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Hero-X: Emerson Air Flow Design Challenge

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Team 12

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Acronyms

P	Power (Watts)
Cp	Maximum power coefficient
ρ	Air density (kg/m^3)
A	Rotor swept area (m^2)
v	Wind speed (m/s)
k	Yield power coefficient (kW)
D	Blade diameter (m)
C_D	Coefficient of drag
F_D	Drag force (N)
F_L	Lift force (N)
V_{FS}	Free stream velocity (m/s)
CFM	Cubic Feet per Minute
FPM	Feet per Minute
T	temperature
MPH	miles per hour
ABS	Acrylonitrile Butadiene Styrene
V	volts
I	current (amperes)
F_w	Wind Force (N)
RPM_f	Rotations per minute of the impeller
QFD	Quality Function Deployment
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
$^\circ F$	Fahrenheit
in	inch
CAD	Computer Aided Design
CNC	Computer Numerical Control

1 Abstract

This report will follow the development cycle as Capstone Team 12 solves the Emerson Airflow Problem. The problem was proposed by Emerson on HeroX: Incentive Competition, Challenges and Prizes forum. This problem is an open competition to any inventors who can solve the dilemma of measuring total air flow in a residential heating, ventilation and cooling system (HVAC). The solutions will be judged against a rubric given by Emerson that includes price-point, accuracy, scalability, ease of installation and ease of use in order of greatest to least importance [5]. The following report outlines the engineering process from interpreting the problem statement up to a proof of concept design. Each section will speak to a critical engineering consideration such as project planning, patent research, cost analysis, evaluation of competition, and design characteristics which lead to the final designs. In the final pages, two carefully designed products which solve the problem statement will be laid out in detail. The first design is a fan matrix which adjusts to fit in any units filter cavity for a non-intrusive reading at the source. The second is small pressure sensor which will traverse a duct and generate a velocity profile for a specific point in the system. Using a simple algorithm, it will determine average velocity in the section. Beyond this report, the team will further prototype and propose the solutions to Emerson by the submission deadline of January 25, 2016.

2 Introduction

This project is part of the HeroX Air Flow Challenge, an initiative to develop a new technology that is capable of measuring total system airflow through a residential HVAC system. HeroX is an online program that allows companies and individuals to create competitions that encourage critical thinkers and design specialists around the world to create breakthrough innovations and develop new technologies that address specific problems [5]. The company that created this challenge is Emerson Climate Technologies, a world leader in assuring comfort, energy efficiency and safety for consumers and retailers with heating, air conditioning, and refrigeration solutions [1].

The decision to pursue this project was made by the team due to experience and interest in the subject matter. Team members Nicholas Harris and Michael Dana have internship experience in the HVAC field and have a strong interest in HVAC engineering. Reid Elleman is an experienced software engineer and excels at utilizing SolidWorks to create complex designs. In the team's preliminary meeting, existing methods of measuring air flow were discussed and compared to the guidelines of the challenge. Following this, more meetings were held to create design specifications based upon the definition of the problem and the guidelines provided by Emerson Climate Technologies.

Emerson Climate Technologies created this competition due to the fact that accurate measurement devices are expensive and inherently intended for commercial systems. The processes to use these devices takes time and can be intrusive. An example would be drilling multiple holes in a duct or a main unit to insert static pressure tips into the system. This requires plugging those holes back up which takes more time, costs more money, and still leaves permanent damage to the system. Such measurement devices are not suitable for residential systems which is what Emerson is interested in.

The design team came up with 90 different concepts that would make it possible to measure total system airflow through an indoor ducted furnace, heat pump, or central Air-Conditioning system. After several meetings these 90 concepts were narrowed down into three main design concepts. Further analysis was done on these three concepts. Reid Elleman did his research and analysis on creating a collapsible rotating fan anemometer. Michael Dana and Nicholas Harris worked on designs that could be inserted into a filter compartment in any HVAC unit. Nicholas worked on a filter insert that uses hot wires such as with hot wire anemometers, to use heat transfer as a mode to measure airflow across the system. Michael worked on a filter insert that utilizes a matrix of five fans to get an accurate airflow reading.

Throughout the development of these designs the team had to make sure it was possible to keep pricing, test time, feasibility, and accuracy in mind. The original plan was to come together after creating these designs and decide which design best met the criteria. But in that meeting the team thought about the possibility of submitting multiple designs to the HeroX challenge. If each team member entered the contest separately, all three of the designs could be submitted. This would require creating three separately Proof of Concept documents and with the deadline approaching, it was decided that only two designs should be further developed to submit to Emerson. Michael and Nicholas worked on the Filter Fan Matrix. Since converting fan RPM into CFM is already known to be a successful airflow measuring technique, the main obstacle for these two team member was designing a collapsible frame in order for the device to be adaptable to any filter compartment size. After further engineering analysis and research was done by Reid on the collapsible rotating fan anemometer, there were some difficulties in with the collapsible design and the accuracy of the measurement it would output. Reid started working on a completely different design that he fully designed within the time constraints provided by Emerson. This design, the Rotating Pitot-tube Differential Pressure Sensor, uses pressure differential as a means to get an airflow reading in CFM. Differential pressure is already a popular method for measuring airflow but this design is much cheaper than existing differential pressure sensors, extremely accurate, and well under the price cap provided by Emerson.

The initial submission deadline for the competition was November 30, 2016. On the 29th of November, once the team had full proposals ready for both designs, an email notification was sent out to all competitors stating that the deadline had been extended to January 25, 2017. This gave the team more time to tweak, improve, and innovate their existing designs. Even if the team does not receive the grand prize, they will continue to develop, fabricate, and market these two designs.

3 Project Planning

During the development of the new method of measuring air flow through duct work, the project plan was developed to keep the design on track and keep the group updated with upcoming important dates such as the submission to the HeroX Competition. The Project Plan can be found in Figures(60-62) on pages (100-102). This depicts the initial meeting with our project sponsor, Professor Nassersharif and the meetings between our team. These meetings were then followed up by research, concept generation, preliminary design, engineering analysis and small scale testing. Along with the flow chart, the Gantt Chart was generated which depicts how much time that each task had been given. The Gantt chart can be found in Figures (60-62) on pages (100-102).

During the semester, Team 12 decided to meet up a good majority of the time to discuss certain tasks that everyone would be in charge of. One person would be in charge of the weekly progress reports and a certain amount of design concepts, another would be in charge of the design work using programs like Solidworks to develop the different design ideas presented by everyone and to develop a cost analysis for the design and another would be in charge of one of the other design as well as cost analysis.The group decided to meet up two to three times a week to discuss possible ideas for the concept generation which were recorded in each person engineering notebook, and to record the tasks that each person would complete that week on the Project Plan. There was ongoing discussion outside of meetings to prepare for presentations and meetings with our sponsor. The tasks would then be divided to accomplish the task in a quick, but effective manner. The group kept our sponsor updated with tasks that were being completed as well as submitting proposals to the sponsor to read over before submission to the University of Rhode Island for possible grant money to put towards our design.

In addition to the meetings within our group and sponsor, Team 12 had multiple presentations that were presented to the Capstone class for evaluation of the overall design and cost analysis. The presentations included preliminary design presentations, critical design presentations, and proof of concept design presentations. Each one of the presentation had a purpose to present the ideas that the group had developed over the semester and the analysis on how these designs would be effective in real world applications.

3.1 Research

During the beginning of the design process, our group was charged with the task of developing thirty (30) design concepts that could be narrowed down to the final design concept. To develop the ideas, research had to be done first. Team 12 needed an idea on what kind of different air flow measurement devices had been developed and were being used in today's market by HVAC technicians. The group found four main ways that HVAC technicians measure airflow: Pressure differential (manometer), fan speed (anemometer), temperature differential, and sonar devices. The group found different companies that develop these types of air flow measurement devices. These companies were Emerson, the competition sponsor, (write in other sponsors). Along with researching the different methods that have been developed the group researched the pricing of the products. The price of these products was used to determine what would be the best solution to allow our products to be better than the competitions.

3.2 Concept Generation

After research, each person in the group was charged with the job of developing thirty (30) different design concepts each. The concepts had to be original be able to solve the problem or task that was presented to the group. The group developed many different ideas that stemmed from research of product that had been already developed. This included ideas such as new ways to use fan speed, temperature and pressure to determine the air flow speed in CFM (cubic feet per minute). Each group member developed their ideas and the group met and narrowed down which ideas were the best to use for the product based on ease of use, the originality of the design and the price that it would take to manufacture the product.

3.3 Preliminary Design

When the concept was finalized, the team decided to go with three (3) different types of designs. The three designs were picked out by the group and then were designed using a 3D design software called Solidworks. These designs were designed using AHU (air handling unit) and fan coil unit specifications. These units produce the air that flows to the duct. Two of the designs dealt with the filter slot that is in the unit and the other dealt with the device being inserted into duct work. To do this the duct work must be drilled into with a $\frac{3}{8}$ in hole which was found through research. The models that were created underwent simulations that tested the overall strength of the design when under the wind velocity conditions specified in the competition.

3.4 Engineering Analysis

Calculations were done after the design was created to make sure that the design would hold up under the conditions specified in the project guidelines. Since the frame work of the design would have a maximum of 2000 CFM of wind applied to it, the calculations were there to make sure that the design would not fail under the conditions. The calculations were used to determine the price of the designs to determine if the design would meet the criteria of the competition which was to be below $100. The calculation were also used to determine the weight of the device to make sure that it would be easy to use in a workplace setting.

4 Cost Analysis

4.1 Product Development Cost

As seen in Table 1, the total cost in the design process for our prototype of the Collapsible Filter Anemometer added up to $278.71. This is not the price of creating the device from a distributor's standpoint. The Hero-X Air Flow Challenge requires that the device must be under $100.00. This total cost shown in Table 1 covers all materials used, including those used in redesigns and edits, as well as all materials required to create a proper testing apparatus.

Component	Unit Price	Quantity	Total
Plastic Gear - 14-1/2 Deg Pressure Angle Press-Fit Mnt, 24 Pitch, 18 Teeth	$6.18	4	$24.72
24 Pitch Rack for Plastic Gear - 14-1/2 Deg Pressure Angle	$7.64	4	$30.56
Lasko B20401 Decor Box Fan, 20", Black	$24.63	1	$28.52
Aluminum Fan	$3.54	1	$3.54
Ball Bearing Trade No. R2 for 1/8" Shaft Diameter, 3/8" OD	$5.94	2	$11.88
Rotary Shaft 12L14 Carbon Steel, 1/4" Diameter	$7.72	1	$7.72
Rotary Shaft 12L14 Carbon Steel, 1/8" Diameter	$2.93	1	$2.93
Brass Screw-to-Expand Inserts for Plastics M8 x 1.25mm Thread Size, 1.25 mm thick Flange	$1.16	4	$4.62
M8 x 1.25mm Screws	$1.11	4	$4.44
DEVCON 5 Minute Epoxy 1oz	$5.59	1	$5.59
Arnold Lumber Trip #1	n/a	n/a	$82.14
Arnold Lumber Trip #2	n/a	n/a	$45.24
1 X WYHP Mini Laser Dot Diode Module Head WL Red 650nm 6mm 5V 5mW Pack of 10pcs	$2.88	1	$2.88
Gorilla Glue Hot Glue Sticks	$5.97	1	$5.97
AIRSUNNY three Legs 5 pairs Infrared Diode LED IR Emission and Receiver	$5.98	1	$5.98
Gikfun USB Nano V3.0 ATmega328 CH340G 5V 16M Micro-controller board For Arduino (Pack of 3pcs) EK1620	$11.98	1	$11.98
TOTAL COST			**$278.71**

Table 1: Product Development Cost

4.2 Market Value

The cost of the actual device is shown below in Table 2:

Component	Unit Price	Quantity	Total
Plastic Gear - 14-1/2 Deg Pressure Angle Press-Fit Mnt, 24 Pitch, 18 Teeth	$6.18	4	$24.72
24 Pitch Rack for Plastic Gear - 14-1/2 Deg Pressure Angle	$7.64	4	$30.56
Aluminum Fan	$3.54	1	$3.54
Ball Bearing Trade No. R2 for 1/8" Shaft Diameter, 3/8" OD	$5.94	2	$11.88
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M8 x 1.25mm Screws	$1.11	4	$4.44
1 X WYHP Mini Laser Dot Diode Module Head WL Red 650nm 6mm 5V 5mW Pack of 10pcs	$2.88	1	$2.88
Gikfun USB Nano V3.0 ATmega328 CH340G 5V 16M Micro-controller board For Arduino EK1620	$3.99	1	$3.99
TOTAL COST			**$97.28**

Table 2: Actual Product Cost

As seen above, the cost of the product using the methods and materials utilized by Team 12 is $97.28, therefore it meets the guideline of keeping cost below $100.00. Since the price of this product is under $100, it makes it very competitive on the open market. Compared to many products on the market which sell for around $150 to $200, the cost to sell a product like the Collapsible Anemometer would be around $120 with the components used in Table 1 and $75 if all the components were produced using injection molding. These values were found by incorporating a 20% increase to account for profit. By having the cost of the Collapsible Anemometer be below the required $100, the device meets the most important part of the design competition. The design competition stressed having less than $100 spent on producing the product. To do this, Team 12 determined using wood and plastic would help keep costs down. since ABS plastic and plywood are very affordable and easy to access, it helped keep the cost down for the prototype. In a manufacturing setting, the design would have to be made by injection molding polypropylene to ensure a cheaper product. This would prevent any problems would parts fitting together and make the product more presentable. Using carbon steel for the shafts drove the price up for the initial design. In the future, aluminum rods will be used to keep price down while making sure the gears can move well without any structural change. By keeping everything polypropylene and aluminum, cost will be significantly decreased.

Overall by using the products used in the prototype design, Team 12 proved that the product can be produced under $100 even with parts that are not considered the cheapest. Due to this any improvements made to part selection will immediately make a huge difference on the price of the product. Though this is outside the scope of work, Team 12 made sure it found the correct materials to be used if it was to be manufactured in a factory setting.

4.3 Cost Analysis based on Human Resources

Time spent on the design was divided up into three (3) sections for each of the group members. The sections for each person include team meetings, product design, product simulations, engineering analysis and preliminary design. Each person from the team spent time on each of these criteria and is reflected in the graphs shown below which divide the time into multiple sections. Team meetings included the time the team met to brainstorm idea the time the team met to discuss what our next task that needed to be complete for the week. Team meeting also included research and development as well as division of tasks. During the fall semester when the team had to present ideas on designs and tests we had done, the group would divide up tasks at the beginning of the week to make sure the team remained on track to present all the designs and testing that had been done to the product. On average these meeting would range from 20 to 60 minutes with some meetings lasting 90 to 120 minutes. Meetings with Professor Nassersharif was included as well. These were held every few weeks to make sure that we were staying on track with our design and to answer any lingering questions that we had.

