque outputted by the stepper motor. Expected outcome: The motor should output enough torque to turn the damper shafts after going through the gear train. This value will be
Motor step testing	15	Test: Connect the motor to a motor driver and Arduino/MPU for external testing. This will give us the ability to power the motor on and test for function without placing the motor in the actuator. Once the motor is powered on, step the motor to test for functionality. Expected outcome: The stepper motor should step .9 degrees every time it is commanded to by the Arduino or MPU.

Table 29: Tests and expected outcomes for optional specifications continued

Test Description	Corresponding Specification Number	Testing plan & Expected Outcome
Verification of motor dimensions	16	Test: Using calipers, verify the measurements of the stepper motor with the dimensions in the CAD files. These values need to be accurate to confirm that the motor will fit properly within the actuator assembly and not cause any issues with mounting. Expected Outcome: The dimensions of the stepper motor should accurate to those in the CAD files. Once dimensions of checked, verify the motor properly fits in the actuator assembly.
Test fitting actuator into enclosure	17	Test: Assemble and actuator and verify all dimensions match the CAD drawings. Once the dimensions are verified, check that the actuator assembly will fit into the enclosure properly. Expected Outcome: The actuator should fit into the enclosure without issue and properly mount to the sheet metal enclosure.
Damper speed testing	18	Test: Fully assembly the actuator and attach the assembly to a HVAC terminal unit. Make sure the damper blades are fully closed, power on the actuator and apply a 10VDC signal to fully open the damper blades. Once the actuator starts rotating the damper shaft, start a timer. When the damper blades have reached the fully open position, stop the timer. This does not need to be an extremely accurate test as we are not looking to open the blades at a specific speed. Expected Outcome: The damper blades will be able to go from the fully closed to the fully open position within 2 minutes of giving the actuator the command to do so.
Gear ratio verification	19	Test: Assembly the actuator so that the gearing is attached to the motor. Using an RPM gauge or through visual inspection, measure the amount of revolutions the input gear must complete before the output gear reaches one full revolution. This will give us our gear ratio with respect to the input at the motor and the output at the damper shaft. Expected outcome: The gear ratio will match the calculated gear ratio shown in the above table. We are not looking for a specific value here, although we would like to be around 1:120 allowing us to run the motor at 120RPM where the motor is making maximum torque.

Table 29: Tests and expected outcomes for optional specifications continued

Test Description	Corresponding Specification Number	Testing plan & Expected Outcome
Gear train reliability and wear testing	20	Test: After the actuator has been assembled, connect the actuator assembly to the largest rectangular HVAC terminal unit (14”x28”). This terminal unit requires the most amount of torque at 44 inch*lbs to turn the damper shafts from a closed position with the gasket fully compressed. Once attached, power on the actuator and run the actuator for 10 minutes. Disassemble the actuator and inspect the gears for wear and broken teeth. Expected Outcome: The gears should have no broken teeth and still be fully functional after the test. This is fully dependent on the material of gears
IoT Cloud tracking intervals	21	Test: After fully assembling the actuator, mount the actuator to a HVAC terminal unit. Apply a signal to the 0-10VDC input and allow the actuator to change position. The allow for appropriate time for the actuator to report the position of the damper blades to the cloud. Expected outcome: The actuator should report the damper positions to the cloud once every five minutes.
0-10VDC input testing	22	Test: Fully assemble the actuator, and power the unit with 24VAC. Attach the actuator to a terminal unit and apply a series of inputs between 0-10VDC. Allow the actuator enough time between each input to reach the specified angle on the dampers Expected Outcome: The actuator should open and close the damper shafts as the 0-10VDC signal is applied to the input.

Appendix **VIII**

Any code or program listing.