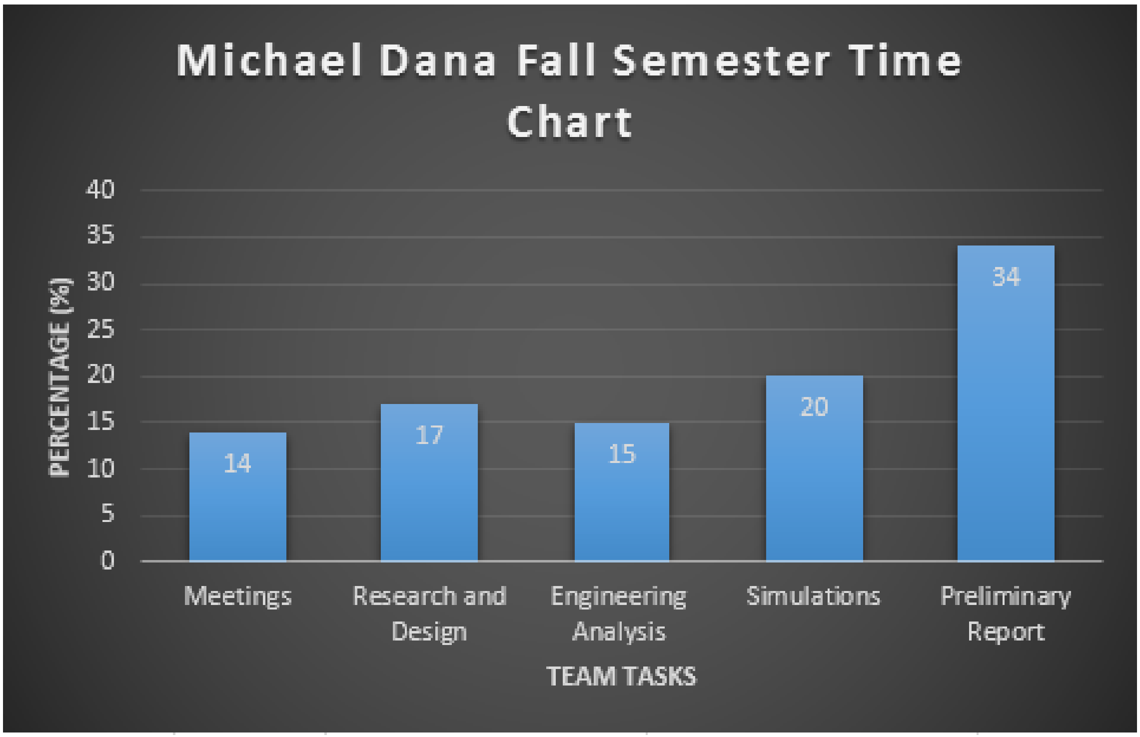


Figure 1: Michael Dana Time Distribution Chart

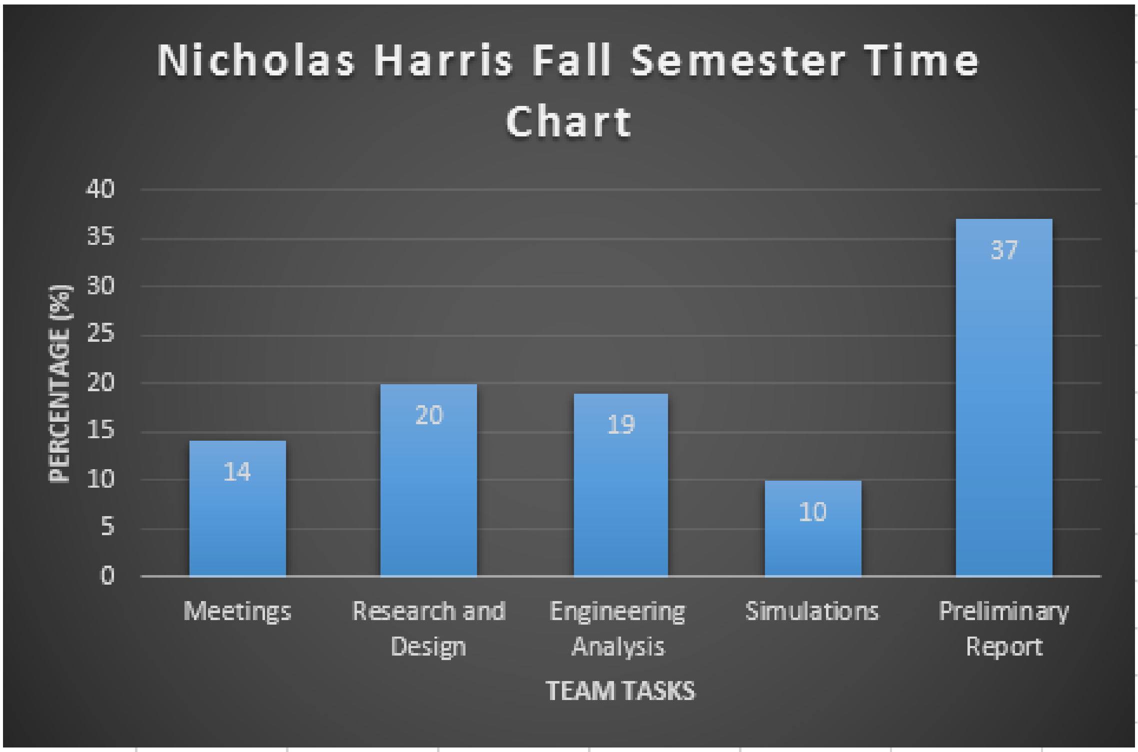


Figure 2: Nicholas Harris Time Distribution Chart

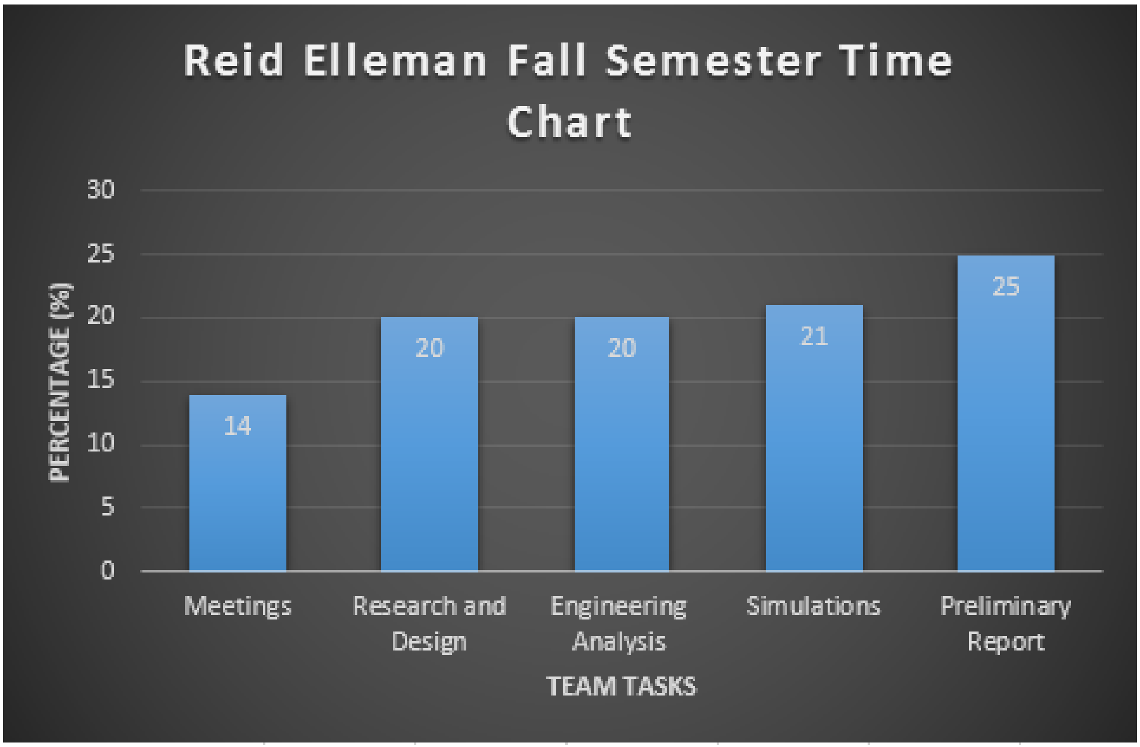


Figure 3: Reid Elleman Time Distribution Chart

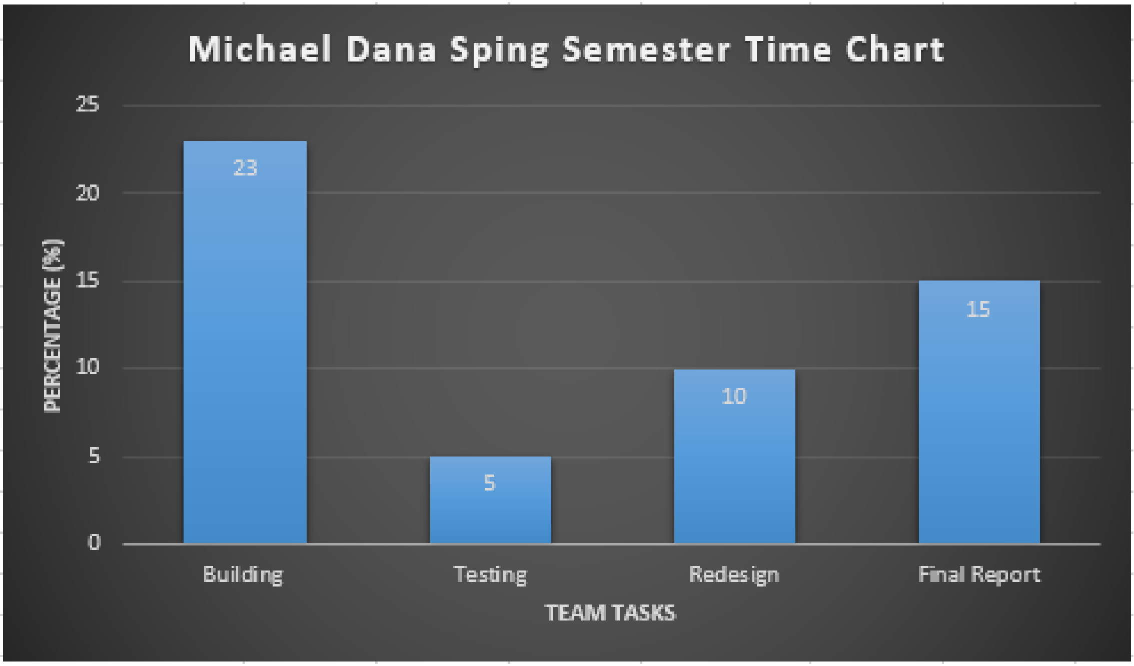


Figure 4: Michael Dana Spring Time Distribution Chart

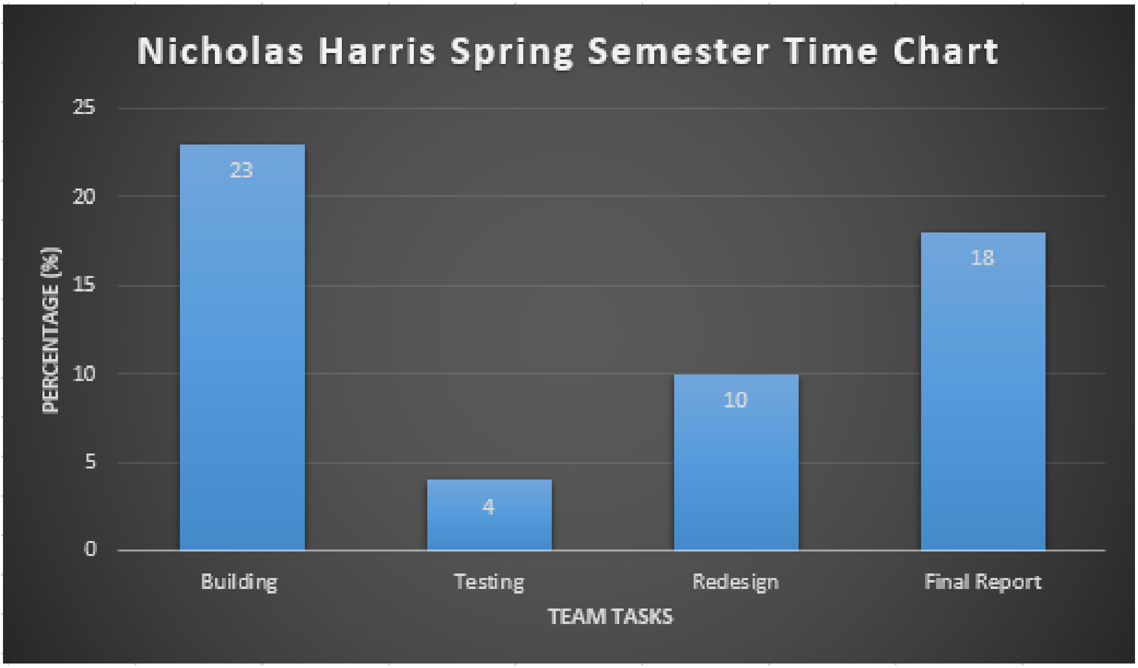


Figure 5: Nicholas Harris Spring Time Distribution Chart

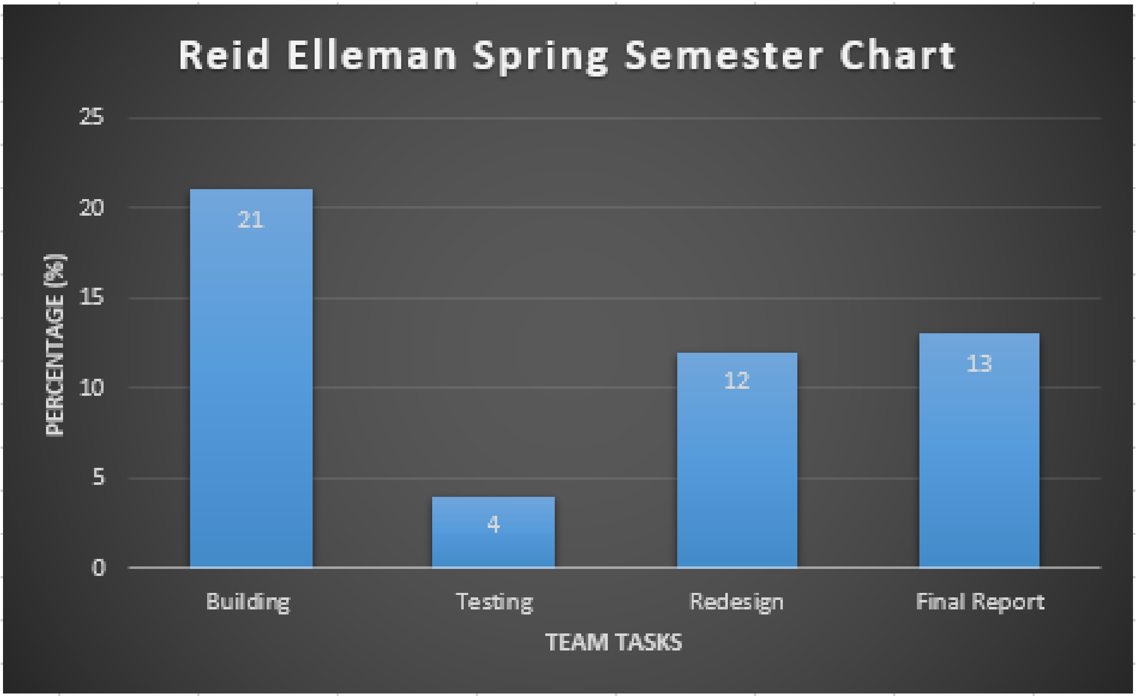


Figure 6: Reid Elleman Spring Time Distribution Chart

4.4 Mass Production Cost

The most important thing with designing a product for the Emerson Competition is that it is more affordable to consumers then most other products.

Thus designing a product that is able to be manufactured at a low cost is of the utmost importance. The design needs to be cheap to fabricate and still reliable. In the problem definition, the product must have an accuracy of +/- 7%. To do this the product must be low cost in the frame work to allow for more expensive software that can be used to reach the accuracy rating that was indicated in the problem definition.

To determine the price of the product many things must be taken into account.Is the part plastic, metal, or another form of material? Is the part cut by a mass production machine or does a human need to shape the product to the specifications indicated on the design drawing? How precise are the dimensions. All of these issues were taken into consideration when the team designed its two products. The manufacturing process and material was then chosen to determine what would be the best for our product if it was to be mass produced by a company.

The manufacturing process was then taken into account. The biggest question was how many manufacturers would be needed to create this product. After finding that answer the next goal was how much it would cost to make molds for the plastic parts of our designs and the cost of bending metal and shaping it to the size we needed for our product. The group determined using injection molding would be the best for our product due to the parts being polypropylene and needing to be mass produced. The team developed a preliminary cost of the material for both products. The Collapsible Anemometer would cost about $97 in material to manufacturer. Tables 2 that demonstrate the cost of the products.

4.5 Funding

To fund this project, Team 12 went through the University of Rhode Island's Undergraduate Research Program which awards teams up to $1400 for their projects. After writing a detailed proposal of the project objectives, goals, and predicted costs, the Undergraduate Research Program awarded Team 12 a grant of $1000. As shown in the financial analysis table above, the team stayed well below that $1000 budget.

4.6 Lowering Cost of Fabrication

Due to unavailability of the 3D printers at Schneider Electric, Team 12 was forced to buy racks to attach to the expandable arms with adhesive. With 3D printer availability, the rack and arm can be printed as one piece and that cost of the racks purchased through McMaster Carr can be eliminated and replaced with a much lower price of 3D printing material.

4.7 Cost of Labor

As for the cost of performing air flow tests with our device for a technician, the average HVAC technician makes about $22 per hour. With a maximum test time of 20 minutes, this means the cost of the test should be no more than $7.33. This is a small price for the owner of the residential HVAC system to pay to ensure that the system is working properly.

To manufacture the product in a factory, the time it takes to manufacture each part must be taken into consideration. Each part will have to go through the stages of injection molding and cooling to produce the final product. Team 12 analyzed the manufacturing of the part and the time and cost it would take for a worker to produce the product. This manufacturing time study can be seen below in Table 3.

Manufacturing Time Study				
Part No.	Part	Number of Parts	Time to manufacture(s)	Price($)
1	Expanding Arms	2	120	0.5
2	Front plate	1	600	2.5
3	Bottom plate	1	600	2.5
4	Rack for gear	2	240	1
5	Gears	4	480	2
6	Carbon Steel Rod 1/4" DIA	1	60	0.25
7	Carbon Steel Rod 1/8" DIA	4	60	0.25
Total		15	2160	9

Table 3: Manufacturing Time Study

The number of parts, part number, time to manufacture and the price are all displayed on the chart. This shows that the price to produce the product would be $9 based on the hourly rate of a worker being $15 per hour. This is relatively cheap and would still produce a good profit if the product was sold at $120. The number of parts for the design to be manufactured out of polypropylene is 15 parts. This keeps the design simplistic and keeps the amount of time to assemble the product from being too long.

The parts that take the longest to manufacture is the front and bottom plate. This is due to the parts consuming the most amount of polypropylene. Due to these parts taking the longest to produce, they cost the most due to the hourly rate of the worker. The price to produce one of the plates is $2.50. To produce both plates, the cost would be $5.00. This is the largest cost of the production. Using a metal fan helps lower the cost of labor since the fan is made out of house by an outside company. Overall cost of labor is very affordable and does not affect how Team 12 designed the product.

5 Patent Searches

Tremendous amounts of research were done by each team member to efficiently develop each design concept. This included cost analysis, statistical analysis, and literature reviews in order to investigate various means of measuring air flow. The team considered cost, ease of use, test time and intrusiveness of variation airflow measurement technologies to see how they fit into the design requirements provided by Emerson Climate Technologies. These requirements included low cost, easy and quick to use by a technician, high accuracy and capable of testing all airflow levels of a typical residential HVAC system. Significant amounts of information were quickly and efficiently gathered throughout the team's patent searches to relate it to the design concepts and the competition guidelines. Listed below are the three most relevant existing patents that apply to the design concepts and guidelines:

Patent Number: US 8430951 B2

Patent Name: Low cost fluid flow sensor

Patent Date: April 30, 2013

Patent Description: A system and method for a low cost fluid flow sensor is described. One embodiment includes a fluid flow sensor comprising a first resistance temperature detector configured for generating a flow signal, wherein the flow signal is based on a fluid velocity, and wherein the first resistance temperature detector is configured for a fluid temperature range; a second resistance temperature detector configured for generating a temperature signal, wherein the temperature signal is based on a fluid temperature; and a controller coupled to the first resistance temperature detector and the second resistance temperature detector, the controller configured for receiving the flow signal and the temperature signal, wherein the controller takes a first controller action when the temperature signal is within a temperature signal range substantially representative of the fluid temperature range, and the flow signal is within a flow signal range, wherein the flow signal range is determined based on the temperature signal.

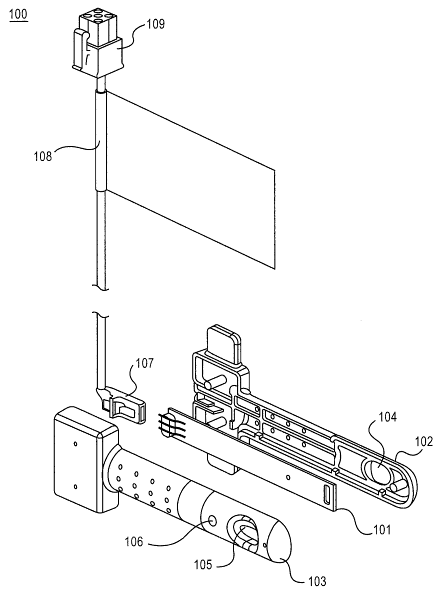


Figure 7: Patent US 8430951 B2 Drawing

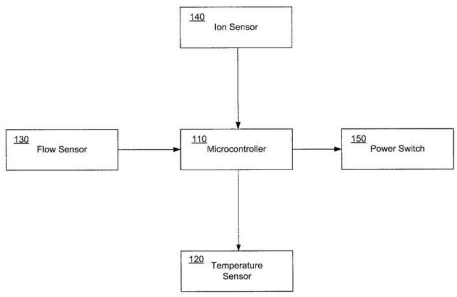


Figure 8: Patent US 8430951 B2 Block Diagram

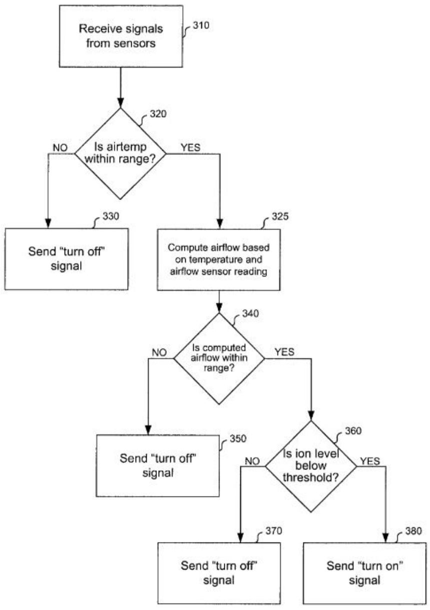


Figure 9: Patent US 8430951 B2 Logic Diagram

Patent Number: US 8235777 B2

Patent Name: Fully articulated and comprehensive air and fluid distribution, metering and control method and apparatus for primary movers, heat exchangers, and terminal flow devices

Patent Date: Aug 7, 2012

Patent Description: The described method and apparatus pertains namely to the HVAC (Heating, Ventilating, and Air Conditioning) industry, though its many functions extend into any and all forms of air-fluid movement, metering, distribution, and containment. Essentially, the scope of operation of the method and apparatus encompasses all forms of scientific and engineering measurement dealing with fluid dynamics, fluid statics, fluid mechanics, thermal dynamics, and mechanical engineering as they pertain to precise, articulated control of air-fluid distribution and delivery. The described method and apparatus offers complete, comprehensive, and correct utilization of air-fluid movers and terminal devices under unique sensor logic control, from initial lab testing stages through to equipment cataloging, selection, design and construction of any and all air-fluid distribution systems in entirety, whereas previously there was no such cohesive, total and terminal method of control for these systems or their components.

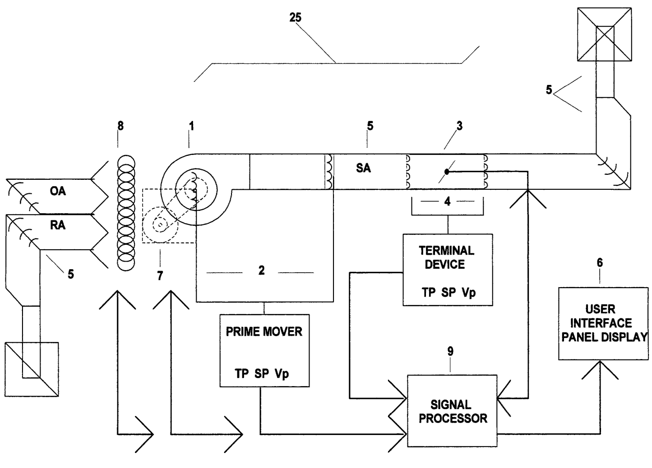


Figure 10: Patent US 8235777 B2 Schematic

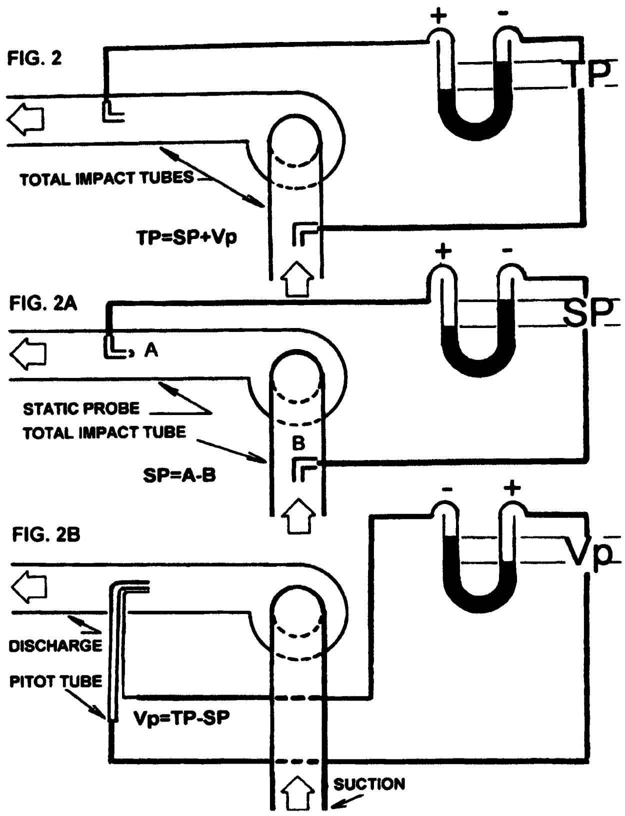


Figure 11: Patent US 8235777 B2 Design Layout

Patent Number: US 20050030172 A1

Patent Name: Detector with dust filter and airflow monitor

Patent Date: Feb 10, 2005

Patent Description: A device for monitoring changes in airflow rates through detector dust filters in addition to assessing air for alarm indicators, including smoke, heat, gas, and relative humidity, is provided. A method monitors airflow through the detection device and provides a maintenance indication when the airflow has been reduced due to contamination of the dust filters.

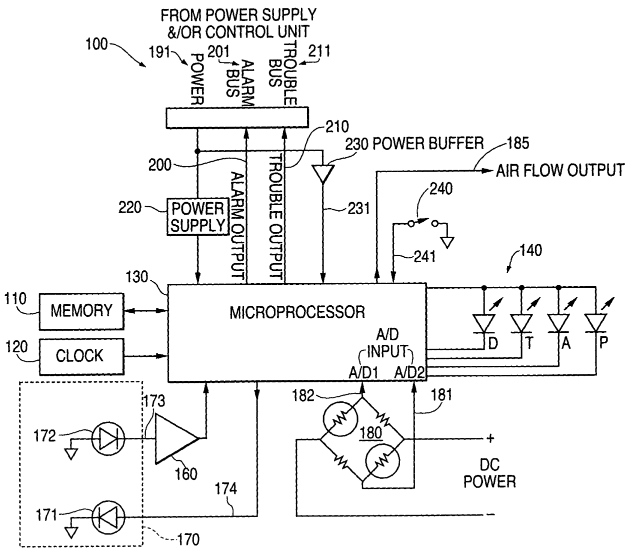


Figure 12: Patent US 20050030172 A1 Electrical Diagram

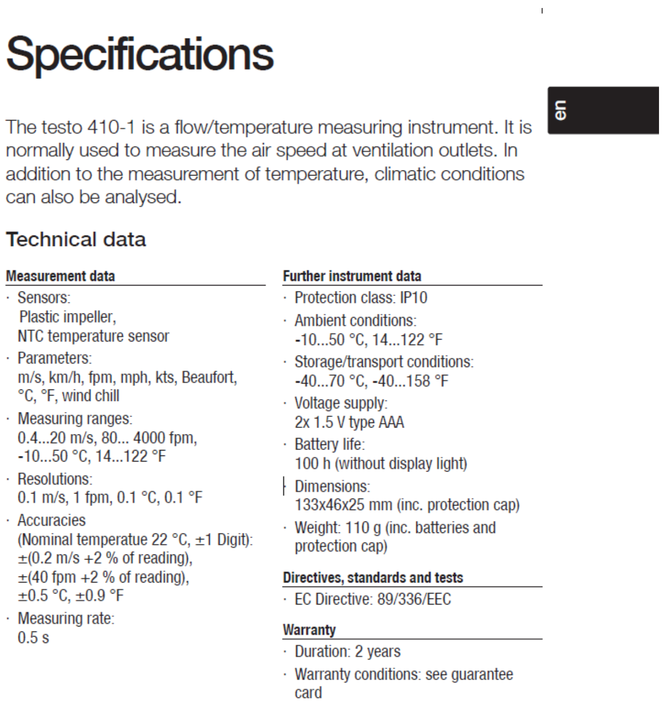
6 Evaluation of Competition

Emerson presented a competition to the team of designing a new method of measuring air flow in residential duct work. To begin, the team had to research other companies and what they had done in the past when creating air flow measurement devices. During this stage, we complied a list of four (4) large companies that have designed methods of measuring air flow and have mass produced these tools to consumers such as HVAC technicians. The company's that the team found were Testo, Airflow monitor, Dwyer, and Truetech tools. Even though these companies make a large array of airflow measurement devices, our group narrowed there products down to different forms of anemometers and manometers. Images of the tools created by the companies are included as well.

6.1 Testo

Testo is a competitor that designs many different types of measurement devices. One of the devices is the Testo Rotating Vane Thermo Anemometer. There are various types of the Thermo Anemometer ranges in accuracy and price. The Testo 410-2 Rotating Vane Thermo Anemometer is the closest to the teams Fan Filter Design because it uses a rotating fan to measurement the speed of the air flow and convert it to CFM.The devices works well as air flow measurement devices due to the accuracy of the measurement device. The device has a range of reading from 80 to 4000 FPM. The accuracy is +/- 40 FPM +/-2% of reading. Figures (10-11) shows the design specification sheet and shows the technical data. The Testo 410-2 Rotating Vane Thermo Anemometer also has a measuring rate of 0.5 seconds from when it reads the air flow to when it outputs FPM of the air flow [15].

Figure 13: Testo 410-2 Rotating Vane Thermo Anemometer



Specifications

en

The testo 410-1 is a flow/temperature measuring instrument. It is normally used to measure the air speed at ventilation outlets. In addition to the measurement of temperature, climatic conditions can also be analysed.

Technical data

Measurement data

- Sensors:
  Plastic impeller,
  NTC temperature sensor
- Parameters:
  m/s, km/h, fpm, mph, kts, Beaufort,
  °C, °F, wind chill
- Measuring ranges:
  0.4...20 m/s, 80... 4000 fpm,
  -10...50 °C, 14...122 °F
- Resolutions:
  0.1 m/s, 1 fpm, 0.1 °C, 0.1 °F
- Accuracies
  (Nominal temperatue 22 °C, ±1 Digit):
  ±(0.2 m/s +2 % of reading),
  ±(40 fpm +2 % of reading),
  ±0.5 °C, ±0.9 °F
- Measuring rate:
  0.5 s

Further instrument data

- Protection class: IP10
- Ambient conditions:
  -10...50 °C, 14...122 °F
- Storage/transport conditions:
  -40...70 °C, -40...158 °F
- Voltage supply:
  2x 1.5 V type AAA
- Battery life:
  100 h (without display light)
- Dimensions:
  133x46x25 mm (inc. protection cap)
- Weight: 110 g (inc. batteries and protection cap)

Directives, standards and tests

- EC Directive: 89/336/EEC

Warranty

- Duration: 2 years
- Warranty conditions: see guarantee card

Figure 14: Testo 410-2 Rotating Vane Thermo Anemometer Specification Sheet

The durability of the Testo 410-2 Rotating Vane Thermo Anemometer is one of the biggest components to their design. The battery can last 100 hours without using the display light. This is powered using two 1.5 volt type AAA battery. The weight specified on the specification sheet is 110 grams or 0.2204 lbs. This allows the user to use a very minimal amount of strength to use the sensor. This puts less stress on the user and makes it easier to test the air flow in the duct work. The temperatures that the sensors can accurately read at ranges from 14 to $122°F$. This allows for the user to test the air at high and low temperatures in the middle of the summer or the middle of the winter. The fan is designed out of plastic and it has a NTC temperature sensor.

The competitor to the pressure differential design of Team 12 is the Testo 510. This design by Testo has an accuracy of +/- 0.03% hPa. This is one of the most accurate measurement devices that Team 12 has observed from the air flow measurement devices. The parameters have a large range, but the two that are the most important to the group is Pa (pascals) and FPM. This devices works under ambient temperature between -40 and $158°F$. This wide range allows the device to work in various conditions. Below is an image of the Testo 510 and the specification sheet provided by Testo.[15]

Figure 15: Testo 510 Pressure Differential Sensor

The voltage that the Testo 510 takes is two 1.5 volts type AAA. This allows the battery life to last 50 hours with the display light turned off. The weight of the Testo 510 is 90 grams or 3.2 oz which allows for a low operating weight. The low operating weight allows for the user to use the device without strain on the user. It has a very low measuring rate of 0.5 seconds which allows the user to be able to read the device and make a judgment in a very quick and effective manner.The device has a two year warranty and warranty conditions vary.

Technical data

Measurement data

- Sensor:
  Differential pressure sensor
- Parameters:
  Pa, hPa, mbar, mm$H_2$0, mmHg, inHG, in$H_2$0, psi, m/s, fpm
- Measuring ranges:
  0...100 hPa, 0...40.15 in$H_2$0
- Resolutions:
  0.01 hPa, 0.01 in$H_2$0
- Accuracies
  (Nominal temperatue 22 °C, ±1 Digit):
  ±0.03 hPa (0...0.30 hPa),
  ±0.05 hPa (0.31...1.00 hPa),
  ±(0.1 hPa+1.5 % of reading)
  (rest of range),
  ±0.01 in$H_2$0 (0...0.12 in$H_2$0),
  ±0.02 in$H_2$0 (0.13...0.40 in$H_2$0),
  ±(0.04 in$H_2$0 +1.5 % of reading)
  (rest of range)
- Measuring rate:
  0.5 s

Further instrument data

- Protection class: IP40
- Pitot-factor: 1
- Ambient conditions:
  0...50 °C, 32...122 °F
- Storage/transport conditions:
  -40...70 °C, -40...158 °F
- Voltage supply:
  2x 1.5 V type AAA
- Battery life:
  50 h (without display light)
- Dimensions:
  119x46x25mm / 4.7x1.8x1.0 in (inc. protection cap)
- Weight: 90 g / 3.2 oz (inc. batteries and protection cap)

Directives, standards and tests

- EC Directive: 2004/108/EEC

Warranty

- Duration: 2 years
- Warranty conditions: see guarantee card

Figure 16: Testo 510 Pressure Differential Sensor Specification Sheet

6.2 Airflow Monitor

Airflow Monitor develops many different types of airflow measurement devices. One of the main competitors to the design designed by Team 12 is the Airflow Monitor AN100. This Vane Thermo Anemometer converts the air velocity of air flowing through duct work from FPM to CFM as well as read temperature. It can present both metric and English units to the reader. This device has an extendable arm which runs from the fan to the sensor. This sensors is primarily designed to read CFM from a diffuser or supply air vent. The device has a range of 80 to 5906 FPM and is accurate to +/- 3% FPM. The resolution of the product is to 1 FPM which means it reads every 1 FPM instead of every 0.1 FPM. Below is diagram of the design of the Airflow Monitor AN100 as well as the specification sheet provided by Airflow Monitor [3].

One main factor that differs from the Testo is the AN100 is 700 grams or 1.543 lbs. This add excess weight to the user and make it more difficult for the user to use. However, the low weight still means there isn't a ton of stress put on the user to use the device. The air temperature range that the device can

Figure 17: Airflow Monitor Model AN100

Specifications	Range	Resolution	Basic Accuracy
Air Velocity	0.40 to 30.00 m/s	0.01 m/s	±3% m/s
	1.4 to 108.0 km/h	0.1 km/h	±3% km/h
	80 to 5906 ft/min	1 ft/min	±3% ft/min
	0.9 to 67.2 mph	0.1 mph	±3% mph
	0.8 to 58.3 knots	0.1 knots	±3% knots
Air Temperature	14 to 140°F (-10 to 60°C)	0.1°F/°C	±6.0°F (3°C)
InfraRed Temperature	-58 to -4°F (-50 to -20°C)	0.1°F/°C	±9.0°F (5.0°C)
(AN200 Only)	-4 to 500°F (-20 to 260°C)	1°F/°C	±2% reading or ±2°F (°C) whichever is greater
Airflow	0 to 9999 CMM (m^3/min)	0.1	
	0 to 9999 CFM (ft^3/min)	0.1	
Dimensions/Weight	7 x 2.9 x 1.3" (178 x 74 x 33mm)/1.6lbs (700g)		

Figure 18: Airflow Monitor Model AN100 Specification Sheet

function is between 14 and 140°F. This allows the user to function in a vast array of temperatures without failure. One function of this design that differs from Team 12's design is the InfraRead Temperature Sensor. This allows the user to test the temperature of the air before running an air velocity. However, this is only provided on the AN200 model of the Vane Thermo Anemometer. The range of CFM that the device can test is from 0 to 9999 CFM. This design can test higher wind velocities compared to Team 12's design which is designed to be able to test in a range of 0 to 2000 CFM.

6.3 Dwyer

Dwyer is a company that designs a variety of fluid flow testing devices such as water flow through pipes and air flow. One of their main devices that compete with Team 12's Fan Matrix device is the Dwyer Model 89088. This device measure air velocity using a small fan. The device is accurate to +/- 5% and it can measure air speed from 60 to 3937 FPM. It has a resolution of 0.1 which allows it to read to the nearest decimal place. Below is an image of the Dwyer Model 89088 and the specification sheet provided by Dwyer [12].

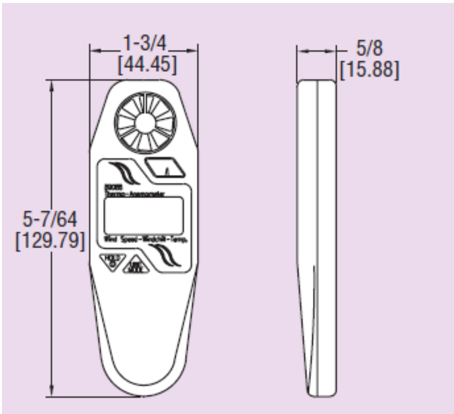


Figure 19: Dwyer Anemometer Model 89088

Units vs. Range as shown on display

Unit	Range	Resolution
M/S	1.1 to 20.0	0.1
FT/MIN	60 to 3937	0.1
KNT	0.4 to 38.8	0.1
KMH	0.8 to 72.0	0.1
M/H	0.5 to 44.7	0.1
BF	1 to 8	1

Figure 20: Dwyer Anemometer Model 89088 Unit vs Range Chart

SPECIFICATIONS
Air Velocity Range: 1.1-20.0 m/s, 60-3937 ft/min, 0.4-38.8 knots, 0.8-72.0 k/hr, 0.5-44.7 mph, 1-8 beaufort.
Wind Speed Limits: 0.5-44.7 mph (60-3937) ft/min.
Temperature/Wind Chill Limits: 0 to 50°C (32 to 122°F).
Accuracy: Velocity: ± 5% or ± last significant digit (whichever is greater); Temperature: ±1°C (±2°F).
Resolution: Temperature: 0.1°; Air velocity: See chart.
Power Requirements: 3 V CR2032 lithium metal battery, included, user replaceable.
Battery Life: 48 hour life under continuous usage. Auto-off: After 5 minutes.
Materials: Impeller: ABS; Case: ABS.
Display: 28 (L) x 16 (W) mm.
Weight: 50 g (1.76 oz).
Agency Approvals: CE.

Figure 21: Dwyer Anemometer Model 89088 Specification Sheet

The Dwyer air measurement device is weighs 1.76 oz which is significantly smaller than the other products mentioned above. This allows the user to be able to use the product and have no physical problems while using the product. This is important to allows for an accurate measurement. The battery lasts 48 hours under continuous usage using a 3 V CR2032 lithium metal battery that is replaceable if needed. The materials used to make the product are ABS plastic which is used to make the impeller fan part as well as the outside casing. This type of air measurement device measures temperature as well. The accuracy of the temperature reader is +/- 1°C or +/- 2°F. The resolution for the temperature reader is 0.1°.

The Dwyer pressure measurement device that is closely related to the design made by Team 12 is the Dwyer Series 475. This is a manometer that measures the differential pressure in the duct work of a HVAC system. It has an accuracy of +/- 0.5% of the value that is outputted. It has a temperature limit to be able to test the differential pressure of 140°F and ranges from 0 to 140°F. It has two barbed connections to fit into the holes that are drilled into the duct. The diameter of the bard is 1/8" and is made of ID tubing. Below is an image of the Dwyer Series 475 and the specification sheet provided by Dwyer.

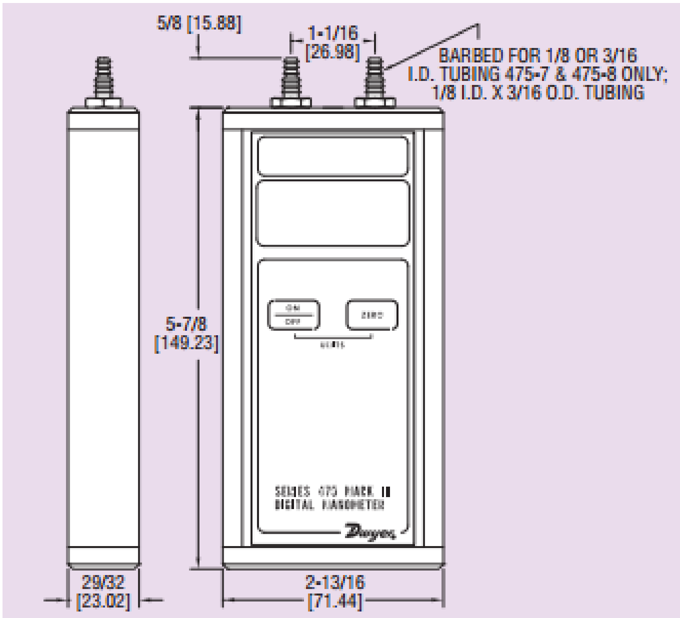


Figure 22: Dwyer Series 475

Model	English Range	Metric Range	Maximum Pressure
475-000-FM	0-1.000 in w.c.	.2491 kPa	5 psig
475-00-FM	0-4.000 in w.c.	0.996 kPa	5 psig
475-0-FM	0-10.00 in w.c.	2.491 kPa	5 psig
475-1-FM	0-20.00 in w.c.	4.982 kPa	10 psig
475-2-FM	0-40.00 in w.c.	9.96 kPa	10 psig
475-3-FM	0-200.0 in w.c.	49.82 kPa	30 psig
475-4-FM	0-10.00 psi	.6895 bar	30 psig
475-5-FM	0-20.00 psi	1.379 bar	60 psig
475-6-FM	0-30.00 psi	2.069 bar	60 psig
475-7-FM	0-100.0 psi	6.895 bar	150 psig
475-8-FM	0-150.0 psi	10.34 bar	200 psig

Figure 23: Dwyer Series 475 Pressure Reading and Range Chart

SPECIFICATIONS
Service: Air and compatible combustible gases.
Wetted Materials: Consult factory.
Accuracy: ±0.5% full-scale, 60 to 78°F (15.6 to 25.6°C); ±1.5% full-scale from 32 to 60°F and 78 to 104°F (0 to 15.6°C and 25.6 to 40°C).
Pressure Hysteresis: ±0.1% of full-scale.
Pressure Limits: See chart.
Temperature Limits: 0 to 140°F (-17.8 to 60°C).
Compensated Temperature Limits: 32 to 104°F (0 to 40°C).
Storage Temperature Limits: -4 to 176°F (-20 to 80°C).
Display: 0.42" (10.6 mm) 4 digit LCD.
Resolution: See chart.
Power Requirements: 9 V alkaline battery, installed non-functional, user replaceable.
Weight: 10.8 oz (306 g).
Process Connections: Two barbed connections for use with 1/8" (3.18 mm) or 3/16" (4.76 mm) ID tubing. Two compression fittings for use with 1/8" (3.18 mm) ID x 1/4" (6.35 mm) OD tubing for 475-7-FM & 475-8-FM only.
Agency Approvals: CE, FM.

Figure 24: Dwyer Series 475 Specification Sheet

The power requirements of the Dwyer Series 475 is 9 V Alkaline battery which can be replaced by the user. The weight of the manometer is 10.8 oz which allows the user to use the manometer in a safe and effective manner. It has a 0.42" 4 Digit LCD. Due to the sensitive nature of the device, the manometer must be stored at a temperature range of $-4°F$ to $176°F$. This shows the device can be stored at even some of the worst climates and still function.

6.4 TruTech

TruTech is a company that makes a wide variety of HVAC measurement devices and HVAC parts and equipment. The product that they provide that is competing against Team 12's pressure differential is the TruTech Dual-Port Manometer - SDMN5. This device measures pressure using two probes that are inserted into the duct work through 1/8" holes that are drilled into the duct work. The Dual-Port Manometer - SDMN5 has an accuracy of +/- 1.5% and a resolution of 0.01 mBar. It has multiple forms of unit measurement which are inWC, mmWC, mbar, PSI. This allows the user to be in English and metric pressure units. The accuracy stated is at a range of temperatures that vary from 32 to $122°F$. The TruTech Dual-Port Manometer - SDMN5 has an operating temperature that ranges from 32 to $122°F$ or 0 to $50°C$. The TruTech Dual-Port Manometer - SDMN5 is compatible with dry, non corrosive media. This involves gases such as dry air flowing through duct work and does not involve fluids such as water or water vapor. Below in Figures()() is the image of the TruTech Dual-Port Manometer - SDMN5 and the specification sheet provided by TruTech [10].

Figure 25: TruTech Dual Port Manometer SDMN5

- Accuracy: Stated accuracy at 0 to 50°C (32 to 122°F): ±1.5% FS
- Battery: Single standard 9-volt battery, NEDA 1604, JIS 006P, IEC 6F22.
- Battery Life: 200 hours with low battery indicator on display.
- Operating environment:
- 32°F (0°C) to 122°F (50°C)
- Compatible Media: Dry, non-corrosive gases
- Over range: "OL" or "-OL" is displayed.
- Auto-Off power: 15 minutes
- Low Battery: symbol is displayed.
- Dimensions: 180mm(~7 1/16")(H) x 60mm(~2 3/8")(W) x 30mm(~1 3/16")(D)
- Weight: approximately 195g (~1/2 pound) including battery

Pressure:

- Pressure Ports: tube connectors for 5mm (~3/16 inch) I.D. flexible tubing
- Units of Measure: inWC, mmWC, mbar, PSI
- Resolution: 0.01 inch WC (0.1mmWC, 0.01mBar)
- Accuracy: ±1.5% FS
- Measurement Range:
- In WC: 0.00 to ±60.0
- mm WC: 0.0 to ± 1500
- mBar: 0.00 to ±150.0
- PSI: 0.000 to ±2.000

Figure 26: TruTech Dual Port Manometer sDMN5 Specification Sheet

The TruTech Dual-Port Manometer - SDMN5 has a weight of 195g or 1/2 pound including the battery. This is a higher weight compared to a lot of competition out there. The battery is a 9-volt battery and the battery life lasts 200 hours with low battery indicator on display. The measurement range of the TruTech Dual-Port Manometer - SDMN5 for PSI is 0 +/- 2.0.

6.5 Evaluation

After careful analysis of all the different types of competition Team 12 was able to determine certain areas to stress during design. Area's such as cost, accuracy, and power were the biggest concerns to the group. Making this product to be able to compete in the open market is important. If the group is able to develop a device that fits within the cost restrictions then it will compete. However, certain parts that the competition developed will not be implemented into the design unless seen fit. The main design specification that will not be implemented into the Fan Filter Matrix is the thermometer or temperature gauge. The temperature gauge is not part of the problem statement that was presented to the group by the competition leader, Emerson. Even though the pressure gauge developed by Team 12 will possess a temperature gauge, Team 12 determined a temperature gauge on the Fan Filter Matrix would not be important to the design and would add unnecessary cost. The main concern of the product is to measure air flow in the guidelines specified. Anything added to the product would add value as long as the budget limit is not exceeded. If the group determines that a temperature gauge would add value to the Fan Filter Matrix, then the design specification will be updated and the part will be added to the design.

Due to cost restriction, the design will not be able to possess some of the same tools that the other competition has implemented into their design, however the design will be more cost effective. Looking at competition the price range for the products ranged from $100 to $200. The cost of Team 12's product will be much less than the competition to make sure that we can compete with the market. The goal of Team 12's design is to be less than $100. This will allow for the product to compete on the market. Due to the cost of other products on the market, a product being less than $100 would sell at a huge rate. To design a product for less than $100 and have it be near the same quality of the more expensive product is a challenge. To develop a device with the same amount of accuracy as the products on the market, precise measurements will have to be taken into consideration. If this is accomplished Team 12's products will be the most cost effective products on the market to date.

The team would like to be able to have a low accuracy to compete as well. This would allow the team's product to compete if it is able to have a low cost high accuracy design. The pressure product designed by Team 12 will be able to be inserted into the same size hole that the competitions is able to inserted into. This will prevent excess material to be drilled out in the duct and make it easy for the technician to test the pressure in the duct work. The goal is to develop a product that is able to read within +/- 1% of the read value. This will allow for less error when reading the CFM in the system. The price of the products will be low compared to market value. Since the goal of this product is to make a low cost product, having a low cost, high accuracy product would add to the market value.

7 Specifications Definition

An essential part of creating engineering product designs for the Fan Filter Matrix and the Rotating Pitot-tube Differential Pressure Sensor was constructing a precise series of design specifications. These specifications were derived through extensive research on competitive designs as well as through the competition guidelines provided by Emerson Climate Technologies. This set of design specifications helped construct successful designs for each product based on the original problem statement proposed by Emerson.

Mechanical Requirements	Value
Low Price	Below $100.00 USD
Capable of measuring total airflow of residential HVAC systems	0-2000 CFM
High Accuracy of Measurement	+/- 7%
Manageable weight of device	Under 5 pounds
Short installation + testing time	Under 20 minutes total
Must be consistent and robust	Lifespan of 5+ years
Maintain air quality for test duration	MERV 8 filtration

Table 4: Specifications Definition Parameters

Table 3 shows the list of mechanical parameters necessary to make the Fan Filter Matrix and the Rotating Pitot-tube Differential Pressure Sensor capable of winning the HeroX Air Flow Challenge and to make them competitive in the airflow measurement market.

1) Keeping the cost low is the most important parameter to win the competition and make the products competitive. Emerson Climate Technologies requires that the submitted designs must have a cost that does not exceed $100.00 USD.

2) The two designs must have the capability of measuring airflow anywhere from zero to 2000 CFM to ensure it is fit to measure total airflow through any residential HVAC system.

3) Most airflow measurement devices on the market air extremely expensive but also very accurate. Most of the competitive devices have accuracies of plus or minus five percent or better. However, these products with such high accuracies are geared more towards commercial or industrial testing. To receive the highest possible judging score, Emerson is demanding any submitted designs to have accuracies of plus or minus seven percent or better. This will ensure that the designs will be accurate enough for residential testing.

4) For the purpose of minimizing time an effort, a weight limit of five pounds was set for the devices. This will allow for a quick and easy test by the technician.

5) Emerson requested that the design will allow for installation plus testing time to be no longer than 20 minutes. This means less money spent on labor hours of the testing technician.

6) The devices will have a lifespan of over five years so that HVAC contractors won't have to continuously repurchase. The devices will maintain accuracy for the whole duration of their lifespan. This will maximize points credited to the team for robustness in the HeroX Air Flow Challenge.

7) For the Fan Filter Matrix design, an accommodation had to be added in order to keep allergens and unwanted particles from entering the ventilation system. A MERV 8 filter was added to the design to maintain filtration for the duration of the test.

These design specifications served as a foundation for the two designs. They were referred to and analyzed repeatedly and vigorously throughout the whole design process. Without having specific numerical limits, or targets, there is no solidity to the course of the design. These specifications created a pathway for the successful design of the two devices.

8 Conceptual Design

To conceptualize product designs for the competition, the team had to pick a starting point. To begin the design process, each team member agreed to generate 30 concepts (90 total) with a brief description of how they could meet Emerson's guidelines. This brainstorming method is very efficient for design teams for conceptualizing design ideas for a certain product. It allows for the familiarization with certain concepts and theories, opens the minds of the engineers to the field of interest, and in the end certain ideas can be collaborated into one improved design. These 90 concepts are listed below with brief descriptions of each:

8.1 Nicholas Harris' 30 Concepts

1. Flow hood with fan attached.

   This flow hood would be sealed over the supply register vent. Air flow would cause the fan to spin at a certain speed and RPM would be converted to CFM

Figure 27: NH Concept 1

2. Flow hood with handheld anemometer

   This flow hood would also be sealed over the supply register vent but instead of having a fan attached within the hood, a handheld anemometer would be used through the traverse measurement method (measurements at different locations averaged).

Figure 28: NH Concept 2

3. Handheld anemometer

   This concept would involve designing a cheap and accurate anemometer and doing a traverse measurement the supply intake vent.

4. Drill holes in main unit and seal “mini flow hoods” over holes

   This concept involves designing and fabricating “mini flow hoods” to be attached to multiple locations around the main unit where small holes are drilled allowing the airflow to escape through these holes.

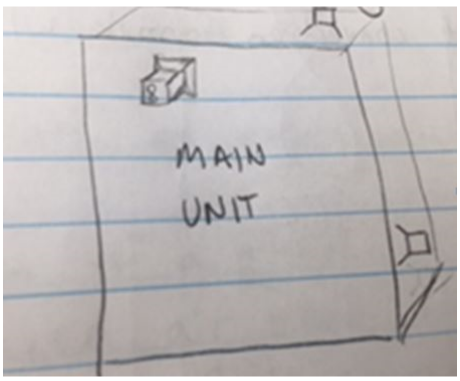


Figure 29: NH Concept 4

5. Temperature probe change in temp over time

   This concept would involve removing the intake vent or drilling a hole the size of the probe in the main unit, and inserting a heated temperature probe into the system. Heat transfer over time would be used as a means to output CFM.

6. Flow hood swing method

   This concept involves a swinging 'door' attached to hinges on end of flow hood. Air flow would then be measured by first measuring the angle of swing to calculate force of air flow and converting this into CFM

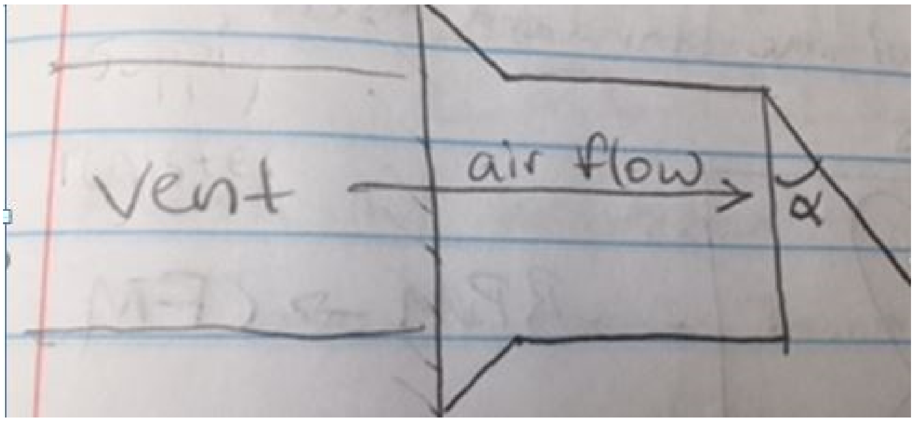


Figure 30: NH Concept 6

7. Evaporation of a fluid

   Increased air speed accelerates evaporation by preventing relative humidity from rising directly above the fluid. Psychrometric calculations would be done to relate evaporation rates to air speed.

8. Filter replacement – Fan Matrix

   Sensors would be attached to each fan and the rotation of the fans would be averaged and utilized to output CFM.