The following code is the entirety of the programming developed for a single or dual damper blade design. The code includes potentiometer feedback for a single damper system which can be commented out if it is needed for a dual damper application. After this code, the feedback function for the single damper application is included.

```
#include <Arduino.h>
#include <Wire.h>
#include <Adafruit_ADS1015.h>     //ADS1115 library for reading ADC
#include "BasicStepperDriver.h"   //Basic stepper functions
#include "DRV8825.h"              //DRV8825 specific functions
#include "math.h"                 //addition, multiplication, rounding,etc library
#include <EEPROM.h>               //Read And Write Library for EEPROM

// All Initialized values:
//Serial Comms for external ADC @ address 0x48
Adafruit_ADS1115 ads(0x48);

//Intialize the Driver to control the stepper motors
#define MOTOR_STEPS 200 // Motor steps per revolution. The motor used in our case is 200 steps/revolution or 1.8-degree step size
#define RPM 120         // Set the Motor RPM
#define DIR1 18         // Direction pin for inner motor, value represents GPIO pin on ESP32
#define STEP1 19        // Step pin for inner motor, value represents GPIO pin on ESP32
#define EN1 23          // Enable pin for the inner stepper driver, value represents GPIP pin on ESP32
#define DIR2 17         // Direction pin for outer motor, value represents GPIO pin on ESP32
#define STEP2 5         // Step pin for outer motor, value represents GPIO pin on ESP32
#define EN2 16          // Enable pin for the outer stepper driver, value represents GPIO pin on ESP32
#define MICROSTEPS 1    // with DRV825, micro stepping is set externally, this needs to match the selected mode. 1 = full step, 2 = half step etc.

//EEPROM size definition
#define EEPROM_SIZE 2   // This is where the location of the dampers are set.

// These are the pin definitions for the ADS1115 external ADC
const int inputsig1 = 1; // inputsig1 = 0-10vdc input for inner damper; value represents pin at ADS1115 external ADC
const int inputsig2 = 2; // inputsig2 = 0-10vdc input for Outer damper; value represents pin at ADS1115 external ADC
const int potsig1 = 0;   // potsig1 = 0-5vdc input for potentiometer; value represents pin at ADS1115 external ADC
//const int potsig2 = 3; //Extra ADC input, Has multiple uses such as an extra Pot

//Initialize all global variables
float inputvoltage1 = 0;
float inputvoltage2 = 0;
float potvalintial = 0;
float potvalafter = 0;
int innerdamperpos = 0;
int outerdamperpos = 0;
int potadjust1 = 0;
int datahigh1 = 0;
int datalow1 = 0;
int datahigh2 = 0;
int datalow2 = 0;

//Constant global integers
//Changing the values will make the adjustments throughout the entire program
//Note: The final step size at the motor HAS TO BE A INTEGER. Calculate the value before running to verify, otherwise you will add error with
every step taken by the stepper motors.
//formula for step size:     number_steps = (gear_ratio * res) / motor_step
```

```
float res = .5;                                 // This is the resolution that the damper shaft will have, i.e. the damper shaft will have .5 degree steps, meaning 180 between 0-90 degrees
int gear_ratio = 180;                           // 90:1 gear ratio >>>> represents   input:output  ratio
float motor_step = 1.8;                         // Represents motor step size, the stepper motor steps 1.8 degrees everytime it is told to move
int number_steps = (gear_ratio * res) / motor_step;       // Including this here since everything above is directly correlated and it only needs to be calculated one time
float voltage_steps = .05;                      // every 50mv is one step at the damper shaft. This means 9v is 90 degrees, and 9-10vdc is left for extra inputs.
float volt_variation = .02;                     // This is the variation of voltage that won't cause a change. i.e. .02 vdc. Must be smaller than the voltage steps above. This is a + or - of the res, so .05 +- .02
int max_voltage_sig = 10;                       // 10vdc is the maximum voltage input
int number_volt_steps = (max_voltage_sig / voltage_steps);  // 200 total steps are used in this case, with 1-180 used for 0-90 degrees with .5 degree resolution
int delaymove = 30;                             // delays between steps. This may need to be adjusted during further testing to make sure steps are not skipped.
int ninety_deg_step = (90 / res);               // This is the number of steps needed for 0-90 degrees. i.e. 180 steps for this case. This is needed because we have up to 200 steps, and need to
                                                // distinguish between the 0-180 and the 180-200 steps
float potonedeg = .014418539;                   // This is the amount of change in the pot found during testing for every degree
// 2-wire basic config, microstepping is hardwired on the driver
DRV8825 innerstepper(MOTOR_STEPS, DIR1, STEP1, EN1);
DRV8825 outerstepper(MOTOR_STEPS, DIR2, STEP2, EN2);



//Program Functions are defined from here forward:


//External ADS1115 ADC Voltage reading
//Max value is 5V(Or VDD) for ADS1115 with nothing external
//Voltage Divider allows for value to go from 0-10vdc, and be calculated after reading
float ADC_Volt_Read(int pin)
{
 //Initalize local variables for this function
 int16_t adc;
 float Voltage = 0.0;

 //Creating voltage divider to correct ADC value
 float R1 = 5.100; //5.1k Resistor
 float R2 = 5.100; //5.1k Resistor - These values can change if needed
 float invVdivider = (R1 + R2) / R1; //For our resistance, this equals 2 - Therefore it multiples the input by two to give us a range of 0-10vdc

 //Read the ADC value
 adc = ads.readADC_SingleEnded(pin);
 Voltage = (adc * 0.1875)/1000;
 Voltage = invVdivider*Voltage;
 delay(25);

 return Voltage;
}



//Function to move the motors to the desired position at the 'same time'
//Will only move the motors that need to move till at proper location
void movemotor() {

  //Initalize function variables
   int var1 = 0; //Desired inner damper location
   int var2 = 0; //Desired outer damper location
   int var3 = 0; //Change needed to move to desired inner damper location
   int var4 = 0; //Change needed to move to desired outer damper location

  //Read Pot Value
  potvalintial = ADC_Volt_Read(potsig1);
```

```
  potvalintial = (potvalintial / 2); //Removes voltage adjustment only needed for motors -- Allows the use of the reading function without an additonal funciton

  //Calculate the number of steps required for the steppers to move the dampers to the correct posistion:
  var1 = round(inputvoltage1 / voltage_steps);  //Value between 0 -> 200, these are steps at the damper with a .5degree step size.
  var2 = round(inputvoltage2 / voltage_steps);  //Value between 0 -> 200, these are steps at the damper with a .5degree step size.
  var3 = var1 - innerdamperpos;              //Value between -200 -> 200, This the the value that move the steppers
  var4 = var2 - outerdamperpos;              //Value between -200 -> 200, This the the value that move the steppers
  potadjust1 = var3;              //stpres the inner damper pos so itll be adjust in the pot function.

   //Move Stepper motors at the same time
   if (var1<= ninety_deg_step && var2<ninety_deg_step) {
      //Turn the stepper motors on!
       innerstepper.enable();
       outerstepper.enable();
    while(var3>0 && var4>0)
      {
       innerstepper.move(number_steps);
       outerstepper.move(number_steps);
       var3 = var3-1;
       var4 = var4-1;

       //Correct position variable
       innerdamperpos = innerdamperpos + 1;
       outerdamperpos = outerdamperpos + 1;

       //Store location in EEPROM
       EEPROM.write(0, innerdamperpos);
       EEPROM.write(1, outerdamperpos);
       EEPROM.commit();

       delay(delaymove);

      }

      while(var3<0 && var4<0)
      {
       innerstepper.move(-number_steps);
       outerstepper.move(-number_steps);
       var3 = var3+1;
       var4 = var4+1;

       //Correct position variable
       innerdamperpos = innerdamperpos - 1;
       outerdamperpos = outerdamperpos - 1;

       //Store location in EEPROM
       EEPROM.write(0, innerdamperpos);
       EEPROM.write(1, outerdamperpos);
       EEPROM.commit();

       delay(delaymove);
      }

      while (var3==0 && var4>0)
      {
       outerstepper.move(number_steps);
       var4 = var4-1;

       //Correct position variable
       outerdamperpos = outerdamperpos + 1;

       //Store location in EEPROM
       EEPROM.write(1, outerdamperpos);
       EEPROM.commit();
```

```
        delay(delaymove);
       }

      while(var3>0 && var4==0)
       {
        innerstepper.move(number_steps);
        var3 = var3-1;

        //Correct position variable
        innerdamperpos = innerdamperpos - 1;

        //Store location in EEPROM
        EEPROM.write(0, innerdamperpos);
        EEPROM.commit();

        delay(delaymove);
       }

      while (var3==0 && var4<0)
       {
        outerstepper.move(-number_steps);
        var4 = var4+1;

        //Correct position variable
        outerdamperpos = outerdamperpos - 1;