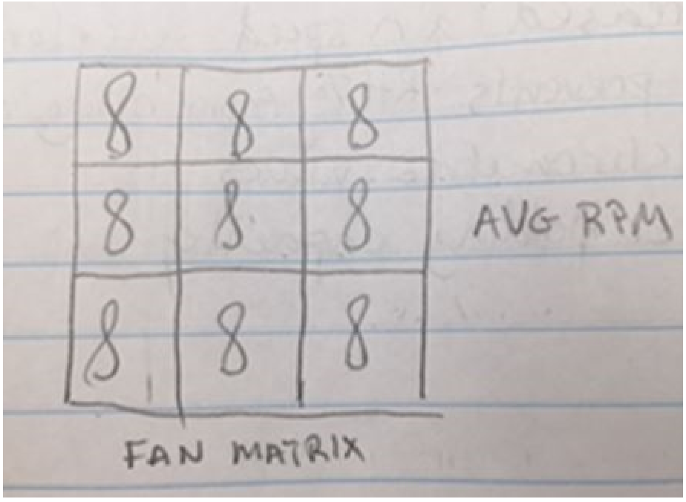


Figure 31: NH Concept 8

9. Filter replacement – One fan

   This concept is the same as the fan matrix but only utilizes one fan so there would be one RPM reading instead of averaging multiple.

10. Filter Replacement - Grid/wired mesh

    This filter replacement would have hotwires attached to it with known thermal properties ad use the same method as hot wire anemometers to measure airflow.

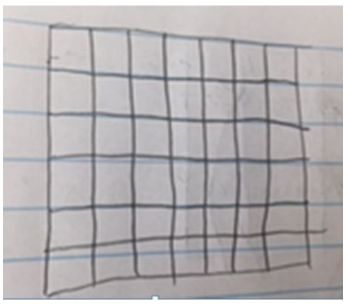


Figure 32: NH Concept 10

11. Filter Replacement – LIDAR

    LIDAR is a technology measures air particle velocity. Attaching a matrix of these filters to different locations on the filter replacement would allow for an average airspeed reading that would give an accurate CFM conversion.

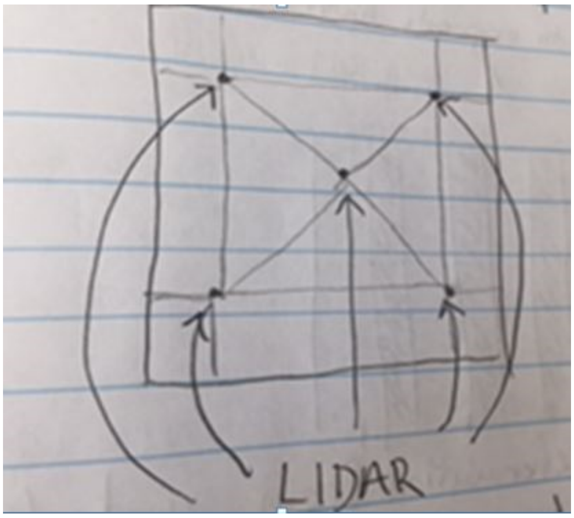


Figure 33: NH Concept 11

12. Filter Replacement – Evaporation

    A filter replacement would be equipped with absorbent material at different locations to measure evaporation rates and relate that to airflow.

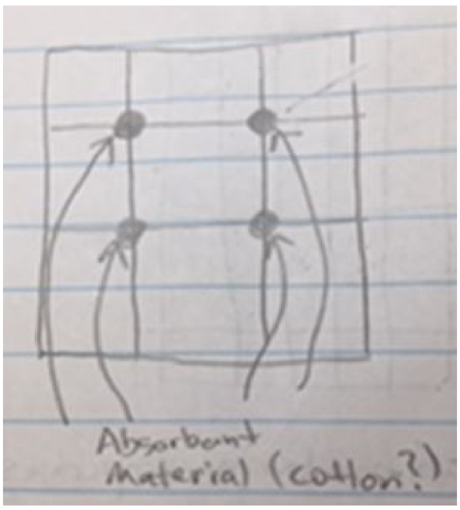


Figure 34: NH Concept 12

13. Filter Replacement – Elastic material

    Strips of a material with a known modulus of elasticity would be placed in a filter replacement frame. Strain from wind load could be measured and converted to wind load, then to air speed, and then to CFM

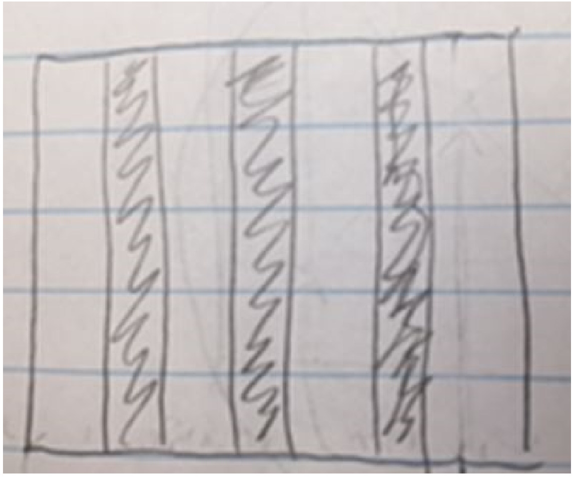


Figure 35: NH Concept 13

14. Flow hood with Fan Matrix at intake

    As with the single fan flow hood, this method would use the rotational speed of the fans to output CFM except with this design an average of the twelve RPM measurements would be used to convert to CFM.

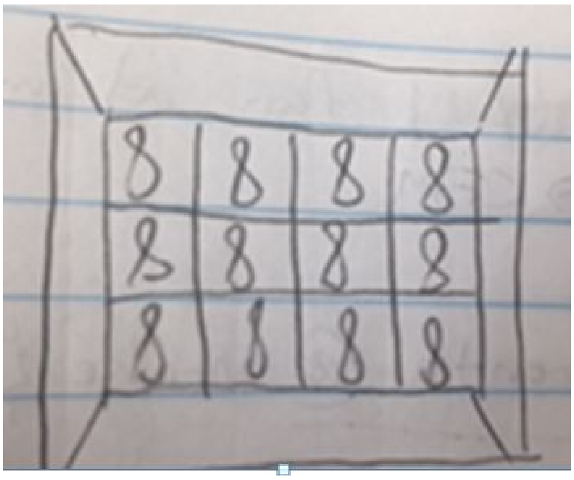


Figure 36: NH Concept 14

15. Enter fine, lightweight particulates into Point A and measure time to reach Point B

    Harmless, lightweight particulates would released into the supply intake and time for them to reach the filter/exhaust would be measured. The distance divided by the time it takes would give an air speed measurement and this can be used to calculate CFM.

16. Pressure differential from intake to exhaust

    This method involves measuring pressure at the intake and the exhaust and calculating the differential so an air speed through the unit could be calculated and converted to CFM

17. Attach sensor to fan in blower

    This concept involves measuring angular velocity of the blower fan with by attaching a sensor to it and using the fans dimensions, and fan curve to convert to CFM.

18. Flow hood at intake

    This concept involved sealing a flow hood over the intake and measuring the RPM of the fan and then using that as well as the known fan pitch and radius to calculate CFM.

19. Flow hood with “umbrella”

    This design involves multiple springs with known spring constants attached to umbrella like structure. Using the displacement of the springs, the force of the air blowing on the ‘umbrella’ could be calculated and used to further calculate CFM.

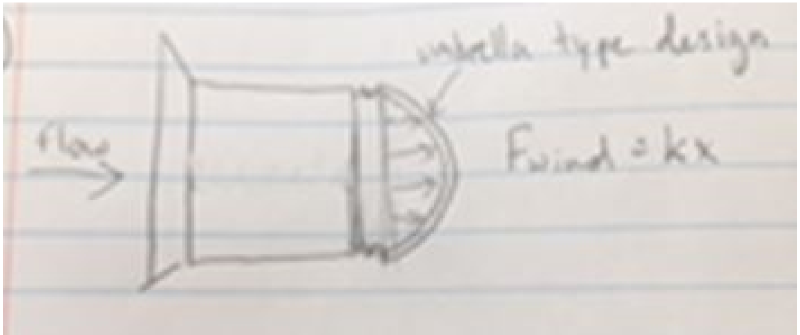


Figure 37: NH Concept 19

20. Flow hood with fan matrix at exit grille/vent

    A flow hood with a matrix similar to the previous fan matrix flow hood concept would be sealed over the exit grille of vent and the same method of calculating average RPM and converting to CFM would be utilized.

21. Add portable duct at intake with pressure probes

    A portable duct similar to any HVAC ductwork would be set up behind the supply intake and sealed over the vent. There would be two pressure probes attached to the inside of the duct, one at the front and one at the back. The pressure differential would be used to calculated air speed and from there calculate CFM.

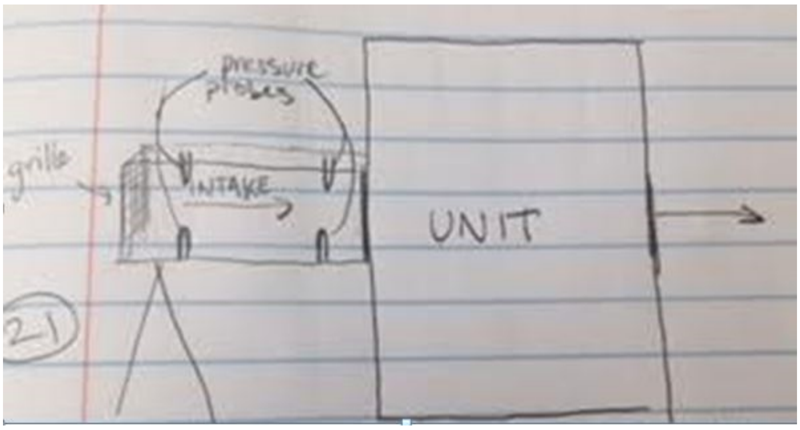


Figure 38: NH Concept 21

22. Funnel flow hood with ball

    This design differs from a standard flow hood. It is shaped like a funnel and has a cylindrical barrel at the end with a lubricated ball that will be forced through the barrel when the unit is operating. The speed of this ball would be measured and used to calculate the total system airflow.

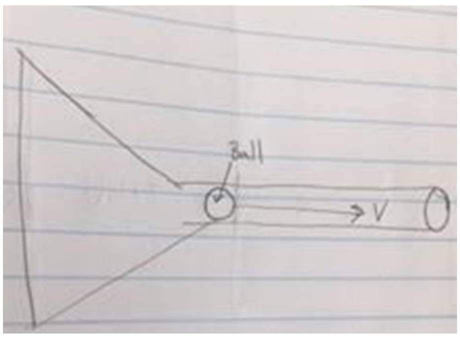


Figure 39: NH Concept 22

23. Flow hood with LIDAR

    This concept incorporates the same looking design as the filter replacement LIDAR concept but has it attached within a flow hood that would be sealed over the supply register vent.

24. Flow hood with evaporation

    This is the same design as the filter replacement evaporation design but with a flow hood instead of a filter replacement frame.

25. Flow hood with wired mesh/grid

    This is the same as the filter replacement design with the heated wire mesh but on flow hood.

26. Filter Replacement fan matrix four fans

    This concept uses the same technique as the design with filter replacement with nine fans but instead uses four to lower cost.

27. Flow hood fan matrix with four fans

    Same method as the flow hood with a matrix of twelve fans but with four fans to lower cost.

28. Filter Replacement LIDAR three sensors

    Same technology as the filter replacement with five sensors but this concept brings the number of sensors down to three to lower costs.

29. Flow hood with LIDAR

    This incorporates the same principles as with the LIDAR filter replacement but instead implements the sensors within a flow hood.

30. Mini Flow Hoods throughout ductwork

    This concept is similar to that which seals mini flow hoods around holes in the main unit. The difference is that this method would involve sealing the mini flow hoods over holes drilled in the ductwork of the system.

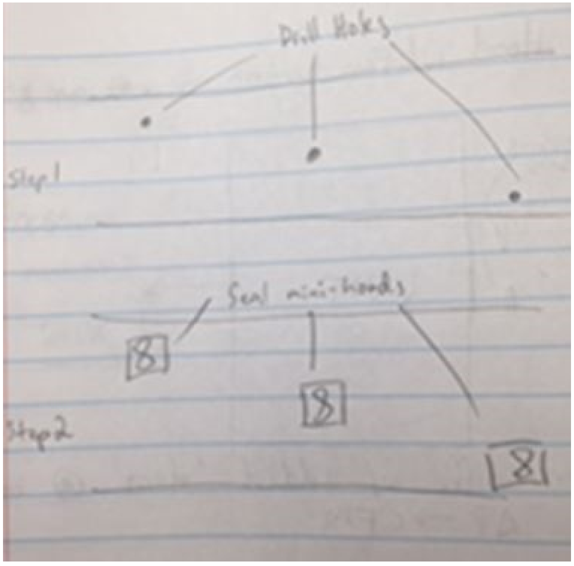


Figure 40: NH Concept 30

8.2 Michael Dana's 30 Concepts

1. Sonar design using two point sources which measures speed from one point to the next probe.

2. Rivet design using differential pressure on rivet to measure the change in pressure on the air in the duct.

3. Change in temperature design that measures a change in temperature using two small probes inserted into the duct.

4. RPM of fan design that runs a sensor using a snake to measure RPM of fan and covert that speed to CFM.

5. Deformation of duct design which when the duct is under a pressure the duct will expand or contract and this will calculate the CFM from the displacement.

6. Smartphone compatible design which allows the use of software being on an iPhone or android device.

7. Change in temperature design which uses headphone jack and probe to measure the change in temperature of the airflow from one-point source to another.

8. Change in pressure design which uses a headphone jack and a probe attached to a smart phone to measure the pressure difference across ductwork after a small hole is drilled.

9. A 3/8th thick anemometer that would be able to insert into the duct and have a headphone jack run back to an iPhone or android device to measure wind speed and CFM.

10. A gauge used to calculate Reynolds Number of the fluid using a small probe and convert that back to CFM.

11. An adhesive seal attached to the probe used for pressure and temperature to allow for an airtight seal so that there is an accurate airflow reading.

12. Small laser that would be run with a software so that when the laser hits a particle the software will read the speed of that particle and from the speed the CFM will be determined.

13. Collapsible pressure probe to determine the pressure differential in ductwork and to allow easy storage and installation.

14. Telescopic temperature gauge to run from user source from drilling 3/8th inch hole in ductwork. This will read the change in pressure at multiple distances to generate an accurate reading.

15. Filter probes that are attached to a custom filter for the air handling, or fan coil unit which will read the CFM from the exhaust airflow that is expelled from the unit.

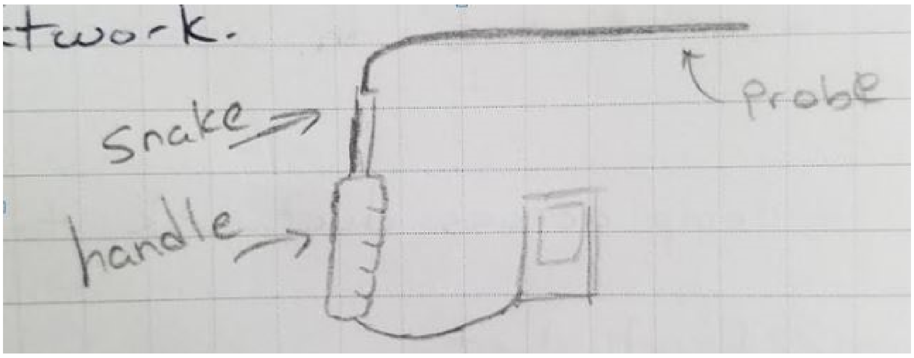


Figure 41: MD Concept 14

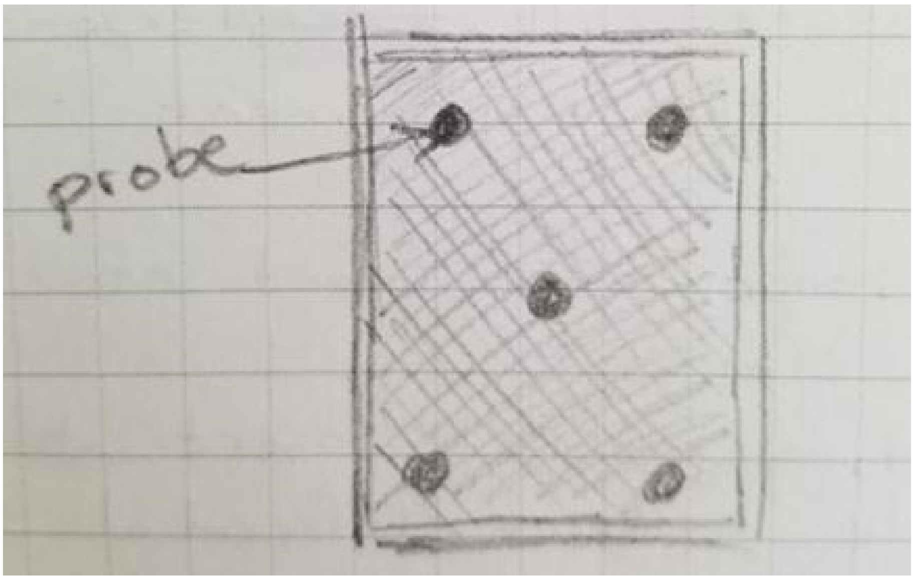


Figure 42: MD Concept 15

16. A small probe that can be attached to the fan of an unit using an adhesive to prevent damage to the fan. The probe will read the RPM of the fan and calculate the CFM from the fans speed.

17. The two temperature design involves attaching two probes to the bottom outside of the ductwork and measures the change in temperature of the duct over a certain length to calculate the CFM.

18. The laser measurement design uses a radar gun type of design which shoots a laser at a moving fan which will determine the speed of the fan and use that to calculate the CFM.

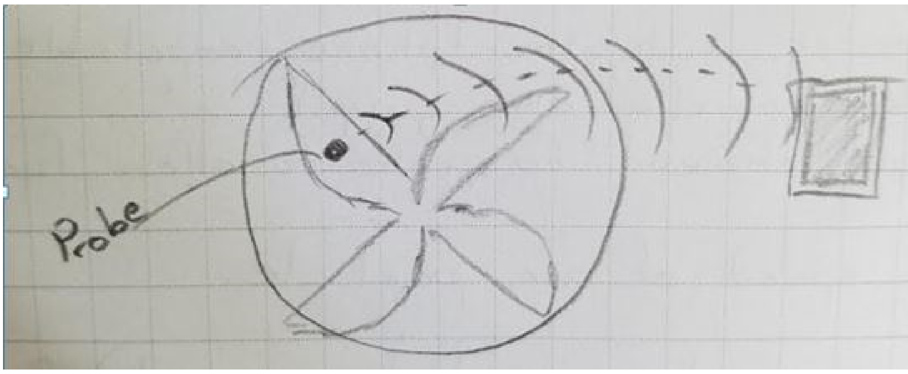


Figure 43: MD Concept 16

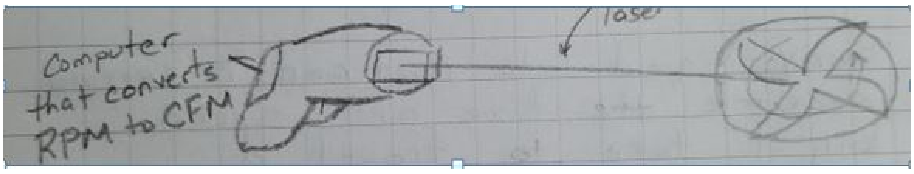


Figure 44: MD Concept 18

19. Pressure gauge to be attached to the outside of the duct using adhesive to measure the pressure difference on the duct between two distances.

20. Smartphone compatible hot wire anemometer to measure the change in temperature surrounding the air by supplying heat to the surrounding. This will be designed with a collapsible neck and handle so the user can hold the probe steady to prevent error.

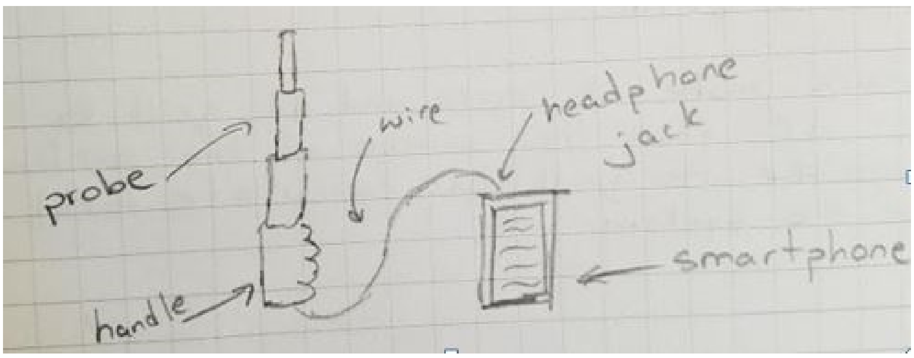


Figure 45: MD Concept 20

21. Capture hood made to be collapsible and easy to be stored and set up. This

will be smartphone compatible and attaches to the duct exhaust to measure the airflow.

22. This design involves the use of liquid such as alcohol and a probe that will be inserted in the ductwork to determine how fast the liquid evaporates in the ductwork and the probe will calculate the CFM from the speed of the fluid.

23. Anemometer designed with 3D printed plastic and is smartphone compatible. To be collapsible for easy storage and set up and will be used to measure the airflow from the exhaust of the unit.

24. Capture hood with a small fan placed at the bottom that will collect air at the bottom and the software will read the RPM of the fan to determine the CFM.

25. Measure pressure differential at the unit and at the ductwork source with a smartphone compatible probe.

26. Collapsible anemometer that is smartphone compatible and the user can press a button and it will open up and close inside of the ductwork.

27. A two probe design which measures the speed of the liquid that is inserted into the duct and evaporates over time. Using Doppler the first probe will sense the liquid moving past it and record the temperature, speed and begin the timer and the second probe will measure the temperature, speed and end the timer after it passes by it. This will determine the CFM of the surrounding airflow.

28. Two probes that at one end heats up the air and the other measures the temperature difference a certain distance from the other.

29. Doppler design which sends waves at airflow to read the airspeed (velocity) and converts that to CFM (cubic feet per minute).

30. Temperature probe at source and at diffuser grill to measure the temperature difference over the entire length of the ductwork. The probes will have wireless

capabilities and Iphone compatible.

8.3 Reid Elleman's 30 Concepts

1. Two external modules that measure the time it takes for a sound to travel from one to the other. It compares the vibrations inside the duct with vibrations outside duct to estimate air velocity.

2. Similar to idea 1 but has a single unit that both emits and records the sounds to avoid distance discrepancies.

3. Also similar to idea 1 but instead of sending the signal in one direction the second module sends a signal back so the speed of air can be observed twice for greater accuracy.

4. Puncture the duct with two rivet style instruments which can measure pressure at their locations and determine pressure drop between the two.

5. Design an insert that takes the place of the filter momentarily that can determine pressure drop across the filter conduit.

6. Design an articulating probe that can enter the duct through an already existing interface and measure pressure at two locations.

7. Design a heat element to take that place of the filter which measures the heat loss to convection and approximate mass flow.

8. Similar to idea 4, but uses only one probe which is heated and measures the heat loss to approximate.

9. Similar to Idea 6 but measures heat loss rather than pressure.

10. Ionize the air externally by ionizing radiation then measure the electrical field generated by the moving charged particles in the duct to approximate velocity.

11. Ionize the air similar to idea 10 and install a rivet style collector which is positively charged and measure the change in charge over time to approximate velocity of air.

12. Add heating element of known power to the exterior of the duct up stream and a thermometer on the exterior downstream and approximate coefficient of convection by the rate of change of temperature. Thermal properties of the duct (K and thickness for example) must be known.

13. Design an anemometer capable of guiding itself into the airstream through an existing diffuser.

14. Design an fan-style anemometer capable of collapsing to fit through a quarter-inch diameter hole which the technician will drill.

15. Design series of fins on an axis that spans the air stream. Technician will have to cut the slit that the fin enters through. The fin will be shaped to respond to air velocity with lift and measure the resulting torque on the axis with strain gauges.