        //Store location in EEPROM
        EEPROM.write(1, outerdamperpos);
        EEPROM.commit();

        delay(delaymove);
       }

      while(var3<0 && var4==0)
       {
        innerstepper.move(-number_steps);
        var3 = var3+1;

        //Correct position variable
        innerdamperpos = innerdamperpos - 1;

        //Store location in EEPROM
        EEPROM.write(0, innerdamperpos);
        EEPROM.commit();

        delay(delaymove);
       }

     //calculate new motor posistion
     //add slight movement between values
     datahigh1 = inputvoltage1+volt_variation;
     datalow1 = inputvoltage1-volt_variation;
     innerdamperpos = var1;  //Stores at the step value i.e. 1 = .5 & 2 = 1.0 degrees at the damper shaft -- this will correct any logic errors
above.
     datahigh2 = inputvoltage2+volt_variation;
     datalow2 = inputvoltage2-volt_variation;
     outerdamperpos = var2;  //Stores at the step value i.e. 1 = .5 & 2 = 1.0 degrees at the damper shaft

     //Corrects EEPROM if needed, this is a failsafe
     EEPROM.write(0, innerdamperpos);
     EEPROM.write(1, outerdamperpos);
     EEPROM.commit();
    }

   //This will add one extra degree to the inner damper just before the outer damper reaches 90 degrees
   //leaving the inner damper at 91 degrees
```

```
else if (var1 == ninety_deg_step && var2 == ninety_deg_step) {
    //Turn the stepper motors on!
    innerstepper.enable();
    outerstepper.enable();
 while(var3>0 && var4>1)
   {
    innerstepper.move(number_steps);
    outerstepper.move(number_steps);
    var3 = var3-1;
    var4 = var4-1;

    //Correct position variable
    innerdamperpos = innerdamperpos + 1;
    outerdamperpos = outerdamperpos + 1;

    //Store location in EEPROM
    EEPROM.write(0, innerdamperpos);
    EEPROM.write(1, outerdamperpos);
    EEPROM.commit();

    delay(delaymove);
   }

  while (var3==0 && var4>1)
   {
    outerstepper.move(number_steps);
    var4 = var4-1;

    //Correct position variable
    outerdamperpos = outerdamperpos + 1;

    //Store location in EEPROM
    EEPROM.write(1, outerdamperpos);
    EEPROM.commit();


    delay(delaymove);
   }

  while(var3>0 && var4==1)
   {
    innerstepper.move(number_steps);
    var3 = var3-1;

    //Correct position variable
    innerdamperpos = innerdamperpos + 1;

    //Store location in EEPROM
    EEPROM.write(0, innerdamperpos);
    EEPROM.commit();


    delay(delaymove);
   }

  while(var3 == 0 && var4==1) {
    innerstepper.move(2*number_steps); //This moves the inner damper an extra 1 degree past 90
    outerstepper.move(number_steps);
    var4 = var4-1;

    //Correct position variable
    innerdamperpos = innerdamperpos + 2;
    outerdamperpos = outerdamperpos + 1;

    //Store location in EEPROM
    EEPROM.write(0, innerdamperpos);
```

```
        EEPROM.write(1, outerdamperpos);
        EEPROM.commit();

        delay(delaymove);
      }

      datahigh1 = inputvoltage1+volt_variation;
      datalow1 = inputvoltage1-volt_variation;
       //The extra '2' is needed to tell the MPU we're at 91 degrees at the inner damper
      innerdamperpos = var1 + 2;  //Stores at the step value i.e. 1 = .5 & 2 = 1.0 degrees at the damper shaft
      datahigh2 = inputvoltage2+volt_variation;
      datalow2 = inputvoltage2-volt_variation;
      outerdamperpos = var2;  //Stores at the step value i.e. 1 = .5 & 2 = 1.0 degrees at the damper shaft

      //Corrects EEPROM if needed, this is a failsafe
      EEPROM.write(0, innerdamperpos);
      EEPROM.write(1, outerdamperpos);
      EEPROM.commit();
    }

    //If inputvoltage1 or 2 are 10volts, Everything resets, returning damper 1 & 2 to the home position.
    //This is done in the setup function. Once setup is done, the system returns to the normal Loop function.
    else if (var1 == number_volt_steps || var2 == number_volt_steps) {
      //Turn the stepper motors on!
      innerstepper.enable();
      outerstepper.enable();
      //This is a force reset -> Will cause the system to defualt back to zero degrees no matter what
      EEPROM.write(0, 182); //182 is 91 degrees, max posistion of innerdamper
      EEPROM.write(1, 180); //180 is 90 degrees, max posistion of outerdamper
      EEPROM.commit();
      inputvoltage1 = 0; // Tricks the program to make the desired location of the inner damper the home position
      inputvoltage2 = 0; // Tricks the program to make the desired location of the outer damper the home position
      setup(); //Calls the setup function to reset the entire logic of the program
    }

    //If the code every reaches this 'else', then var1/2 are between 180 & 200, but not exactly 180/200.
    //The values between 180 & 200 can be set to different things, up to the programmer.
    else {
      delay(2500);
    }

   //Turn the motors off!
   innerstepper.disable();
   outerstepper.disable();

   //read the pot val
  potvalafter = ADC_Volt_Read(potsig1);
  potvalafter = (potvalafter / 2); //Removes voltage adjustment only needed for motors -- Allows the use of the reading function without an
additonal funciton
}

void potadjust(){
 float pothalfdeg = potonedeg / 2;
 float potadjust2 = potadjust1 * pothalfdeg; //number of steps taken by inner dameper motor
 float potvalchange = potvalafter-potvalintial;

   innerstepper.enable();
   outerstepper.enable();

while (potvalchange >= (potadjust2+.002)){


   //Read Pot Value
   potvalintial = ADC_Volt_Read(potsig1);
   potvalintial = (potvalintial / 2);
```

```
   innerstepper.move(-10);
   delay(100);
   delay(delaymove);

   //read the pot val
  potvalafter = ADC_Volt_Read(potsig1);
  potvalafter = (potvalafter / 2); //Removes voltage adjustment only needed for motors -- Allows the use of the reading function without an
additonal funciton
  potvalchange = potvalchange - (potvalintial - potvalafter);
}

while (potvalchange <= (potadjust2-.002)){

   //Read Pot Value
   potvalintial = ADC_Volt_Read(potsig1);
   potvalintial = (potvalintial / 2);

   innerstepper.move(10);

   delay(delaymove);
   delay(100);
   //read the pot val
  potvalafter = ADC_Volt_Read(potsig1);
  potvalafter = (potvalafter / 2); //Removes voltage adjustment only needed for motors -- Allows the use of the reading function without an
additonal funciton
  potvalchange = potvalchange - (potvalintial - potvalafter);
}
   innerstepper.disable();
   outerstepper.disable();
}


// This runs initally to move the dampers to the 'home' or zero degree position
// Will only run again if setup function is called
void setup() {

   //Initialize the stepper drivers
   innerstepper.begin(RPM, MICROSTEPS);
   outerstepper.begin(RPM, MICROSTEPS);

   //Set the enable as active low on the stepper drivers
   innerstepper.setEnableActiveState(LOW);
   outerstepper.setEnableActiveState(LOW);

   //Turn on the stepper drivers - (power the motors)
   innerstepper.enable();
   outerstepper.enable();

   //Initalize the EEPROM storage of the ESP32
   EEPROM.begin(EEPROM_SIZE);

   //Initialize the ADS1115 ADC
   ads.begin();

   //Setup to move the steppers to the home position based on the last EEPROM position.
   innerdamperpos = EEPROM.read(0);
   outerdamperpos = EEPROM.read(1);
   movemotor();      //This will move the system back to zero. Note: If a 10 volt signal is applied, it will cause the system to move back to zero,
and 'jump' till a full cycle of 90 degrees is done.

   innerdamperpos = 0; //Failsafe. This is needed only if setup is called a somepoint.
   outerdamperpos = 0; //Failsafe. This is needed only if setup is called a somepoint.
   EEPROM.write(0,innerdamperpos);
   EEPROM.write(1,outerdamperpos);
   EEPROM.commit();
   delay(1000); //one second delay
```

```
  //Turn the stepper motors off
  innerstepper.disable();
  outerstepper.disable();
}


//General loop
//Continously ran till powered off or system is reset
void loop() {

  // Read the first 0-10VDC signal
  inputvoltage1 = ADC_Volt_Read(inputsig1);
  delay(100);
  // Read the second 0-10VDC signal
  inputvoltage2 = ADC_Volt_Read(inputsig2);

  // Check to make sure inner damper is open further or the same as outer.
  // The inner damper cannout be behind the otter damper
  // This will cause the motor and damper angle to be incorrect in the program
  // because the outer damper will force the inner damper open further.

  //Added A 10mv Value below to fix a slight issue with voltage supply bias voltage
  if ((inputvoltage1 + .01) < inputvoltage2) {
   delay(2500);
  }

  //Determine if the first motor value has changed from the last read
  else if (inputvoltage1 > datahigh1 || inputvoltage1 < datalow1) {
   movemotor();
   delay(100);
   //Read Pot values - call function
   potadjust(); // Comment out to remove pot feedback
  }

   // Determine if the second motor value has changed from the last read. Will skip next part if value doesn't change
  else if (inputvoltage2 > datahigh2 || inputvoltage2 < datalow2) {
   movemotor();
   delay(100);
   //Read Pot values - call function
   potadjust(); // Comment out to remove pot feedback
  }
   // If neither value has changed, wait 2.5 seconds and check the two 0-10vdc signals again
  else {
   delay(2500);
  }
}
```

Feedback Function for Single Damper Terminal Unit

```
void potadjust(){
 float pothalfdeg = potonedeg / 2;
 float potadjust2 = potadjust1 * pothalfdeg; //number of steps taken by inner dameper motor
 float potvalchange = potvalafter-potvalintial;

   innerstepper.enable();
   outerstepper.enable();

while (potvalchange >= (potadjust2+.002)){


   //Read Pot Value
```

```
    potvalintial = ADC_Volt_Read(potsig1);
    potvalintial = (potvalintial / 2);

    innerstepper.move(-10);
    delay(100);
    delay(delaymove);

    //read the pot val
   potvalafter = ADC_Volt_Read(potsig1);
   potvalafter = (potvalafter / 2); //Removes voltage adjustment only needed for motors -- Allows the use of the reading
function without an additonal funciton
   potvalchange = potvalchange - (potvalintial - potvalafter);
}

while (potvalchange <= (potadjust2-.002)){

    //Read Pot Value
    potvalintial = ADC_Volt_Read(potsig1);
    potvalintial = (potvalintial / 2);

    innerstepper.move(10);

    delay(delaymove);
    delay(100);
    //read the pot val
   potvalafter = ADC_Volt_Read(potsig1);
   potvalafter = (potvalafter / 2); //Removes voltage adjustment only needed for motors -- Allows the use of the reading
function without an additonal funciton
   potvalchange = potvalchange - (potvalintial - potvalafter);
}
    innerstepper.disable();
    outerstepper.disable();
}
```