16. Emit a detectable particle into the air stream through the filter and measure the presence at a diffuser to approximate volume flow.

17. Similar to idea 16, but instead of intruding the particulate at the filter enter the duct with a rivet-style nozzle on the duct.

18. Use the Doppler Effect with an infrared light source and sensor that can penetrate the duct.

19. Use light and source in the visible spectrum through a window hole that the technician drills.

20. Use the same principal of idea 19 but done at a diffuser or already existing opening.

21. Design a hood that can measure the momentum of the air leaving the duct at a diffuser.

22. Design a membrane that fits into the filter compartment that can measure the momentum of the passing air.

23. Design a collapsing fin that can fit through a narrow hole then open inside the duct. Once open, the momentum of the air will cause a strain on the fan which can be related to velocity.

24. Pitot-tube type instrument that uses rivets to enter the side of the duct. Measure the pressure differential between perpendicular orifices to determine air velocity.

25. A heated slender wire that enters the air stream and cools by convection. Uses rate of cooling to approximate coefficient of convection. Operator will look up average air velocity from a look-up table.

26. Measure vibrations of the duct to approximate air velocity. Use accelerator on the outside of the duct to gather data and determine frequency mathematically.

27. Introduce a thin-walled open cylinder into the air stream and measure the amplitude of the resonant frequency (like blowing over the top of a bottle).

28. Introduce a fly-swatter shaped object that deflects from air momentum. Measure strain at the base to determine air speed.

29. Measure the heat of the unit and determine output power from the power consumption minus heat generated.

30. Create a window in the duct and use DIC analysis to determine particle movement in the air-stream.

9 QFD

As a means to ascertain the appropriate parameters and significant aspects of the design, an elaborate QFD, Quality Function Deployment analysis was performed.

QFD is a method commonly used to determine how customer requirements can be rendered to product specifications. The most important tool used in QFD analysis is the house of quality. This tool can aid a designer by focusing their attention on the design characteristics that are key components to the foremost demands of the customer [4]. The house of quality is made up of several sections including the demanded quality, quality characteristics and target values, interaction between the quality characteristics, relationship matrix, difficulty, quality characteristic importance weight and competitive analysis. After the user lists the demanded qualities, with weights, and the quality characteristics of the project a series of symbols with assigned values are given to each corresponding block in the relationship matrix depending on the strength of the relationship. Upon entering all values into the house of quality, an importance weight is derived based on the weight of the requirement and the number of relations in the relationship matrix. The quality characteristics, or "functional requirements" that have the highest importance values are to be considered primary to other characteristics with lower importance values [7]. These characteristics will have the most significant impact on the final design of the product. The QFD House of Quality table can be seen on Page 89 of Appendix A.

9.1 Demanded Quality

The first section included in the house of quality is the demanded quality, otherwise known as the "Customer Requirements" or "What's" section. This section is located on the left side of the house of quality lists the main objectives for the project. All of the requirements listed came from the Judging Criteria section of the Competition Guidelines provided by Emerson Climate Technologies through HeroX. The requirements were ranked on a 100-point scale, with 30 points for cost of solution, 20 points for accuracy of measurement, 20 points for ease of use, 15 points for robustness of solution, and 15 points for ease of installation. These values were used as the importance, or weight values for each requirement in the QFD analysis. These directly translated into relative weight values.

9.2 Quality Characteristics and Target Values

The following portion of the QFD diagram contains the quality characteristics, also referred to as the "Functional Requirements" or "How's" section. This section includes all of the features of the product that could be altered to meet the desired customer. The direction of improvement section is located directly above the quality characteristics. This section shows whether each quality characteristic must be maximized ($\triangle$), minimized (∇), or remain neutral (X) with the values located in the target values section seen on the bottom of the QFD diagram. Each customer requirement from the previous section was derived from the Judging Criteria section of the competition guidelines provided by Emerson Climate Technologies through HeroX. Each of these requirements had a quantitative description alongside it. With the cost of solution requirement, a description was given stating that the solution must cost less than $100.00 USD. For accuracy of measurement, Emerson provided a value of plus or minus seven percent accuracy to be met. The robustness of solution had a description stating that the instrument must be consistent and scalable. Regarding the ease of use, Emerson demanded that the time to train contractors to use this new technology must be low. Regarding the ease of installation, Emerson asked for a total set-up time for the testing device to be under 20 minutes. These descriptions were used to create the functional requirements section on the house of quality along with other parameters the team felt were important to meet the customer requirements like weight, thickness, and complexity of the device's software.

As seen in the direction of improvement section, the range of airflow in CFM that the device can measure, along with consistency must be maximized. Cost, accuracy, and scalability are all on target and will therefore remain neutral. Parameters that must be minimized based upon QFD analysis are weight, installation time, software complexity, and thickness of the device.

9.3 Interaction of Specifications

Located on the top of the QFD diagram is the interaction of specification section. Due to its appearance, this section is commonly referred to as “roof” of the house of quality. The purpose of this section is to illustrate how each of the functional requirements relate to one another. The interactions between each functional requirement are shown in the form of a matrix, containing various symbols that show if the requirements have a strong positive correlation (++), strong negative correlation (∇), positive correlation (+), negative correlation (-), or no correlation (blank) to one another.

The “roof” portion of the QFD analysis for this project shows a strong negative correlation between low cost and the range of measurement in CFM. There is also a strong negative correlation between low cost and weight of the device. The interaction between range of measurement and CFM and accuracy of the device yields a strong positive correlation between the two functional requirement. There is also a strong positive correlation between weight of the device and installation time, accuracy and thickness, complexity of software and installation time, installation time and consistency, and lastly, between consistency and scalability of the device.

9.4 Relationship Matrix

The center portion of the QFD diagram is referred to as the relationship matrix. This section shows how each functional requirement affects each customer requirement. The relationship matrix utilizes a set of symbols that signify the strength of the relationship between each quality characteristic and the demanded quality. The θ symbol is represents strong relationships and has an assigned value of three. The O symbol represents any moderate relationship and is given a numerical value of two. The symbol △ signifies a weak relationship between a certain quality characteristic and the demanded quality This symbol has value of one. Lastly, no symbol implies that there isn't any relationship between the quality characteristic and the customer requirement.

9.5 Difficulty

Located on the bottom of the QFD diagram below the target values is the difficulty section. This section determines the difficulty associated with altering a certain quality characteristic. The difficulty section is comprised of numerical values ranging from zero to ten with zero representing a quality characteristic that can easily be changed and ten representing a quality characteristic that is difficult to change. For this project, the difficulty value for each quality characteristic was determined through analyzing the specifications and guidelines provided by Emerson Climate Technologies on the Air Flow Challenge webpage.

9.6 Quality Characteristic Importance Weight

Located below the difficulty section is the quality characteristic importance weight section. This section determines how significant the impact of each quality characteristic is to the project. The value for importance weight is calculated by multiplying the relative weight for each demanded quality by the value held by the symbol shown in the relationship matrix. Then the values are summed for each quality characteristic. The resultant value is the quality characteristic importance weight. This value is then normalized and placed in the relative weight section. The quality characteristics that yield the largest relative weight values are the most significant design parameters. As seen on the QFD diagram for this project, the most significant design parameter is the cost remaining below $100.00 USD.

9.7 Competitive Analysis

The right hand section of the QFD diagram shows how the Fan Filter Matrix and the Rotating Pitot-tube Differential Pressure Sensor compares to the competitor airflow measurement devices. This is the competitive analysis section. It takes each of Emerson's demanded qualities and shows how efficiently the competitor products meet those demanded qualities. Values ranging from zero to five were given to the competitors for each demanded quality. Zero implies the least effective at meeting the demanding qualities whereas five is the most. Based on the values assigned in this competitive analysis matrix, a graphical representation was plotted to give a visual representation of how the devices designed by the team compared to the competition. The five products used in this competitive analysis were the Testo 410-2 Rotating Vane Thermo Anemometer, Airflow Monitor AN100, Dwyer Model 89088, the Emerson Rosemount 3051SFA Annubar Flow Meter and the TruTech Dual-Port Manometer - SDMN5. Each product was ranked based on extensive research and comparison to the demanded qualities. The results of the competitive analysis show that the Fan Filter Matrix and the Rotating Pitot-tube Differential Pressure Sensor are above or on par for each demanded quality except for accuracy [2].

9.8 Trade-Off Analysis

Table 4 shows a pairwise comparison between all of the demanded qualities. This method was utilized in order to perform an efficient trade-off analysis for this project. A value of 1 was given when two customer requirements were thought to be of equal value, a value of 3 was given when the primary requirement was considered to be more important, and a value of 9 was assigned if the primary requirement was considered to be significantly more important. Based on this analysis it was determined that the cost of the solution is the most important customer requirement by far. To give a visual representation of the significance of each demanded quality, a pie-chart was constructed based upon the summed values for each quality. This pie chart is shown in Figure 43.

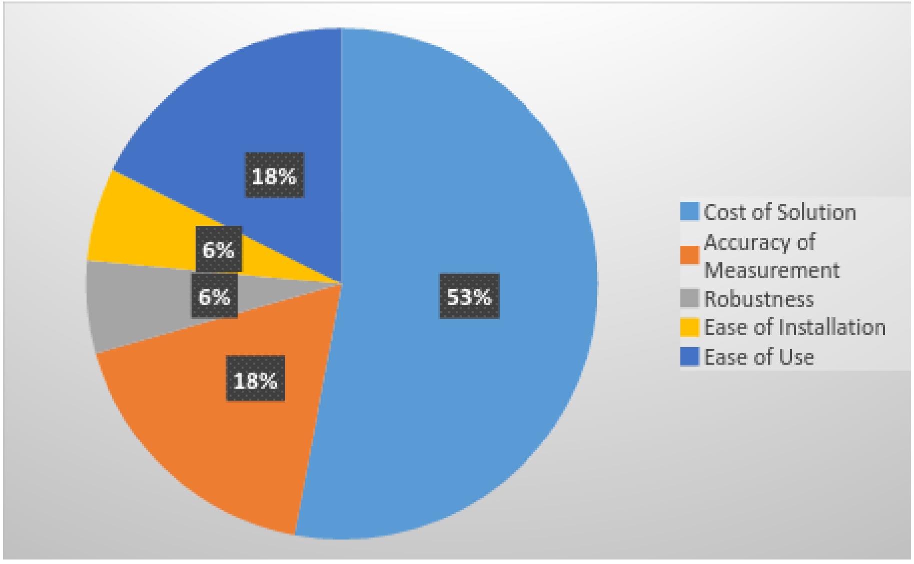


Figure 46: Trade off Pie Chart

	Cost of Solution	Accuracy of Measurement	Robustness	Ease of Installation	Ease of Use
Cost of Solution	1	0.33	0.11	0.11	0.33
Accuracy of Measurement	3	1	0.33	0.33	1
Robustness	9	3	1	1	3
Ease of Installation	9	3	1	1	3
Ease of Use	3	1	0.33	0.33	1
TOTAL	25	8.33	2.77	2.77	8.33

Table 5: Pairwise Comparison Table

10 Design for X

10.1 Safety

When first designing the new method of measuring air flow inside of duct work research must be done to determine what kind of risks can be involved during testing. After research Team 12 determined that the overall risk for testing air flow was very low. This is due to the fact that the tester is not going inside of duct work. This minimizes the risk of injury and allows the design to be made without worrying to much about user safety. The only thing that has to be designed for safety is the user can not be testing the air flow inside of a unit or duct work when the AHU or fan coil unit is on. Having a design that can be inserted into duct work with out having the user making contact with the moving air will make the overall design safe and effective.

10.2 Cost

The cost the design was the most important factor when designing both designs. This is due to the fact that the project asked for a design that was less than $100. Because of this material and software were big components in the design. The fan Filter Matrix design had to be made out of a cheap plastic that would also be strong enough to be able to handle the wind force applied to it. If the plastic was not strong enough then when the 2000 CFM was applied to the frame or impeller it would fail. The mesh had to be cheap and affordable as well as clean the air. Due to ASHRAE standard there are only a certain amount of particulates that can pass through a filter before flowing back to the AHU or fan coil unit. This means that filter, even though it is not part of the main problem of a way to measure air flow, still needs to be an important part of the design to allow for the Fan Filter Matrix to sit inside of the unit.

10.3 Manufacturability

When designing both the pressure differential and the Fan Filter Matrix, Team 12 wanted to make sure that these tools could be mass produced if needed. The designed needed to made of parts that were easy to be mass produced without needing a lot of man power to make them. The Fan Filter Matrix being made of plastic allowed for this. Due to it being made of polypropylene the parts of the matrix were all injection molding. This allows an assembly line to feed the mold into an injector and for the injector to inject the plastic into the mold and allow the mold to harden before being taken apart by the worker. Though the parts would need to be assembled by a worker, the time to manufacture each part would not be a huge concern.

Another big issue was the tolerances. The tolerances on each part of the Fan Filter Matrix could not be to complex where they would need to be machined down after fabrication to reach the correct tolerance. The Team was able to design each part to not have a very complex geometry. This was the same for the pressure differential designed by Team 12. Since it is not an overly complex design it allows for the manufacturer to not have to put a ton of man hours into manufacturing it. This allows for mass quantities to be made at a very effective rate.

However, there are parts on both that need to be designed to a specific tolerance due to the sensitivity nature of the part. The impeller part for the Fan Filter Matrix must be manufactured to the dimensions produced by the designer. This is due to the fan pitch must be accurate to allow the sensor to read the correct FPM that is flowing through the fan. If the fan pitch is off then the sensor will read the FPM and thus read the wrong CFM. The part on the pressure differential designed by Team 12 that is very important is the pitot tube. This tube is inserted into a 0.078 inch hole inside of the duct work and is used to measure the pressure differential that is given off by the air speed in the duct work. The dimensions and accuracy of this tube is very important to the accuracy of the sensor. Since one of the projects main concerns is accuracy, the manufacturing of the two parts to their exact dimensions is very important to allow for a +/- 7% accuracy.

10.4 Reliability

One of main design specifications in the competition is to design a device to measure air flow that is durable and robust. When working in a confined environment, the user might cause damage to the device. The device must be designed to withstand impact as well as being used more than one time. Team 12 wanted to design a product that would compete with outside competitors in terms of reliability. Some competitors have a warranty on their products of two years after the purchase date.[12] One way to produce a product that would last is using materials that are affordable, but also durable. Using a plastic that will hold its shape is important to make sure the device always gives an accurate measurement. The plastic can not wear away after only a year of usage especially the impeller parts which are essential to testing the air flow. The pressure differential being made out of sheet metal allows for less wear over time. It will keep its shape which is important to testing. If the parts that connected the area where the pitot tube can become vertical and horizontal then the design would fail.

The mesh for the Fan Filter Matrix must be durable as well. The user does not want to be replacing the mesh every time there needs to be an air flow test. The mesh must be able to be cleaned without damage to allow for the part to be used more than a few times. Because of this, the mesh can not be the cheapest mesh that is available [15]. Choosing a mesh that is designed for commercial use allows it to be able to handle much larger wind velocities than what will be experienced in a household. This will allow it to last for a long time. If the mesh part does have to be replaced, the design has been made to be able to change it without damage to the rest of the frame. This will keep the frame in tack for a long time.

When designing the parts that would hold the frame to the correct size and the mesh in place, it was important to make them as durable as possible while still being under the specified budget. The clips were made of aluminum to make sure that they were stronger than the actual frame [11]. These parts need to last longer than the actual frame because they allow for everything to be kept in the right place for the test. If one fails, replacing it would involve buying a new clip and the user having to take the time to remove the pin joint and put in a completely new one. Since the pin joint is not easy to handle because of its size, these clips must be robust to prevent needing repairs.

10.5 Environment

The environment that both of these designs would be put into had to be taken into affect. Since they would be put into an environment with high wind velocities they need to be able to withstand those forces. Making sure that they did not break under the force of the wind or the pressure produced in the duct was important. This is especially important due to the fact if the parts that connect to the sensor fail then the device as a whole will fail as well. The environment that the testing is usually done in is basements of home which does not cause a problem unless the device is dropped. Sudden contact with a cement floor can cause damage to the sensor. In the winter the basement can drop significantly in temperature to the sensor must be able to operate at low temperatures ranging from 30 to $140°F$.

11 Project Specific Details and Analysis

11.1 Problem Statement

The problem statement, as described by Emerson Climate Technologies on the HeroX Air Flow Challenge webpage is as follows: Develop a new air flow measurement apparatus to measure total system airflow across an indoor ducted furnace, heat pump, or central Air-Conditioning system. The apparatus should be easy to use by a trained technician with average total set up and testing time less than 20 minutes. The measured airflow should meet or exceed an accuracy of +/- 7% and the total first cost to the service contractors should be less than $100. The tool or system should be capable of measuring 0 to 2,000 cubic feet per minute, typical of residential HVAC air flow range and could be an actual physical device or an advanced algorithm using other available system information to accurately approximate a measured value.

11.2 Importance of Accuracy

Accurate Measurement devices are expensive and inherently intended for commercial systems and the process takes time. Such measurement devices are not suitable for Residential systems which is what we need. The apparatus should be easy to use by a trained technician with average total set up and testing time less than 20 minutes. The measured airflow should meet or exceed an accuracy of +/- 7% and the total first cost to the service contractors should be less than $100.

11.3 Meeting the Judging Criteria

Based off of Emerson's priorities, the guidelines were placed into a 100-point judging system with each guideline having a specific weight. Team 12 used this judging criteria shown in Table NUMBER to decide what areas to emphasize the most in the design process.

Judging Criteria	Description	Points
Cost of solution	Does the solution cost less than $100?	30
Accuracy of measurement	Must meet or exceed an accuracy of +/- 7%	20
Robustness of solution	Must be consistent and scalable	15
Ease of installation	Total set up time should be less than 20 minutes	15
Ease of use	Low training time for service contractors	20
Total:		**100**

Table 6: Judging Criteria

As seen in the financial analysis, the cost of the device remained below $100 and should fall even further below this limit after design/fabrication improvements are made. To test the accuracy of the device, Team 12 used an Extech Thermo Anemometer provided by Nassersharif. The accuracy of this device is +/-3% in feet per minute. The Collapsible Filter Anemometer displayed readings within 1% of the Extech Thermo Anemometer, therefore the accuracy can be guaranteed to be within +/-7% in feet per minute. To ensure robustness of the device, Team 12 performed multiple tests at the three different fan settings and had consistent results throughout all tests. As seen in the Test Matrix, the set up time for testing is around 5 minutes which is well under 20 minutes. Any educated HVAC technician should be able to learn to perform air flow tests with the Collapsible Filter Anemometer in a few minutes. This means all guidelines have been met and Team 12 should receive 100 points for their design. The design report was submitted through the HeroX webpage on March 15, 2017 and the judging results will be received on June 30, 2017.

12 Detailed Product Design

The design of the Fan Filter Matrix was based around the idea of being non invasive. The design uses the same concept of an anemometer, but it measures the complete velocity profile and can measure the air flow from the source, the blower. Five impellers were used to allow for the velocity profile to be measured from top to bottom to allow for a very accurate reading of the air speed. The idea of this design was presented to us by Professor Nassersharif and Team 12 built on this idea to make sure it would work in a real life application. When the idea was first presented there was concern on how the design would be able to be adjustable to all the different frame sizes that exist in today's market. Since sizes range from 15 in by 4in to 36 in by 36 in there needed to be a way for the frame to adjust so that the product would not need to be changed depending on the size of the duct. If the product did not have a adjustable frame then the technician would have to have background knowledge of the product before arriving to the site for testing. Figure () shows how the frame is vastly different from others on the market.

The frame must be able to adjust to many different sizes which was one of the main concerns when developing this design. It also needed to be able to lock in place for testing and hold a mesh over it in a manner where little particulates would pass through the filter. The design still needed to act as a filter because of standards stated by ASHRAE. Since ASHRAE only allows a certain amount of particulates to pass through a filter when the unit is running, it was important that this design had a mesh. The mesh had to be adjustable as well to accommodate all the different size filters. All of these specifications needed to be met to allow for the design to be successful. If one of these design specifications was not met then the Fan Filter Matrix would not be able to do the job needed.

12.1 Design of the Frame

The frame is one of the main parts to this design. To design the frame Team 12 looked at all the various sizes that were on the market to date and decided to make the frame adjustable by a 0.25 in from 0 to 30 inches. To do this there needed to be multiple sections created so that the frame would adjust down to a small enough size to test even the smallest of duct work which was determined through research to be 15 in by 4 in. Team 12 wanted the design to be able to stored easily to prevent damage during transportation. By using 10 parts each 3 inches long, the frame was able to collapse down to 3 inches which is makes it easy for storage. In each 3 inch part 12 rectangular sections were cut to allow for a pin joint to be placed through the hole. This allowed the frame to be adjusted every 0.25 in on every 3 in long rectangular piece. Each part of the telescopic frame was designed to fit just loose enough to allow for friction in between the pieces. This would allow for the pieces that are not being held in place by the pin joint to stay in place during the testing. This design is similar to that of an antenna. The design the corners was then developed. Each corner had to have specific dimensions to allow for the frame to adjust in size correctly. The corners had to hold the arm bar for the impeller and hold the clips and pin joints that held the structure of the design in tact. To do this the corners were each designed differently with each having different joints then the others. The biggest corner had joint sizes of 1 in by 1 in and the smallest size had joint sizes of .45 in by 0.45 in. The frame was also designed to be 1 in thick due to the specifications of other filter. The filter size found through research had a thickness ranging from 1 in to 4 in. To accommodate these sizes, the filter was chosen to have a size of 1 in to make sure that it fit all the respective sizes [8]. The corners are each designed with two thin magnets

12.2 Design of the Pin Joint and Clip

Pin joints were designed to be able to hold the frame together. This part was designed like a spring clip that had a tooth of 0.5 in long by 0.05 inches in width. This allows the pin to grip onto the changing sizes of the frame all the way down to the smallest size. This allows the user to adjust the size to the size of the slot the filter is inserted into in the unit. By using two pin joints per corner, the frame was able to keep its stability during test. The frame would not change size and keep a tight fit to prevent particulates from passing through gaps between the wall and the frame. The pin joint was designed using the material polypropylene to make sure it remained sturdy and would not wear away over time.

The clip was designed as a way to attach the back plate to the frame. This clips main purpose is to allow for the adjustment of the mesh size to accommodate all the different sizes that are present in today's market filters. The clip was designed to be made of aluminum 6061-T6 to be able to hold the frame rigidly and to wear away over time. Since this part does deal with one of the main components of the design, it needs to be sturdy and robust. Team 12 wanted to make sure the small parts of the design would be strong to prevent failure. The thickness was made to be 0.016 in to allow for strength but not take up a space. The width was 0.5 in and the length was made to be 0.75 in to make it usable on all frame corners.

12.3 Bill of Materials

When designing the product Team 12 wanted to make sure the product would stay below $100. This is the most important part of the judging criteria since it is worth the most. The materials that were used were relatively cheap and affordable. In Table 1, the total material are shown. The total material it took to produce the product and the homemade duct are 35. This included the plywood bought from Arnold Lumber and the parts used to manufacture the Collapsible Anemometer. The total cost to produce the entire project which includes the duct and the product is $275.71. Though this cost a good amount of money, it is a fraction of what was provided to the group by the University of Rhode Island Grant. The grant gave Team 12 $1000 so the amount we spent was 27% of the total amount.

The majority of the cost came from the manufacturing of the duct. The amount it took to manufacture the Collapsible Anemometer was $97. This is about 35% of the total cost where the other 65% comes from the manufacturing of the duct. This is due to the amount of materials that was needed to produce the duct. The duct was 5ft long by 2 ft tall. To build the box, it took 64 square feet of plywood. The angle brackets and screws were a large percentage of the cost since the entire duct asked for 16 angle brackets and 32 countersink screw. To build the funnel for the box fan to connect to the box, 20 square feet of plywood was used as well as the angle brackets and screws listed above. The 20" box fan cost $23 and was used to supply air to the duct.