Appendix IX

Economic feasibility (Cost of prototype vs. Mass production cost)

Table 30: Laser Cut Prototype B.O.M Breakdown

Description	Part Number	Manufacturer	Qty	Price per unit ($)	Price per lot ($)
12ft 3/8" Keyed shaft	KS212	Metals Depot	695	229.44	159,460.80
12" 1/4 Unthreaded Spacer	92377A211	McMaster Carr	11,667	7.21	84,119.07
Gear 1	N/A	Custompart.net	20,000	1.21	24,200
Gear 2 Large	N/A	Custompart.net	20,000	1.62	32,400
Gear 2 Small	N/A	Custompart.net	20,000	1.29	25,800
Gear 3 Large	N/A	Custompart.net	20,000	2.60	52,000
Gear 3 small	N/A	Custompart.net	20,000	1.33	26,600
Gear 4	N/A	Custompart.net	20,000	3.36	67,200
Polycarbonate sheets 72"x96"	PUV1WR9M	ACME Plastics	138	253.84	35,029.92
Shaft Adapter	985-004	Black Hawk Supply	20,000	8.24	164,800
Stepper Motor	17HS08-1004S	Stepper Online	20,000	6.57	131,400
Potentiometer	6637S-1-102	Bourns	20,000	14.95	299,000
ESP32 Microprocessor	ESP32 – DevkitC-V4	1	10.00	7	Espressif
DRV8825 Dev Board	2133	2	8.95	7	Pololu
ADS1115 Dev Board	1085	1	14.95	7	Adafruit
5.1k Resistor	MBB02070C5101FCT00	4	0.29	7	Vishay BC Components
5vdc Voltage Regulator	LM7805CT/NOPB	1	1.54	7	Texas Instruments
100uF capacitor	EEU-FR1H101B	3	0.50	7	Panasonic
.1uF capacitor	C315C104M5U5TA7303	1	0.24	7	KEMET
.22uF capacitor	C410C224M5U5TA7200	1	.31	7	KEMET

Table 31: Injection Molding B.O.M Breakdown

Description	Part Number	Manufacturer	Qty needed per unit	Min Qty	Price per unit ($)	Price per lot ($)
12” 1/4 Unthreaded Spacer	92377A211	McMaster Carr	1	11,667	7.21	84,119.07
Gear 1	N/A	Custompart.net	2	20,000	1.21	24,200.00
Gear 2	N/A	Custompart.net	2	20,000	2.91	58,200.00
Gear 3	N/A	Custompart.net	2	20,000	3.93	78,600.00
Gear 4	N/A	Custompart.net	2	20,000	3.36	67,200.00
Polycarbonate sheets 72”x96”	PUV1WR9M	ACME Plastics	1	138	253.84	35,029.92
Shaft Adapter	985-004	Black Hawk Supply	2	20,000	8.24	164,800.00
Stepper Motor	17HS08-1004S	Stepper Online	2	20,000	6.57	131,400.00
Potentiometer	6639S-301-103	Bourns	1	5,000	10.90	54,500.00
Screw Terminal	282837-2	TE Connectivity	3	1	1.04	1.04
Screw Terminal	282837-4	TE Connectivity	2	1	1.58	1.58
Screw Terminal	282837-3	TE Connectivity	1	1	1.18	1.18
ESP32 Microprocessor	ESP32-WROOM-32D	Espressif Systems	1	650	3.80	2470.00
Stepper motor driver	DRV8825PWPR	Texas Instruments	2	2,000	4.24	8480.00
Voltage Regulator	LM7805MPX/NOPB	Texas Instruments	1	2,000	.53	1060.00
LDO voltage regulator	LM1117MPX-3.3/NOPB	Texas Instruments	1	2,000	.44	880.00
Analog to Digital Converter	ADS1115IDGS	Texas Instruments	1	2,500	2.59	6475.00
.22uF 35V Ceramic Capacitor	CGA2B1X7R1V224K050BC	TDK Corporation	3	10,000	.025	250.00
.1uF 10V Ceramic Capacitor	GRM033R61A104ME15D	Murata Electronics	2	15,000	.002	30.00
1uF 10V Ceramic Capacitor	CL10A105KP8NNNC	Samsung ElectroMechanics	2	4,000	.006	24.00
22uF 10V Ceramic Capacitor	GRM21BR61A226ME51L	Murata Electronics	1	3,000	.055	165.00