The Collapsible Anemometer used about 2 square feet of plywood for the expanding arms and the top portion. Using the 3D printer cut cost significantly and kept Team 12 from having to use excess plywood. The shafts for the design were one the largest portion of the cost. This is due to the type of steel used. If aluminum had been used instead of carbon steel, then the price would have dropped significantly. The fan was very affordable with it being under $10. The electrical component of the design were some of the least cost effective. The total cost for all the electrical components which includes the Arduino, the battery, the laser and the light sensor are about $18. Though these are more expensive then the majority of the components for the design, they are important for the device to produce accurate data. These components will not have to be replaced except for the battery which is very affordable. The largest portion of the cost was the gears and the racks for the gears to travel on. These can be seen as the top 2 components in Table 1. This is due to the large volume of the product. To design the Collapsible Anemometer, 4 gears and 4 racks are needed to creating the expanding motion. Each gear and rack needed to have the same size teeth to make sure they would increase and decrease in size without any restriction. This drove the price up to $24.72 for the gears and $30.56 for the racks. This accounts for 20% of the total spent on the project.

13 Engineering Analysis

13.1 Fan Filter Matrix

Through engineering analysis Team 12 was able to determine that the design was sound and safe under the conditions that the device would be acted upon. There are three sections that the analysis was divided into. This was the wind force on the arm bar holding the impeller, the percent of coverage of the impeller to the maximum size of the frame and the pitch of the fan as well as the size of the frame. Since there are many different types of air flow measurement devices that have already been developed there is a blueprint to the ways that those devices measure air flow. Even though the Fan Filter Matrix measures air flow using a different method then most do, the math behind them is very similar to an anemometer. This is due to the fact that both measure air flow based on how fast the air spins the impeller part of the sensor. This then sends a signal to the software which outputs a CFM or FPM value for the air flow.

13.1.1 Wind Force Analysis

Determining the wind force that is applied to the arm bar is important to determine the strength of the arm bar. The arm bar is the part that connects the impeller to the frame of the Fan Filter Matrix. During testing this experiences the force of wind that is generated by the blower. Since there is a maximum value of 2000 CFM which is equal to 0.55 mph in a 30in x 14in duct, the force is not that large on the arm bar.[16] To determine the wind velocity the maximum value of CFM was changed to FPM. This was then changed to MPH (miles per hour) using dimensional analysis. The work below demonstrates how this was done.

$$CFM = FPM \times A \tag{1}$$

$$2000\frac{ft^3}{min} = FPM \times 5.56ft^2 \tag{2}$$

where CFM is cubic feet per minute of the air, FPM is the feet per minute of the air and A is the area of the duct. After determining the FPM, the velocity in MPH can be determined using dimensional analysis to be 4.08 MPH. The wind force must then be determined to see if the force will be too large and cause too much stress and deflection on the arm bar. To determine the wind force the equation below is used:

$$F_w = \frac{1}{2}\rho v^2 A \tag{3}$$

$$F_w = \frac{1}{2}(1.2041\frac{kg}{m^3})(1.827\frac{m}{s})^2(0.006m)^2 = 0.0121\ N = 0.0027\ lb_f \tag{4}$$

Using the values that were determined above were then used in simulations to determine the deflection that the a bar would experience.[13] The deflection had to be minimal to the fact that the bar is holding the impeller. If the deflection of the arm bar is too high then the fan will not get a proper reading of the air flow. [13] The pressure could also be too great for the arm bar to handle so it needed to be tested to see if the arm bar would fracture under pressure. Using Abaqus, a Dassualt Systems software, a stress test using the wind load was done. Figure (42), (43), and (44) demonstrate the three measurements that were taken. The measurement of deflection, principle stress and maximum tensile and compression Von Mises stress.

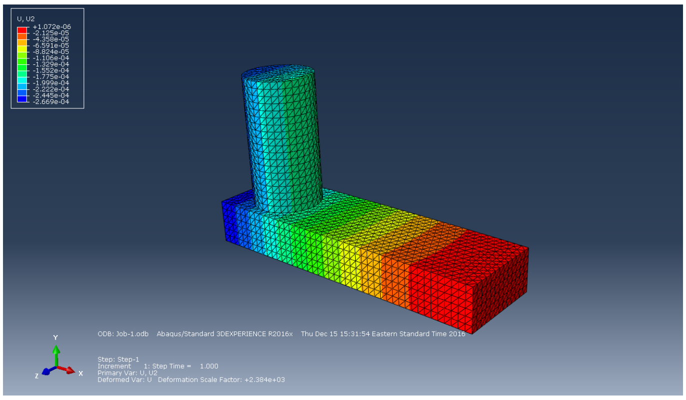


Figure 47: Deflection Analysis on Arm bar

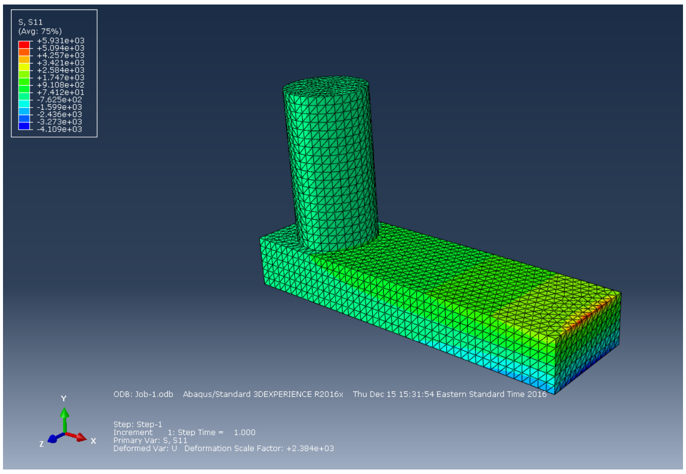


Figure 48: Principal Stress Analysis Arm bar

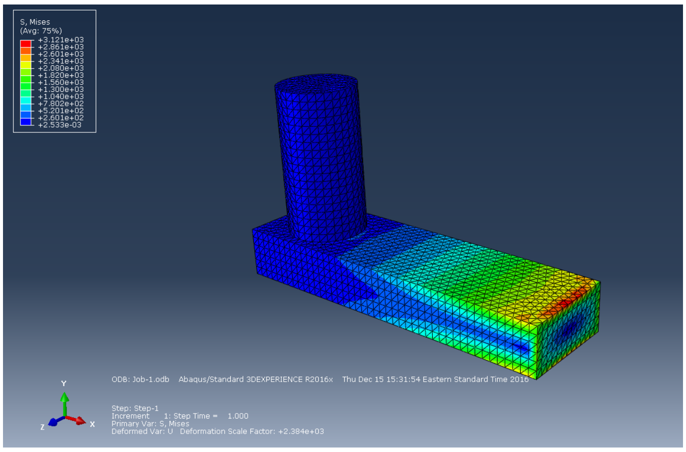


Figure 49: Von Mises Stress Analysis on Arm bar

After testing it was determined that the maximum deflection was 0.0002669 m or 0.0105 inches. this value is low enough where the compressive force by the wind will not cause a problem. Since the deflection is very minimal, the fan will be able to get an accurate reading without worrying about possible problems do to deflection of the support arm.[13]

13.1.2 Percent Coverage

The next analysis that needed to be preformed was to see how much area the five (5) impeller parts would cover. Since the design is made to measure the entire velocity profile as seen in Figure (45) it is important the fan parts cover a decent percentage of the area. This was then used to determine the impeller size to see when the frame is collapsed, are these impellers going to damage each other during the test.

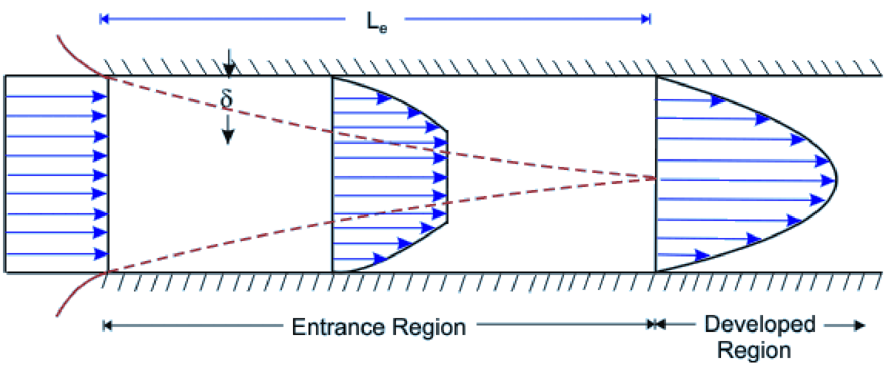


Figure 50: Velocity profile in Duct Work

First, the group determined how small is the smallest size that ducts are usually. Duct work usually reaches a smallest size of 15 in by 4 in. [15] This was then used to determine the maximum diameter the impeller could reach with allowing a 0.25 in space between them to prevent them from making contact between each other. The length from the walls of the frame was then taken into account to allow for 0.25 in from the wall of the frame. This prevents the impeller from being damaged by the frame and vice versa. These tolerances to prevent damage take a total of 1 in on the length and 1 in on the width. After determining the space left, the maximum impeller size was determined. Each impeller had to be the same dimension to allow for the velocity profile in each corner and at the middle to be read the same. The percentage of coverage of the largest size the frame can reach, 30 in by 30 in, is 0.27% and the percent coverage for the smallest size, 15 in by 4 in, is 4.18%. [15]

13.1.3 Pitch of the Impeller

The pitch of the impeller is the most important part to the design because it determines the overall accuracy of the product. The impeller's blade pitch must be design to a specific angle to allow for the correct amount of air to pass after one revolution. The speed that this air is moving determines the FPM or CFM of the air moving inside of the duct work. The equation below shows how the pitch of the impeller relates to CFM:

$$Pitch(ft) \times A_f(ft^2) \times RPM_f(1/min) = CFM(ft^3/min) \quad (5)$$

Where A_f is the Area of the impeller. Using this equation, the air flow measurement device can be calibrated the correct pitch. Once it is calibrated to the correct pitch, the CFM can be found accurately. Since accuracy is a huge part of this assignment, it is important to get the pitch of the fan correct. If the pitch of the fan is off by a slight amount then it will affect the overall accuracy which is one of the most important criteria of the project. The accuracy must be +/- 7% or lower. The more accurate the device is then the more likely it will be able to compete with the products that are already on the market.

14 Build/Manufacture

Throughout the process of the design and build portion of the project, Team 12 developed an effective way of manufacturing the product that would be cost effective, quick, and easy to manufacture. Some of the original features of the design were changed to be able to manufacture in time for the deadline, but the majority of the design was kept the same.With some changes made to the material being used for the product instead of the protoype, the original design would come together quickly and as intended. Each step was critical to the overall design and had to be followed to prevent any error during testing. In a factory, the product could be produced within a day with it being ready to be used that same day. The design can be disassembled if needed by the user to allow for cleaning and new parts to be inserted.

14.1 Producing the Product

In this section, Team 12 will discuss the steps to produce the Collapsible Filter Anemometer.To begin the production, the team 3D printed the bottom half of the design. This bottom half was designed to hold all the electrical components such as the Arduino and the mechanical components such as the fan, shafts, bearings, and rack and pinions. This frame was 3D printed to allow for durability during testing and to certain design features to match the top plate that was printed later. After the Arduino was tested and calibrated to read RPM (rotations per minute) of the fan, it was inserted into the specific slot designed to hold the electrical components and connected to a light sensor and battery. The fan had a 1/8th inch hole bored in it where the laser would shine a light through. As the fan rotated, the laser would pass through the hole and contact the light sensor. This would allow the Arduino to read RPMs of the fan. The rack and pinions were then manufactured using the CNC machine. The CNC machine, or the Computer Numerical Control machine, was used to cut the arms that would be attached to the rack that the gear would come in contact with. The racks were designed to fit inside of each other to allow for the arms to collapses to 10 inches, the smallest size filter on the market. The width of the inner arm was 8 inches and the width of the outer arm was 9.5 inches. This would allow them to fit inside of the top and bottom plates and give enough room for the gears to move. The shaft for the gears was then installed into holes that were specified on the design before 3D printing, these shafts were hammered into to ensure a snug fit. The gears were then placed on the shaft and the racks were then placed between the gears. This created the expanding part of the design which allowed the design to reach any size filter between 10 to 20 inches. For bigger filters, attachment pieces are used and connected to the end of the expanding arms.The top piece was then printed to be ready to be screwed into the top. Screw inserts were used on specified holes on the bottom plate to create threads for M8 screws to be fed into them from the top plate. The fan is then tightened to the shaft and the shaft is cut to the necessary size. The ends are sanded to allow for a smooth finish. The bears are then attached to the ends of the shaft. This will allow the fan to spin freely without any resistance. With very little resistance, the fan will give an accurate output of FPM. The fan with the shaft and bearing are then placed into the bottom and top piece and all other necessary shafts are lined up to fit into each hole. The parts are then all hammered in lightly to allow for a tight fit. A switch is connected to the battery to allow for the user to turn the Collapsible Filter Anemometer on and off. The M8 screws are then inserted in to the hole and screwed in. The Collapsible Filter Anemometer is assembled and ready for use.

14.2 Manufacturing Analysis

When designing the product, Team 12 wanted to make sure that the product would be easy to manufacture in a short amount of time. To improve the manufacturing process, Team 12 decided that the product should be manufactured using injection molding. Injection molding would allow all the mechanical parts to be assembled in a quick and accurate manner. One problem that was found when manufacturing the prototype was the glue that was used to hold the racks to the expandable arms would increase the tolerance between the rack and the gear. This would now allow a smooth path for the arms. When the part is produced through injection molding, the tolerances will be correct to allow for a smoother path. The tolerances for the screw inserts will be more accurate as well. When 3D printing the bottom plate, the holes for the shafts and screw inserts were too small and had to be bored out again. With injection molding the holes will be more accurate to the size they were designed for. Even though the plastic used injection molding might cause the holes to be bored out again, a tool path can be built into the manufacturing process to remove any excess plastic. Team 12 was worried to remove excess plastic by hand with the risk of damaging the bottom frame and offsetting the hole's location. This process of producing the mechanical parts would be done on an assembly line of machines. The assembly of the mechanical and electrical parts would need to be done by a human. The worker would assemble the necessary electrical parts and continue it down the assembly line where another worker would assemble the mechanical parts. This whole process could be done in less than an hour with some time put aside to allow for a worker to check the quality of the product and test the product. This product, due to it being able to be produced in a short amount of time, would be able to produce a large amount in a day. The estimation would be about 6 to 7 per day depending on if there is an error during the manufacturing process.

15 Testing

During the process of testing the Collapsible Anemometer there were certain criteria that had to be met. In this section, Team 12 will discuss the full scale testing of the Collapsible Anemometer and how it produced the data that was needed to call the test an overall success. The full scale test of the Collapsible Anemometer produced an accurate reading of the air flow while meeting all the necessary criteria expressed in the design specification. The Test Matrix can be found on pg 144 in Appendix F.

15.1 Airflow Reading/Accuracy Test

During the test of the Airflow Reading and Accuracy, the Collapsible Anemometer had to read the air inside a duct that was produced by Team 12. The goal the accuracy test was for the Collapsible Anemometer to read within +/- 7% of the control anemometer produced by ExTech. During the test the expandable arms had to increase in size and hold the anemometer on the walls of the duct. This test wan an overall success due to the arms being able to increase in size from 8in to 14in. When the Collapsible Anemometer was placed inside the duct, the duct was then turned up to a maximum speed of 680 FPM. The fan of the anemometer then began to spin and a light sensor would read the rotations per minute of the fan. To do this a laser shines a light through a hole in the fan and as the fan rotates the light shines through the hole and is picked up by the light sensor. This was an overall success because it read the correct value of RPMs of the fan.

Once the values of RPM are calculated by the Arduino connected to the light sensor, the value of FPM is then produced using a conversion from RPM to FPM:

$$FPM = RPM \times Diameter\ of\ Fan \tag{6}$$

$$FPM = 200\frac{rev}{min} \times 0.75ft \tag{7}$$

This reading satisfied the condition of project where the product had to read from 0 to 2000 CFM. The product was able to read 685 CFM which was less than 1% of the actual air speed. To find the percent error an error analysis was done:

$$\% = ABS(\frac{experimental - actual}{actual}) \tag{8}$$

Since the product met both the design specification of measuring between 0 to 2000 CFM and the accuracy of being +/- 7% of the actual data, the test of the accuracy and reading was an overall success.

15.2 Robustness Test

When looking at what Emerson wanted from the product, they expressed that they wanted a product that was strong enough to handle multiple testings and would last for awhile. To test the robustness of the product, a test on the battery had to be done to see how long the battery would last. The goal was for the product to not have to be taken apart to replace the battery for an extended period of time. To determine the life on the battery, Team 12 calculated the amount of amps the light sensor and the laser would use per minute. From there, Team 12 determined how long would the 9V battery would last.

$$Life\ of\ Battery = Energy_{battery}/Power_{circuit} \tag{9}$$

$$Energy_{battery} = 580mAh = 18792J \tag{10}$$

$$Power_{circuit} = 5V(I_{LightSensormax} + I_{LightEmitter}) \tag{11}$$

Note that the arduino is powered via computer USB Cable.

$$Power_{circuit} = 9V(5mA + 60mA) = 0.325W \tag{12}$$

$$Life\ of\ Battery = Energy_{battery}/Power_{circuit} = \frac{18792J}{0.325W} = 57821.5s \quad (13)$$

The conclusion came to about 16 hours of non stop use before the battery would need to be change. This allows an ample amount of uses for the technician to assess the air speed of a residential ducted system. If the technician needed more power, he could simply remove the front plate from the Collapsible Anemometer and replace the battery. To remove the front plate the technician would only need a Phillips Head Screwdriver and the replacement process would take no more than 5 mins.

To test the strength of the design, Team 12 preformed a drop test. This test would simulate the product being used on a consistent basis. Team 12 wanted the product to be able to withstand multiple uses over time. The product was dropped from 2 ft up and then put into the duct to see if it would read the same data as before the test. The expandable arms were also tested during this test to see if they would expand to the same size as before the test. The arms expanded to the correct size after the test from 8 to 14 inches.

15.3 Set Up Time

In the design specification that were request by the HeroX competition, they wanted a design that would be able to be set up and preform an air speed reading within 20 mins. To preform this test, one team member would set up the test and run the test while the other would time the time it takes for from the beginning until the completion of the test.The time it took to run the test took about 5 mins. This included the time to place the anemometer inside the duct using the expandable arms, the time to start up the software that would read the air flow and the time to turn on the fan that would produce the accelerated air for the test.

15.4 Expandable Arms

To be able to meet different sizes for filters in air handling and fan coil units, the product had to be able to expand to different sizes. To do this, arms were built to allow for the product to meet different size filter. The important part about the expanding nature of the product was the fan had to stay in the middle of the design to produce the best air flow reading from the velocity profile. The arms had to expand from 8 to 14 inches to pass the test of the expandable capabilities of the design. To do this, one group member would pull both arms apart from each other until they reach the maximum size. The maximum size that was found was 14.5 inches. This passed the overall test for the expanding capability of the design. The next test was when the arms are expanded they have to be able to suspend the design in the duct. To test this, the arms were expanded inside the duct and the box fan was turned on. The arms were able to hold the design and kept it from falling. This test was done at the highest air speed to simulate the conditions in a residential ducted system.

15.5 Standards Applied to Testing

There were no standards that had to be met by ASHRAE for our testing. There were only materials, assembly and manufacturing methods that had to be met. These are covered in other parts of the report.

15.6 Discussion of Results

After testing each of the criteria that had to be met for the project, Team 12 evaluated the success and failure of each criteria. We checked to see if the criteria met the guidelines that were expressed by the design specifications or by the group itself. To make a product that would be safe to use and effective when being used, the product must be able to pass all of the criteria. Team 12 then determined at the end of the evaluation if the product would be successful on the open market. Below is how each test faired.

15.6.1 Airflow Reading/Accuracy Test

The requirements of this test was the apparatus had to read airflow from 0 to 2000 CFM and reach within an accuracy of +/- 7% from the control apparatus. The Collapsible Anemometer was able to read within 1% of the values of the control anemometer. The values that were outputted by the control anemometer averaged around 685 FPM. An average value had to be taken due to the fluctuation of the air passing through the measurement device. Since the box fan created a swirling vortex of air within the duct, the air was not always constant. However, the values stayed within +/- 5% of 685 FPM. The Collapsible Anemometer was able to read an average value of 685 FPM. Below in Table 6 the values of the Collapsible Anemometer and the control anemometer produced by ExTech are shown.

Time (s)	ExTech Anemometer Reading (FPM)	Collapsible Anemometer Reading (FPM)	Error Percentage
1	685	675	1.459854015
2	700	685	2.142857143
3	689	689	0
4	691	681	1.447178003
5	682	682	0
6	691	675	2.315484805
7	683	680	0.439238653
8	685	679	0.875912409
9	683	678	0.732064422
10	675	682	1.037037037
11	682	678	0.586510264
12	687	683	0.58224163
13	692	687	0.722543353
14	680	678	0.294117647
15	683	679	0.585651537
Average	685.8666667	680.7333333	0.881379394

Table 7: Results Produced From Air Speed Test

In the table, the average error was found. The average error produced was 0.88%. This error is greatly less than what was asked of the competition. Due to the Collapsible Anemometer reaching within 0.88% of the actual air speed reading, the test can be called a success. The Collapsible Anemometer meets the most important test criteria of the project.

15.6.2 Robustness Test

The requirements of this test was the apparatus had to be able to withstand multiple uses over time and last for a long time on a single battery. The results found from these test were positive and the Collapsible Anemometer passed all of them. The drop test was preformed by taking the Collapsible Anemometer and dropping it from 2 ft off the ground onto concrete. From there the user had to check the integrity of the Collapsible Anemometer and check to see if the mechanical and electrical components still functioned as they were intended. The test was a success because the device was able to withstand the impact and still function as it was made to. The expandable arms were able to still work as they were intended and the air speed was measuring accurately. This provided a good idea that even in the field and under certain conditions, the device would be able to function as intended.

The other test for robustness was to test to see how long the battery would last. Team 12 wanted the battery to be able to last an extended period of time to prevent the user from having to replace the battery. The battery life was determined to last about 16 hours of non stop use. This provided a good idea of how long it would take until the user would have to replace the power supply of the design. The goal for Team 12 was to have it last for over an hour of non stop use and the test proved that would not be a problem.

15.6.3 Set Up Time

The requirements of this test was the apparatus had to be able to be set up and run a test within the 20 min time limit. After preforming this test, Team 12 determined that the Collapsible Anemometer would have non problem being set up and take a reading within the 20 minute time table. The whole set up and testing of the air speed with the Collapsible Anemometer took about 5 minute from beginning to end. The most time was the testing part due to the time it took to turn on the software and make sure it was calibrated correctly. To determine the total CFM from the FPM reading would take another 5 minutes. This would involve the user measuring the length and width of the inside of the duct and then multiplying that by the average FPM reading. Overall the whole time that the set up and testing would take is approximately 10 minutes. This is under the recommended amount of time and gives the user some time in case of set up error or a malfunction with the reading.

15.6.4 Expandable Arms

The requirements for this test was the arms that are used to adjust the size of the Collapsible Anemometer must be able to increase and decrease in size from 8 to 14 inches. After preforming the test, Team 12 determined the design would be able to adjust to all sizes within 8 to 14.5 inches. This allows the user to adjust to a variety of size filters. The second test that was run on the expandable arms was to check to see if the arms would hold the weight of the anemometer. The arms needed to prevent the anemometer from changing position during testing and hold it firmly in place. The test wan an overall success because there was no movement of the anemometer during testing and the expanding arms kept the anemometer centered and held in place. To increase the size to anything bigger than 14.5 inches, attachment pieces must be used. These pieces will increase the length the arms can extend therefore accommodating all filter sizes, while still providing a stable base for the anemometer.

15.7 Testing Conclusion

Overall the testing was a success. Every one of the specified requirements were met. Team 12 exceeded the expectations of ourselves and the expectations of the project. One addition test that could have been preformed was to preformed an air speed reading inside a residential air handling or fan coil unit. This would have given an accurate depiction of whether the device would be work in a real life setting or fail. The tests run by Team 12 produced good results, however running the test inside a household ducted system would provide necessary information to see if the device would be able to work in the field. Another test that could have been run was a pressure drop test. A filter from a air handling or fan coil unit produces a pressure drop when air passes through it. This pressure drop must be a certain value to prevent an increase in pressure of the duct as the supply air is fed into the ductwork. If the device does not reach this pressure drop then damage can be caused to the air handling or fan coil unit. A final test that could have been run was a safety test to see what kind of precautions would need to be added to the device. If the device was to become dislodged from the rack that holds the filter, then it could damage the internal components of the unit such as the evaporator. Team 12 would want to make sure if something did go wrong then the user would be able to fix the problem without causing damage to the internal components of the unit or the anemometer. If the device was able to pass this final test, then the product would be ready for marketing.