Table 31: Injection Molding B.O.M Breakdown Continued

Description	Part Number	Manufacturer	Qty needed per unit	Min Qty	Price per unit ($)	Price per lot ($)
.47uF 50V Ceramic Capacitor	GRM155R61H474KE11D	Murata Electronics	2	10,000	.028	280.00
10nF 16V Ceramic Capacitor	C0402C103K4RECAUTO	KEMET	2	10,000	.023	230.00
.1 uF 35V Ceramic Capacitor	GRM033R6YA104ME14D	Murata Electronics	9	15,000	.008	120.00
100uF 50V Aluminum Electrolytic Capacitor	UWT1H101MNL1GS	Nichicon	4	500	.15	75.00
4.7 uF 35V Ceramic Capacitor	GRM219R6YA475KA73D	Murata Electronics	2	4,000	.046	184.00
5.1k 1% Resistor	MBB02070C5101FCT00	Vishay BC Components	4	5,000	.03	150.00
10k 5% Resistor	RC0603JR-0710KL	Yageo	7	5,000	.0022	11.00
1.5k .1% Resistor	ERA-2AEB152X	Panasonic Electronic Components	2	10,000	.043	430.00
100m 5% Resistor	CHV2512-JW-107ELF	Bourns Inc.	4	12,000	.108	1296.00
10k Potentiometer	23BR10KLFTR	TT Electronics/Bl	2	4,000	.068	272.00
SPST .3A 12V Switch	50-0014-00	Judco Manufacturing Inc.	1	1	1.64	1.64
1.5k Ferrite Bead	MMZ2012Y152BT000	TDK Corporation	2	4,000	.024	96.00
	Total Price for First Unit:	$351.17				

Appendix X

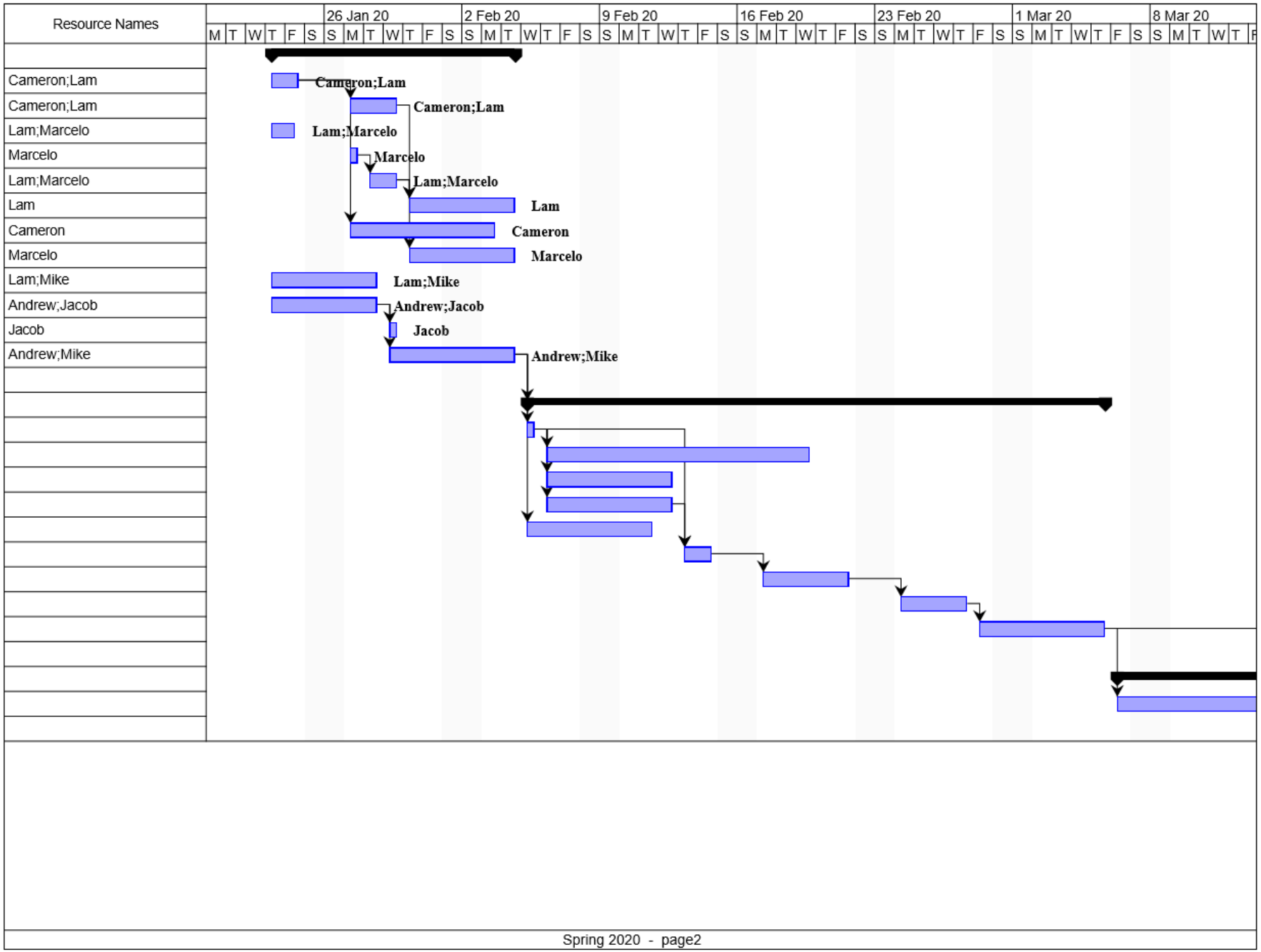
Timelines and milestones with dates

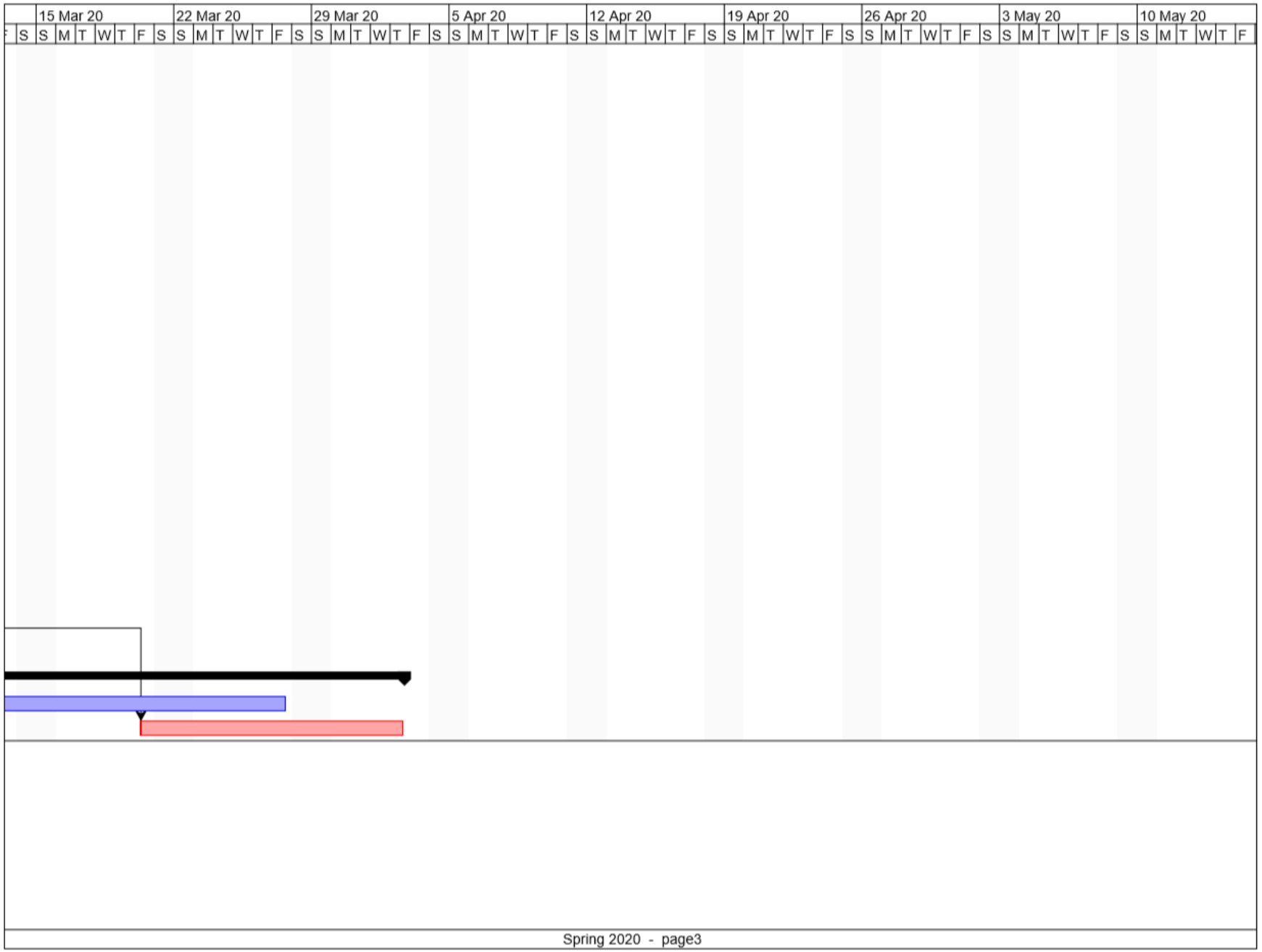
Included below is the milestone table with the expected and actual date of completion as well as the original timeline of the project.

Table 32: Milestone table with expected and actual completion dates

Milestones	Original Expected Completion Date	Completion Checklist	Date Completed
Concept Statement	9/6/2019	X	9/6/19
Questions for sponsor	9/18/2019	X	9/18/19
Met with sponsor	9/20/2019	X	9/4/19
Specifications Sign Off	10/18/2019	X	10/21/2019
Concept Selection	10/25/2019	X	10/28/2019
Faculty Design Review	11/15/2019	X	11/12/2019
Customer Design Review	12/3/2019	X	12/3/2019
Approval to order	12/6/2019	X	12/3/2019
Prototype Sign Off	12/6/2019	X	12/3/2019
CAD Model for Potentiometer Mount	1/29/2020	X	2/2/2020
Re-Design Housing	2/4/2020	X	2/4/2020
CAD model of Actuator	2/4/2020	X	2/4/2020
Begin testing	2/5/2020	X	3/16/2020
Assemble the final product	3/9/2020	X	4/15/2020
Team Testing Complete	3/20/2020	X	4/24/2020
HVAC Testing Complete	4/1/2020	X	4/28/2020
Project Completion	4/2/2020	X	4/28/2020