16 Redesign

16.1 Initial Design

16.1.1 Mechanical Design

At the beginning of the test phase, the design used four telescoping arms to expand length and width. This proved to be too tricky to manufacture, and commercial hardware is too expensive. the solution was the opposing rack and pinion design featured in the final prototype. The opposing Rack and pinion configuration uses far less moving parts while also ensuring that the impeller is centered in the wind stream. This is a huge design advantage because not only will less moving parts theoretically wear less, but the impeller being centered will also provide more consistent readings.

Below is an image of the Final Design in Figure 51.

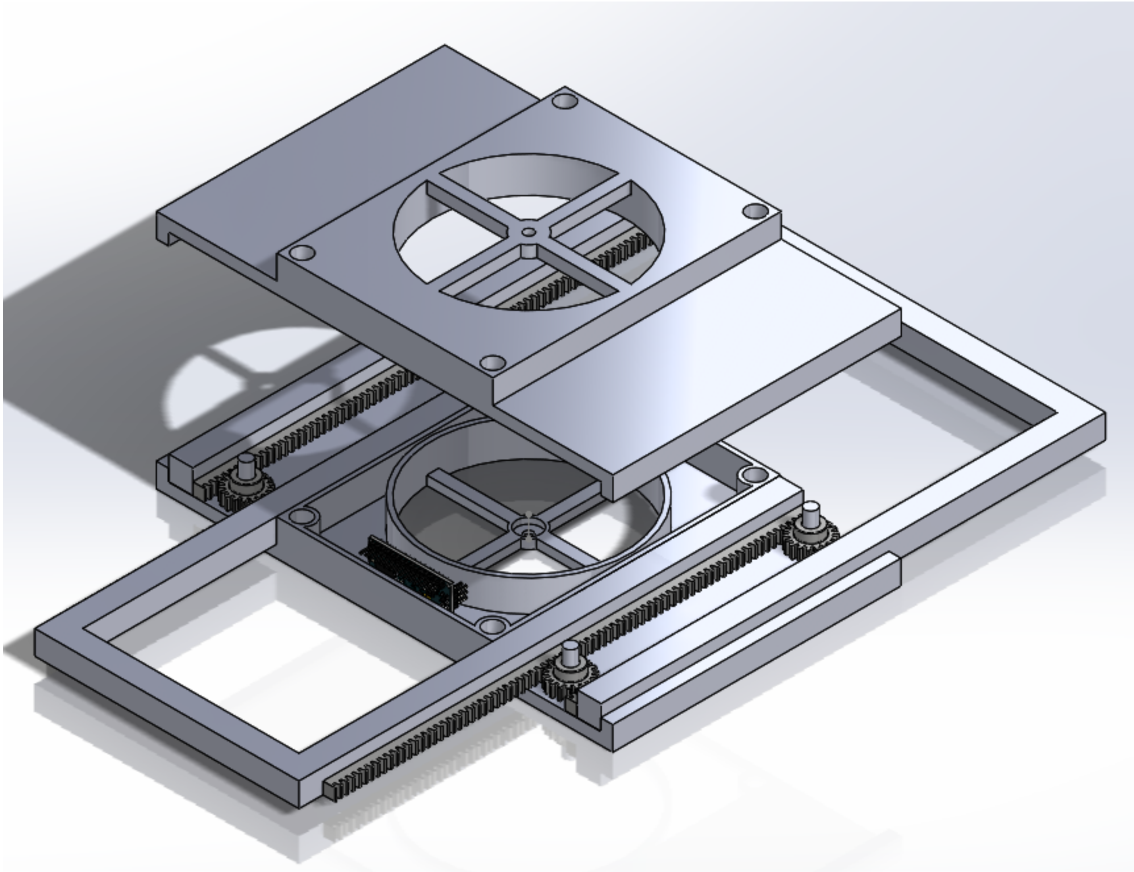


Figure 51: Final Design

16.1.2 Electrical Design

To collect the data we need, we had to design a way to read the angular velocity of the impeller without disturbing it. The solution was to replicate the way optical encoders work. A light is shined through a small hole in the fan blade and onto a photo-resistor which acts as a light sensor for the arduino nano. The fan blade will then move, interrupting the light stream, and the arduino will count micro seconds until the light passes through again. Every second the arduino will ignore the light sensor to display the frequency of light in the past interval. If the arduino does not actively ignore the photo resistor then it can interrupt the printing function and cause errors. The light sensor work via a contant $1K\Omega$ resistor in series with a photoresistor. The Photoresistor varies from about $10K\Omega$ to about 0Ω when saturated. If we use the two as a voltage dividing circuit, then the measured voltage between the two resistors will jump from about 1V to 5V when activated. The arduino will read signals greater than 3.3V as "HIGH", so this will give us a large margin for error.

16.2 Design Modifications

16.2.1 Improved Expandability Range

During the first round of testing, It was clear that the arms could not quite expand to the target lengths. A simple new design feature would allow the anemometer to fit larger and larger filter shelves. Although it was never prototyped, team 12 has plans for arm extensions that would allow at least an extra 10 inches of arm travel. Rather than needing a whole new device, the plans described small extensions which would attach end to end to extend the arms.

16.2.2 Electrical Changes

In order to run the whole circuit without cables, there needed to an on-board power supply. 9V batteries have plenty of energy, but the light emitter and receiver both operate at 5V. To accommodate this, we added a 5V regulator to the circuit board. That way we could run the device independently for over 2hr before needing a replacement, which is easily accessible.

16.3 Redesign Conclusions

We wanted to make sure our product was as easy to use and maintain as possible. The first design was not practical in terms of manufacturing and cost, so changes were necessary. The physical design was flimsy and too intricate to manufacture ourselves, so we compromised with the opposing rack design. This turned out to be an advantage because now the fluid velocity sensor was guaranteed to be in the center of the air stream. Some Electrical changes were necessary as well to allow the device to be portable. By adding a 5V regulator to the circuit, the device could be powered for over two hours with a standard 9V battery. This makes setup time and maintenance far better.

17 Operation

The Collapsible Filter Anemometer operates in a manner that is quick and easy for the technician testing the air flow of any residential indoor ducted furnace, heat pump, or central Air-Conditioning system. The technician must open the main unit of the system which contains the blower, which produces all the air flow in the system. For safety purposes, the system should be temporarily shut down while the technician retrieves the filter out of the main unit. Once the filter is removed, the collapsible anemometer is to be placed in the filter compartment to test the air flow.

The device is designed utilizing a rack and pinion method so that the device can expand or contract according to the size of the filter compartment on the unit being tested. When the size is adjusted, the rack and pinion method keeps the fan in the middle of the airstream. The fabricated prototype can test on compartments from 8 inches to 14 inches. Residential filters range from 10 inches to 34 inches so this requires that two different sized models of our prototype be designed to cover the whole range of residential filter slots. Once the device is adjusted to the appropriate size and secured in place, the system is to be turned back on, and the Arduino code will produce a reading of air flow in feet per minute. This reading is to be multiplied by the area of the filter compartment to obtain a measurement of air flow in cubic feet per minute. The HeroX Air Flow Challenge required that the device can read air flow from zero to 2000 cubic feet per minute. Once the measurement is obtained, the system can be shut down again for the device to be removed and the filter to be re-inserted. This overall test time for the technician is under 20 minutes which was another requirement of the HeroX Air Flow Challenge.

18 Maintenance

The Collapsible Filter Anemometer utilizes a 9V battery as a power supply. Depending on how often tests are performed, the battery will have to be replaced routinely. After every use the device should be wiped down with a dry rag to remove any dust or particulates from the air the passed through it during the test. The rotary bearings on the fan shaft should also be greased periodically to mitigate drag. Other than these simple maintenance requirements, there is nothing left to do to ensure accurate performance of this device. The lifetime of the device is infinite unless of course it is misused or broken.

19 Additional Considerations

19.1 Economic Impact

Emerson manufactures many products used in the HVAC Industry. These products are used in a variety of ways to measure air speed in residential and commercial units. They produce products such as anemometers, pressure sensors, temperature sensors, humidity sensors, and flow hoods. The new anemometer design produced by Team 12 will be easy to manufacture and produce a low cost, effective way of measuring air flow inside a residential indoor ducted system. The design keeps the user from having to hold the product during test given a more consistent reading, while keeping the user from exerting energy. Using expanding arms allows the user to read any type of residential air unit. The cost to produce the Collapsible Anemometer would be around $97. Compared to the market price of anemometers, which is around $100 to $200, the price of the Collapsible Anemometer would be more affordable than the market price. If the anemometer could be produced with only injection molding parts, Team 12 estimated the price would be around $75. If the product was sold for $90 then that would be a $15 profit per unit. Industry

By having a low cost and extremely accurate product being produced at a low price, the market on this product would be very good. The product would sell well due to the increased demand due to more home being installed with central air conditioning units. This would provide a technician with a cheap and effective way of measuring airflow without having to exert much energy. Putting this product on the market would allow Emerson and Team 12 to compete with all other air measurement devices and the companies that make them.

19.2 Environmental Impact

To produce the Collapsible Anemometer a good amount of plastic has to be used. To produce the plastic used for the Collapsible Anemometer, plastic must be heated until it is in a liquid state. An excess amount of plastic will be produced and must be disposed off. this plastic can be potentially harmful to the environment due to it either being disposed in landfills or being burned. This burning plastic can create a large carbon emission.

Though this is important to the environmental impact, the bigger consideration is the energy that it takes to produce an injected molding part. Parts produced using Injection Molding are produced using three different methods, hydraulic, hybrid and all electric. These three methods can produce a large amount of energy. According to an analysis produced by the Alexandre Thiriez and Timothy Gutowski from the Department of Mechanical Engineering from MIT, the energy usage determined fro hydraulic, hybrid and all electric machines were 19.0, 13.2, and 12.6 MJ/kg. (17) This amount increases due to polymer consumption to 100 MJ/kg. If the product produced by Team 12 is 1 kg of polymer, then the amount of energy to produce 100 products would be around 10,000 MJ of energy. This causes a large amount of carbon emission do to the amount of energy that it takes to make this large amount of energy. Though this is not beneficial to the environment, it is much safer than producing a product out of steel or a refined metal. The deposits from the refined steel can be harmful when they are deposited back into the environment. Though using injection molding takes a large amount of energy to produce the product, using all electric would take much less energy than hydraulic would. Hydraulic as previously stated would take around 19.0 MJ/kg just to run the machine. Compared to the 12.6 MJ/kg that all electric would take that is about a 33.6% decrease in energy. This is a large improvement in energy consumption and would drastically decrease the energy requirements over a year of use.

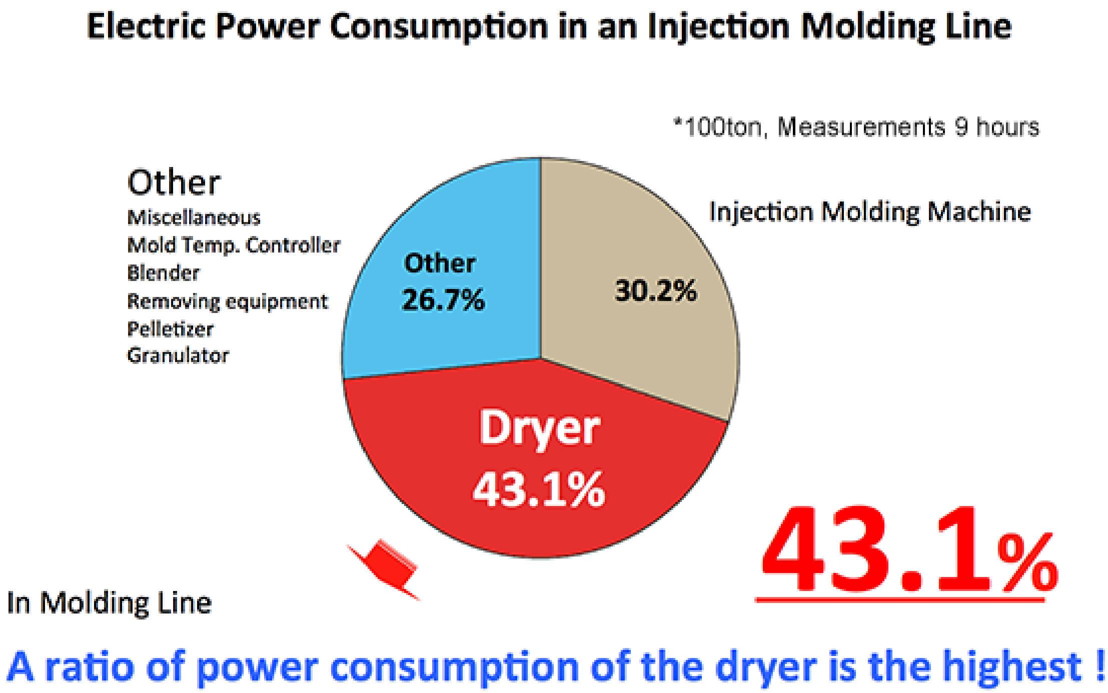


Figure 52: Electric Power Consumption in an Injection Molding Line

Though the energy consumption would seem to be high, it is extremely small compared to what the United States produces on a yearly basis. The United States annually consumes about 2.06 x 10^8 GJ of energy. Compared to the 100 MJ used to produce the product, the difference is massive. Using all electric would help keep the energy consumption down and benefit the production of the product over the span of the year.

19.3 Societal Impact

Although the societal impacts of the anemometer can go easily unnoticed, it actually makes a huge impact on the lives of individuals. Though it is not directly responsible to the comfort of people, it can make sure the system is working well and functioning at the highest efficiency. Without the anemometer, if a problem arose in the system, the technician would have trouble determining the area of the problem. Determining the area of the problem is important for people to get back to being comfortable in there homes during the summer and staying warm during the winter.

A study was done on the increase of the percentage of people owning central air conditioning system over the past 30 years. The study shows a steady increase in the amount of people owning central air conditioning systems. Due to this, more technicians are needed to inspect the system over time to see if they work correctly. The technicians need a device that is reliable to test the airflow in case of a malfunction in the system. It is important for the technician to diagnose the problem and return the system back to working status as quickly as possible. The sooner the technician finds the problem; the sooner the home owner can get back to living comfortably.

Not only is this important in residential systems, this is also important in commercial systems. Though the design was not originally built to handle the wind speed produced from a commercial design, the design can be modified to fit the air speed of the commercial system. Determining the problem with the system is the same for residential as it is for commercial, but the amount of people it affect are on a much larger scale. If an office is supplied with 10,000 CFM of air and the system all of a sudden break, then the conditions can get very uncomfortable in the workplace. This can affect a person work output and the amount of work they can get done. Being comfortable in the work environment is very important to the overall success of the company. If the workers are not producing at an efficient rate, then the company loses profit. A tool like the Collapsible Anemometer can help the technician find the problem from the source and fix the problem as quickly as possible.

19.4 Political Impact

Though there is political impact of the Collapsible Anemometer, it is not a large scale like some products are. The HeroX Competition was a worldwide competition that featured people from all different backgrounds trying to create a new method of measuring air flow in a residential ducted system. This provided ideas from all different types of people all trying to work towards a common problem. The overall results of the competition will help improve the way that companies all over the world build devices that measure air flow.

Since measuring air flow in ductwork is something that happens all over the world, not just one company is involved in this type of engineering. With the growing market of central air conditioning system, more products need to be created to more efficiently measure the air flow of a certain system. This creates worldwide competition where companies from multiple countries compete with each other to build the best product on the market. Companies such as Emerson and ExTech have produced products that are world renowned and considered some of the best. To build a product to compete with these companies, the product must be accurate and affordable by the user. That was the end goal in the HeroX competition, to build a cheap, accurate product that would measure the air speed as well as be reliable.

The political considerations are minimal due to the design following similar design specifications are any anemometer. The units on the device will change whether it is foreign or domestic, but the material will remain the same due to there is no problems with the material being used in other countries. There would need to be some evaluation of the materials if the product would be produced outside of the United States, but the materials should not create any type of foreign problems.

19.5 Ethical Considerations

By using anemometers, technicians are able to determine the overall efficiency of the system. This allows a technician to pinpoint a problem and fix the problem as quickly as possible. Avoiding the use of this product can result in a much longer diagnosis of the problem. Due to the product being able to determine the problem from the source, the time to diagnose the problem is significantly decreased.

By decreasing the time of finding the problem, the price of the diagnosis significantly decreases. Since some HVAC technicians get paid by the hour, the sooner they find the problem and fix it, the less money the home owner has to pay for the problem to be fixed. Finding the problem from the source also makes sure the diagnosis is correct. A correct diagnosis makes sure the correct pieces are ordered to fix the problem. This saves the homeowner time and money to fix their system.

The anemometer must meet all criteria that is laid out by ASHRAE. The design must be verified using a pitot tube to measure the air speed. Safety of these devices are of the utmost concern especially since the device will be place inside of a working central air system. Ethically Team 12 would not want our device to be placed inside of a unit without verifying that it would not damage the internal components of the system. The anemometer must be placed through severla tests of the components of the design to make sure it is safe for use. These tests provided by ASHRAE include testing of the fan rotation to make sure that it is providing the correct air speed.

The way to determine a good product is the overall efficiency of the product. The product must be read the correct amount of air flow as efficiently as possible. The technician wants to make sure that the reading that he receives from the anemometer is correct to diagnose where the system is malfunctioning. Making sure the fan and the electrical systems work correctly will make sure the device is producing good results.

19.6 Health, Ergonomics, and Safety Considerations

When designing any type of prototype, Health, Ergonomics and Safety must all be taken into consideration. For this specific component the material used to manufacture the product and disposal of the certain parts of the product must be considered in this analysis. It is important to apply this analysis when designing the product to make sure there is no harm to any person during the disposal. The safety of using the product must be taken into consideration due to the user will be working around moving mechanical parts.

The Health and Ergonomics of the product deals with the materials using to produce the product and the disposal of parts when they no longer are functioning. Parts such as the 9V battery used as the power supply will need to be disposed of correctly to prevent any leakage of battery acid. This battery acid can be harmful and needs to be handled with care. The materials were chosen for this product due to the structural strength and the temperature resistance the materials could handle. Due to the temperatures reaching greater than 100°F the material choice is very important to prevent damage to the device and other internal components. To prevent harm from the battery, the battery should be recycled. A new battery should be installed correctly and the battery should from a package that has not already been tampered with. If the battery is leaking, then the battery cannot be used and must be disposed of properly.

The safety of the product is very important to Team 12. We wanted to make a product that was safe to use while filling necessary criteria as well. However, the use of the product must be taken into consideration when considering safety. The product is used around a lot of moving parts in a central air unit. The product must be able to be inserted safely without harm to the user. Correct training is required to use the product to prevent any user from harm. A trained professional will know how to turn off the air unit before inserting the anemometer. The professional will have to be trained to use the product in case of a malfunction and the product became dislodged from the tray holder. Though there are no moving parts of the design that can be harmful, it is important to consider the environment of the testing. One part that could be harmful to the user is the fan. Since the fan can spin at a maximum RPM of 12000 RPM, the user does not want to have any appendages in the area of the fan. This is a hands free device so no hands should be near the rotating parts of the device.

19.7 Sustainability

In sustainability, the three most important terms are to reduce, reuse, and recycle the product. (21) This standard produced by the Environmental Protection Agency (EPA) promotes these three guidelines to allow for a greener Earth. Team 12 practices these three guidelines with the Collapsible Anemometer to make sure the anemometer is safe for the environment. To practice this, we apply the three guidelines to different parts of the design.

19.7.1 Reduce

To fit the criteria of reduce, we reduced the amount of material used from the original design to the new design. The original design asked for 10 times more plastic then that of the Collapsible Anemometer. This was due to the Fan Filter Matrix needing over 45 pieces to produce the product. The Collapsible Anemometer needed 23 pieces to produce the product. That saves more than half the amount of plastic. The plastic can cause harm to the environment and reducing it helps the overall product and the environment.

19.7.2 Reuse

To fit this criteria, Team 12 wanted to make sure that the product would be able to be used for multiple uses. The product was designed to be used for years without having to dispose of any of the large components that were produced using injection molding. This saves energy from having to constantly produce a product from injection molding. Since the amount of energy it takes to produce a product using all electric takes about 12.6 MJ/kg, having less products to produce over time saves a lot of energy. (17)

19.7.3 Recycle

To fit this criteria, Team 12 promotes recycling any electrical components of the product when they no longer function. The EPA recommends recycling electrical components since the majority of electrical components are made of plastic, minerals, and glass which can all be used again. (21) Due to the product being made of polypropylene, the mechanical parts can be recycled as well. This saves a large amount of plastic from having to be produced multiple times. Minerals such as copper and silver that are used in electrical components can be used again if the components are recycled correctly. Team 12's design is all made out of components that can be recycled. By recycling a product that is broken or can no longer be used, Team 12 is helping to promote a better environment and helping to raise awareness on sustainability.

20 Conclusions

In conclusion, the development of the prototype for the Collapsible Filter Anemometer was a success. Further work was done after submission of the design report to the HeroX web page that would likely have an effect on the judging of this device. No testing had been done before submission to HeroX but once it had been completed, Team 12 proved that their device was extremely accurate and consistent in its reading of air flow in feet per minute. There are further improvements that can be made on the Collapsible Filter Anemometer. One addition that would improve the device is a locking mechanism to keep the arms in place to stay the size of the filter being tested. An idea to fulfill this was to spring load the arms of the device so that it automatically expands and locks into the filter compartment. Furthermore, Team 12 wanted to 3D print the arms of the device with the rack design included in the arms as one piece. Due to unavailability of the 3D printers, Team 12 was forced to use the CNC at Schneider Electric to cut out wooden arms and attach plastic racks to the arms adhesively. This is more costly and causes the rack and pinion system not to move as smoothly as it could. In the end, this device, the Collapsible Filter Anemometer, will save HVAC contractors a substantial amount of time and money when called upon to test residential HVAC systems such as indoor ducted furnaces, heat pumps and central Air-Conditioning units. The final product met all guidelines specified by Emerson on the HeroX Air Flow Challenge web page while keeping the project cost well under budget. Right now there are no accurate and affordable products on the market for residential HVAC testing. With further development, mass production, and proper marketing, the Collapsible Filter Anemometer can change the way residential HVAC systems are tested and maintained by technicians.