		Name	Duration	Start	Finish	Predecessors
1		**Phase 1**	**9 days?**	**1/23/20 8:00 AM**	**2/4/20 5:00 PM**	
2		Gather information from gear experts	2 days	1/23/20 8:00 AM	1/24/20 5:00 PM	
3		Finalize O.T.S. gear train (CAD)	3 days	1/27/20 8:00 AM	1/29/20 5:00 PM	2
4		Research and develop POT	1.5 days	1/23/20 8:00 AM	1/24/20 1:00 PM	
5		Design meeting with Barakat	1 day	1/27/20 8:00 AM	1/27/20 5:00 PM	
6		CAD design for POT	2 days	1/28/20 8:00 AM	1/29/20 5:00 PM	5
7		CAD new actuator	4 days	1/30/20 8:00 AM	2/4/20 5:00 PM	3;6
8		CAD new housing	6 days	1/27/20 8:00 AM	2/3/20 5:00 PM	2
9		Investigate different housing materials	4 days	1/30/20 8:00 AM	2/4/20 5:00 PM	6
10		Acquire PCB from HVAC MFG.	4 days	1/23/20 8:00 AM	1/28/20 5:00 PM	
11		Develop testing procedure	4 days	1/23/20 8:00 AM	1/28/20 5:00 PM	
12		Dissect PCB/learn default program	1 day?	1/29/20 8:00 AM	1/29/20 5:00 PM	11
13		Conduct tests on PCB	5 days	1/29/20 8:00 AM	2/4/20 5:00 PM	11
15		**Phase 2 (prototype testing)**	**22 days**	**2/5/20 8:00 AM**	**3/5/20 5:00 PM**	**13**
16		Recieve approval from HVAC to proceed	1 day	2/5/20 8:00 AM	2/5/20 5:00 PM	13
17		Order gears/wait for shipping	10 days	2/6/20 8:00 AM	2/19/20 5:00 PM	16
18		Manufacture housing	5 days	2/6/20 8:00 AM	2/12/20 5:00 PM	16
19		Manufacture actuator	5 days	2/6/20 8:00 AM	2/12/20 5:00 PM	16
20		Continue testing/tweaking HVAC PCB	5 days	2/5/20 8:00 AM	2/11/20 5:00 PM	13
21		Build prototype	2 days	2/13/20 8:00 AM	2/14/20 5:00 PM	16;19
22		Test prototype	5 days	2/17/20 8:00 AM	2/21/20 5:00 PM	21
23		Analyze prototype resuls	4 days	2/24/20 8:00 AM	2/27/20 5:00 PM	22
24		Make necessary design changes	5 days	2/28/20 8:00 AM	3/5/20 5:00 PM	23
26		**Phase 3 (Finalize project)**	**20 days**	**3/6/20 8:00 AM**	**4/2/20 5:00 PM**	
27		Test and Tweak final product	16 days	3/6/20 8:00 AM	3/27/20 5:00 PM	24
28		End of semester paperwork	10 days	3/20/20 8:00 AM	4/2/20 5:00 PM	24


Resource Names
26 Jan 20
2 Feb 20
9 Feb 20
16 Feb 20
23 Feb 20
1 Mar 20
8 Mar 20
M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F
Cameron;Lam
Cameron;Lam
Lam;Marcelo
Marcelo
Lam;Marcelo
Lam
Cameron
Marcelo
Lam;Mike
Andrew;Jacob
Jacob
Andrew;Mike
Cameron;Lam
Cameron;Lam
Lam;Marcelo
Marcelo
Lam;Marcelo
Lam
Cameron
Marcelo
Lam;Mike
Andrew;Jacob
Jacob
Andrew;Mike
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15 Mar 20
22 Mar 20
29 Mar 20
5 Apr 20
12 Apr 20
19 Apr 20
26 Apr 20
3 May 20
10 May 20
S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F
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Appendix XI

ARCI chart

Table 33: ARCI chart shows responsibly of individual team members

Legend: A = Accountable R = Responsible C = Consulted I = Informed	**ARCI Chart**					
	Andrew Aiken	Lam Trinh	Michael Fults	Jacob Adams	Cameron Timbes	Marcelo Zavala
General HVAC research	I	C	I	A	R	I
Stepper motor research	C	I	A	R	I	I
Driver board research	A	I	C	R	I	I
MPU research	C	I	R	A	I	I
IoT research	R	I	A	C	I	I
Gear train research	I	A	I	I	R	C
Decide on initial motor	A	I	R	C	I	I
Decide on initial motor driver board	R	I	C	A	I	I
Decide on initial MPU(s) (order)	R	I	A	C	I	I
Design initial gear trains	I	A	I	I	C	R
3-D Print initial gear train design	I	C	I	I	A	R
Design initial feedback system	I	I	I	R	C	A
Design initial actuator housing	I	A	I	I	R	C
Create/3-D print actuator housing	I	R	I	I	A	C
Check for component compatibility	I	C	R	A	I	I
Create functioning single actuator model for presentation	R	I	C	I	I	A
Create testing program for motor/driver board	C	I	R	A	I	I
Assemble first prototype of co-axial actuator	C	I	I	I	R	A
Test the first prototype	I	A	I	R	C	I
Evaluate the accuracy of the prototype	A	C	I	I	R	I
Evaluate the torque of the system	C	A	I	I	R	I
Revaluate the housing design	I	C	I	I	A	R
Revaluate the gear train	I	R	I	I	C	A
Revaluate feedback system	I	C	A	R	I	I
Revaluate motor selection	C	I	R	A	I	I
Progress testing program	R	I	C	A	I	I
Impliment IoT provisions to the testing program	C	I	A	R	I	I
Evaluate first prototype	I	I	I	C	R	A
Begin design on second prototype	I	A	C	I	R	I
Test second prototype	I	R	I	A	C	I
Evaluate second prototype	A	C	I	R	I	I
Begin design on third prototype	C	I	I	I	A	R
Test third prototype	I	I	A	R	I	C
Evaluate third prototype	I	C	R	I	I	A
Final Product Assembly	C	R	I	A	I	I
Finalize final design	A	I	R	I	C	I
Test final product	I	I	A	R	C	I