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22 Appendices

22.1 Appendix A: Project Planning

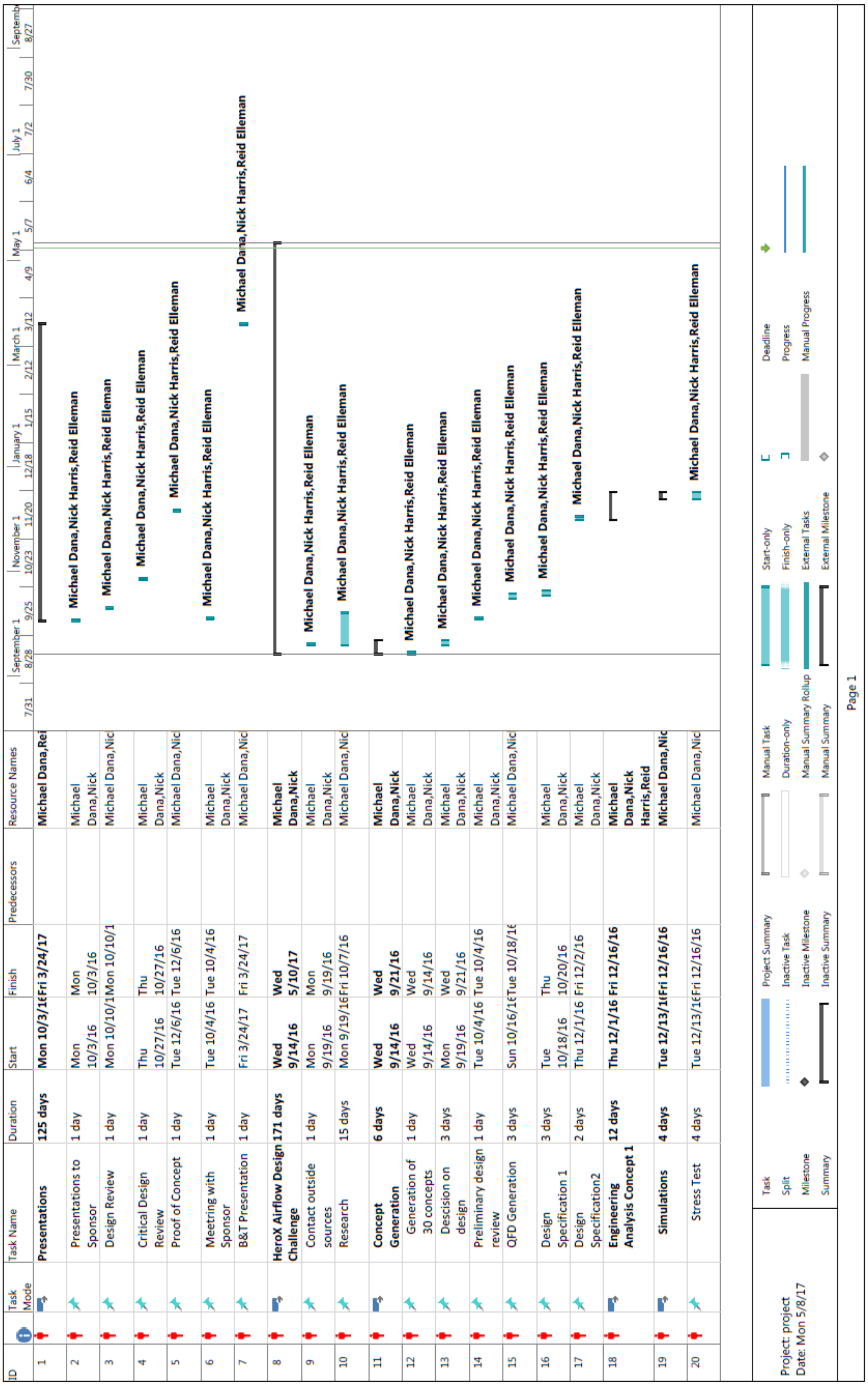
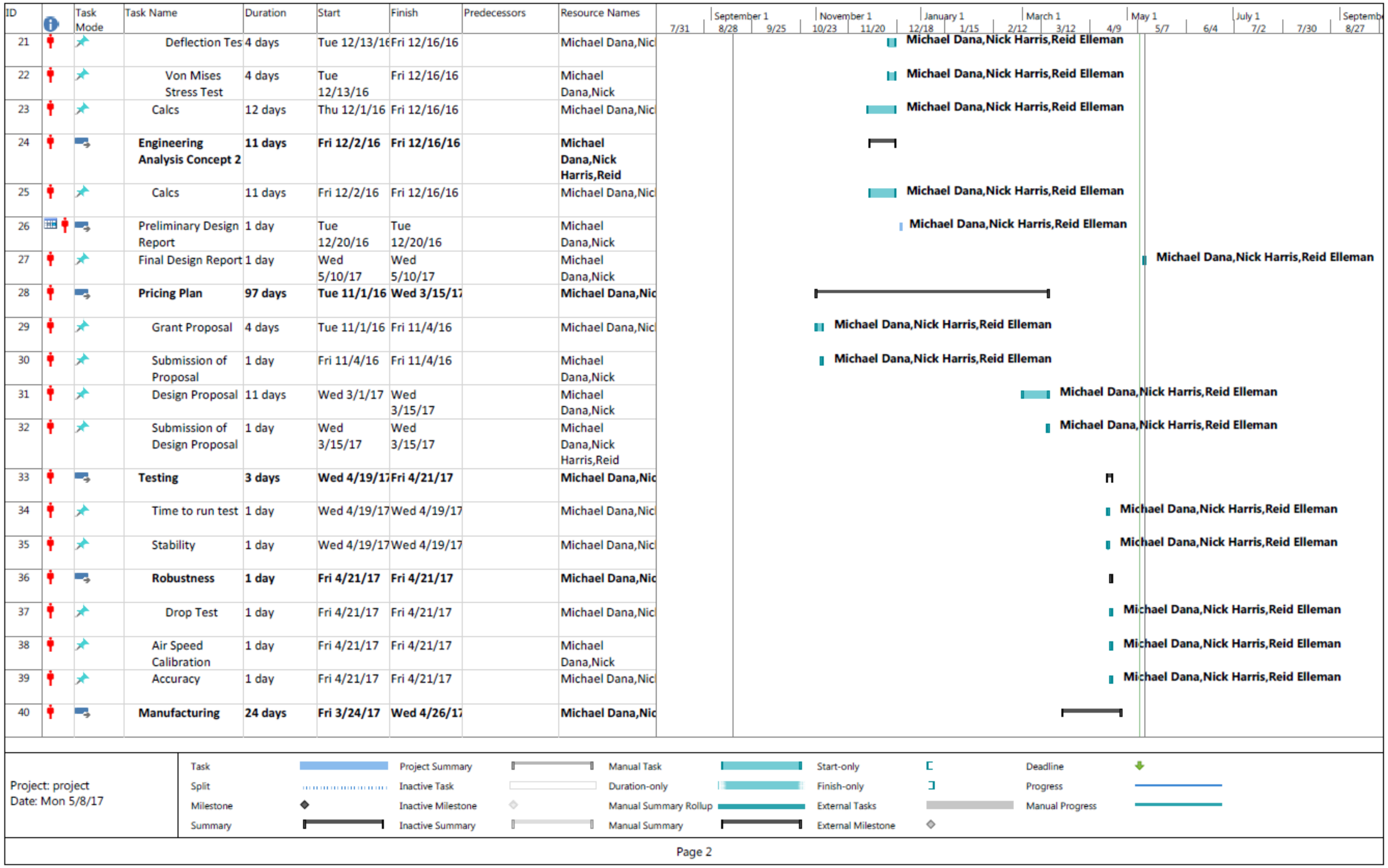


Figure 53: Project Plan Part 1



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
21		Deflection Tes	4 days	Tue 12/13/16	Fri 12/16/16		Michael Dana,Nic
22		Von Mises Stress Test	4 days	Tue 12/13/16	Fri 12/16/16		Michael Dana,Nick
23		Calcs	12 days	Thu 12/1/16	Fri 12/16/16		Michael Dana,Nic
24		**Engineering Analysis Concept 2**	**11 days**	**Fri 12/2/16**	**Fri 12/16/16**		**Michael Dana,Nick Harris,Reid**
25		Calcs	11 days	Fri 12/2/16	Fri 12/16/16		Michael Dana,Nic
26		Preliminary Design Report	1 day	Tue 12/20/16	Tue 12/20/16		Michael Dana,Nick
27		Final Design Report	1 day	Wed 5/10/17	Wed 5/10/17		Michael Dana,Nick
28		**Pricing Plan**	**97 days**	**Tue 11/1/16**	**Wed 3/15/17**		**Michael Dana,Nic**
29		Grant Proposal	4 days	Tue 11/1/16	Fri 11/4/16		Michael Dana,Nic
30		Submission of Proposal	1 day	Fri 11/4/16	Fri 11/4/16		Michael Dana,Nick
31		Design Proposal	11 days	Wed 3/1/17	Wed 3/15/17		Michael Dana,Nick
32		Submission of Design Proposal	1 day	Wed 3/15/17	Wed 3/15/17		Michael Dana,Nick Harris,Reid
33		**Testing**	**3 days**	**Wed 4/19/17**	**Fri 4/21/17**		**Michael Dana,Nic**
34		Time to run test	1 day	Wed 4/19/17	Wed 4/19/17		Michael Dana,Nic
35		Stability	1 day	Wed 4/19/17	Wed 4/19/17		Michael Dana,Nic
36		**Robustness**	**1 day**	**Fri 4/21/17**	**Fri 4/21/17**		**Michael Dana,Nic**
37		Drop Test	1 day	Fri 4/21/17	Fri 4/21/17		Michael Dana,Nic
38		Air Speed Calibration	1 day	Fri 4/21/17	Fri 4/21/17		Michael Dana,Nick
39		Accuracy	1 day	Fri 4/21/17	Fri 4/21/17		Michael Dana,Nic
40		**Manufacturing**	**24 days**	**Fri 3/24/17**	**Wed 4/26/17**		**Michael Dana,Nic**

Figure 54: Project Plan Part 2

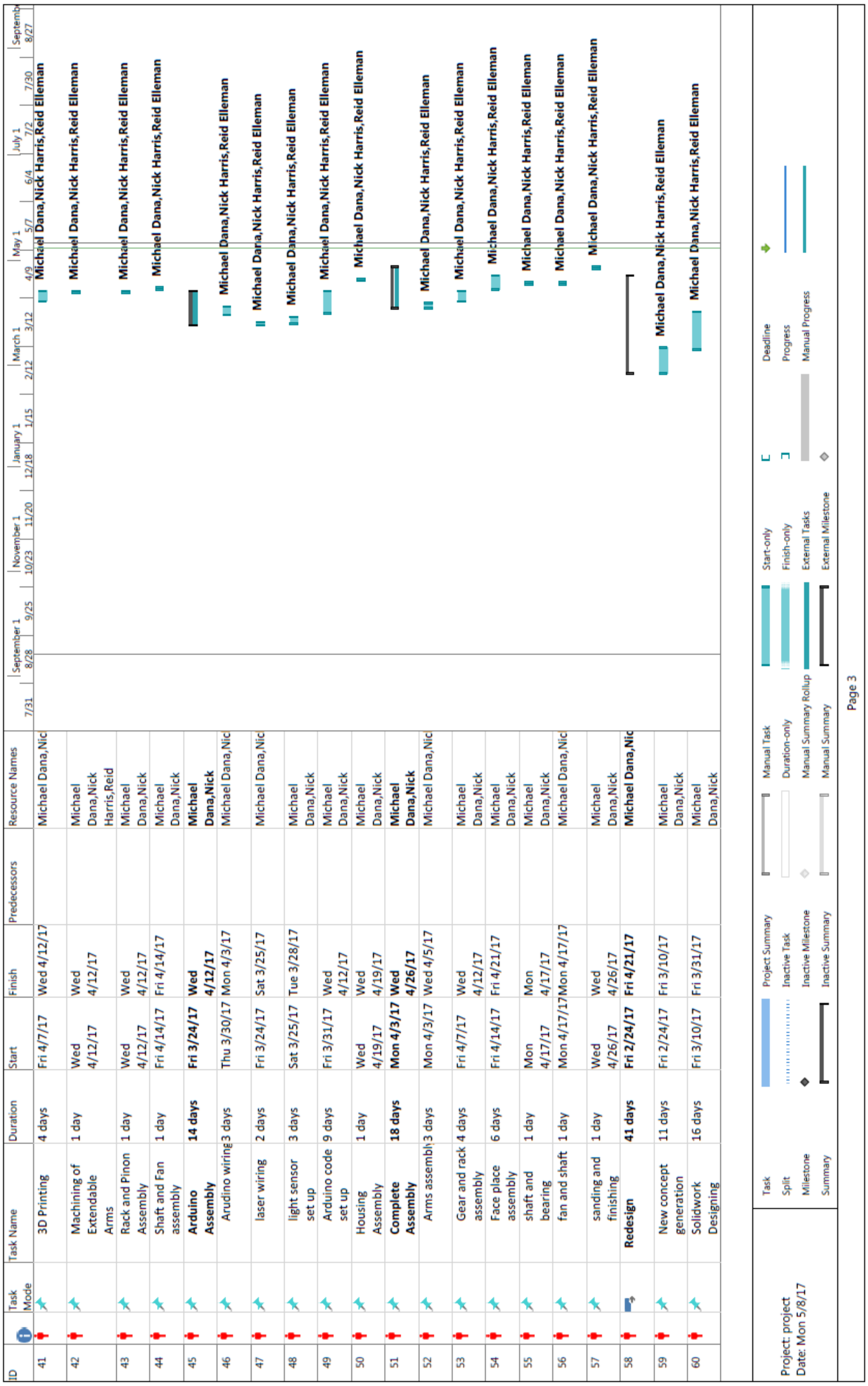


Figure 55: Project Plan Part 3

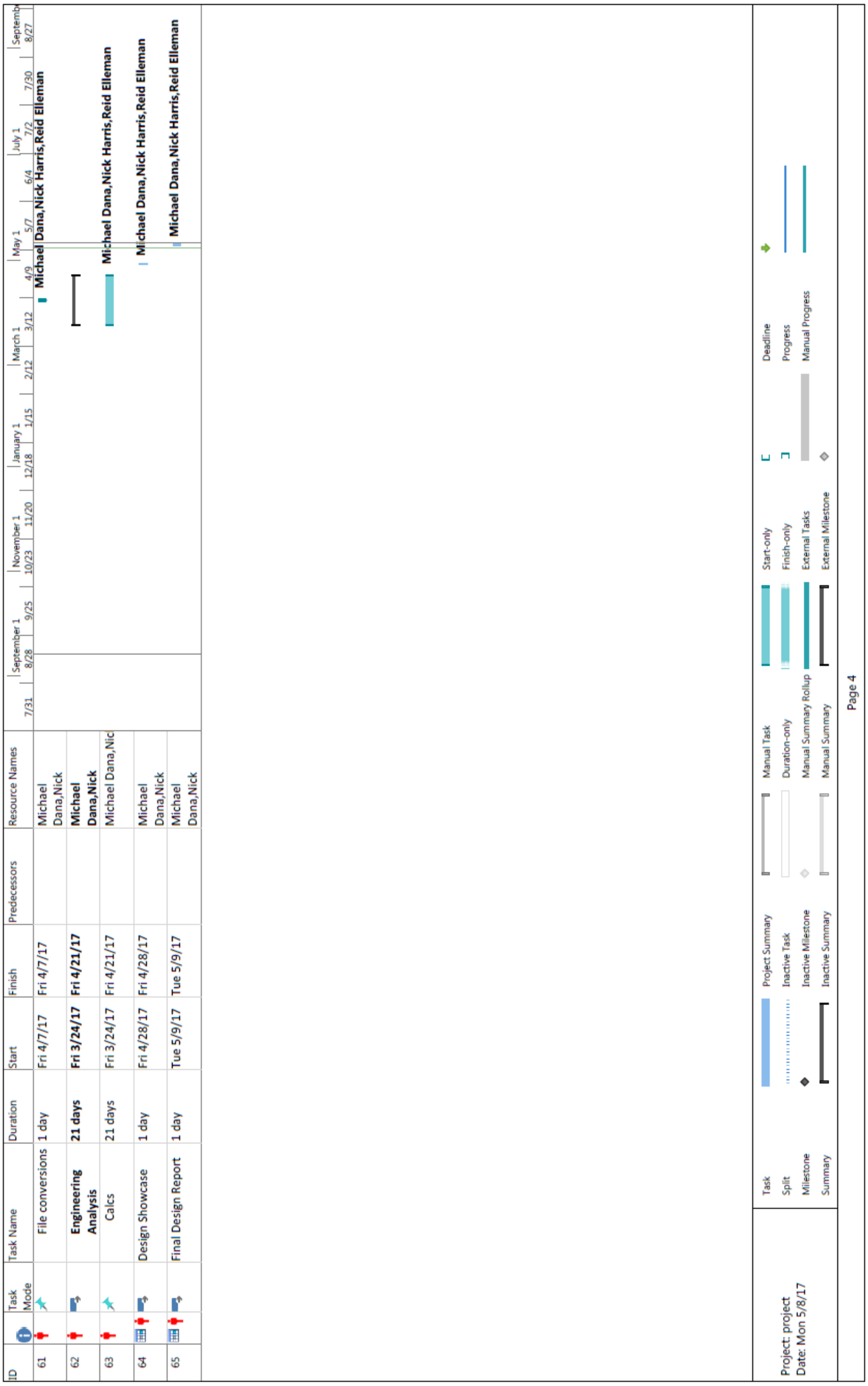


Figure 56: Project Plan Part 4

22.2 Appendix B: QFD

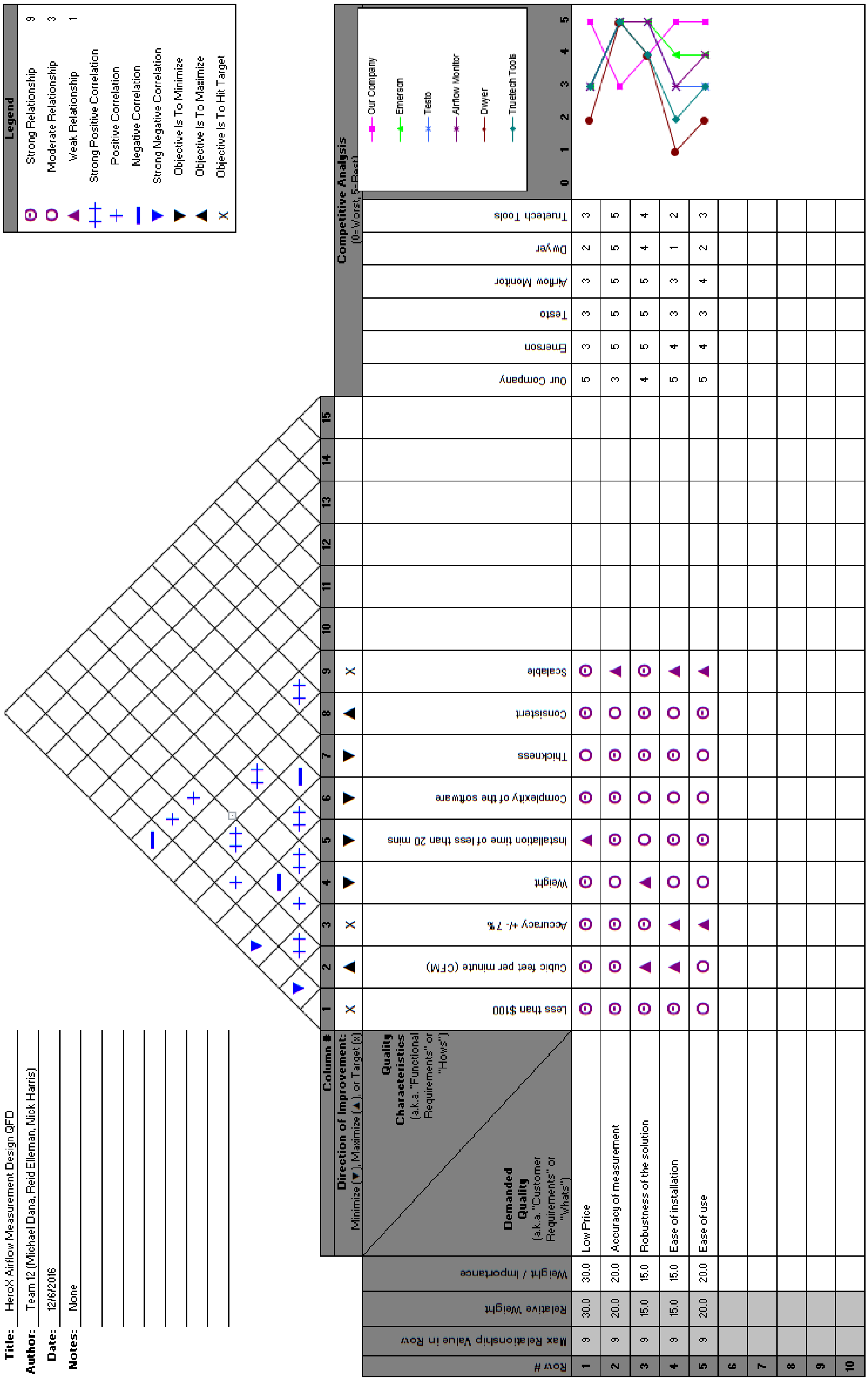


Figure 57: QFD Full Size Chart

22.3 Appendix C: Cost Analysis

Component	Unit Price	Quantity	Total
Plastic Gear - 14-1/2 Deg Pressure Angle Press-Fit Mnt, 24 Pitch, 18 Teeth	$6.18	4	$24.72
24 Pitch Rack for Plastic Gear - 14-1/2 Deg Pressure Angle	$7.64	4	$30.56
Lasko B20401 Decor Box Fan, 20", Black	$24.63	1	$28.52
Aluminum Fan	$3.54	1	$3.54
Ball Bearing Trade No. R2 for 1/8" Shaft Diameter, 3/8" OD	$5.94	2	$11.88
Rotary Shaft 12L14 Carbon Steel, 1/4" Diameter	$7.72	1	$7.72
Rotary Shaft 12L14 Carbon Steel, 1/8" Diameter	$2.93	1	$2.93
Brass Screw-to-Expand Inserts for Plastics M8 x 1.25mm Thread Size, 1.25 mm thick Flange	$1.16	4	$4.62
M8 x 1.25mm Screws	$1.11	4	$4.44
DEVCON 5 Minute Epoxy 1oz	$5.59	1	$5.59
Arnold Lumber Trip #1	n/a	n/a	$82.14
Arnold Lumber Trip #2	n/a	n/a	$45.24
1 X WYHP Mini Laser Dot Diode Module Head WL Red 650nm 6mm 5V 5mW Pack of 10pcs	$2.88	1	$2.88
Gorilla Glue Hot Glue Sticks	$5.97	1	$5.97
AIRSUNNY three Legs 5 pairs Infrared Diode LED IR Emission and Receiver	$5.98	1	$5.98
Gikfun USB Nano V3.0 ATmega328 CH340G 5V 16M Micro-controller board For Arduino (Pack of 3pcs) EK1620	$11.98	1	$11.98
TOTAL COST			**$278.71**

Table 8: Product Development Cost

Component	Unit Price	Quantity	Total
Plastic Gear - 14-1/2 Deg Pressure Angle Press-Fit Mnt, 24 Pitch, 18 Teeth	$6.18	4	$24.72
24 Pitch Rack for Plastic Gear - 14-1/2 Deg Pressure Angle	$7.64	4	$30.56
Aluminum Fan	$3.54	1	$3.54
Ball Bearing Trade No. R2 for 1/8" Shaft Diameter, 3/8" OD	$5.94	2	$11.88
Rotary Shaft 12L14 Carbon Steel, 1/4" Diameter	$7.72	1	$7.72
Rotary Shaft 12L14 Carbon Steel, 1/8" Diameter	$2.93	1	$2.93
Brass Screw-to-Expand Inserts for Plastics M8 x 1.25mm Thread Size, 1.25 mm thick Flange	$1.16	4	$4.62
M8 x 1.25mm Screws	$1.11	4	$4.44
1 X WYHP Mini Laser Dot Diode Module Head WL Red 650nm 6mm 5V 5mW Pack of 10pcs	$2.88	1	$2.88
Gikfun USB Nano V3.0 ATmega328 CH340G 5V 16M Micro-controller board For Arduino EK1620	$3.99	1	$3.99
TOTAL COST			**$97.28**

Table 9: Actual Product Cost

MCISE Capstone Order Request Form

4103 | 03/29/17
McMaster Carr
200 New Canton Way | Fax Number:
Robbinsville, NJ 08691 | XXX-XXX-XXXX
401-874-2524
Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
92 Upper College Road, 203 Wales Hall, Kingston RI 02881 | mceoffice@egr.

Team # 12 | Michael Dana, Reid Elleman, Nick Harris | MPA #:
Project Sponsor: | Name of Sponsor | Professor B. Nassersharif
Project Name: | Title of Project | HeroX Airflow Design Competition

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	Part Number	Description	Unit $	Subtotal	
4	57655K52	Plastic Gear - 14-1/2 Deg Pressure Angle Press-Fit Mnt, 24 Pitch, 18 Teeth	$6.18	$24.72	https://www.mcmaster.com/#orders/=16hvytk
4	57655K63	24 Pitch Rack for Plastic Gear - 14-1/2 Deg Pressure Angle	$7.64	$30.56	
				$0.00	
				$0.00	
				$0.00	
				$0.00	
				$0.00	
				$0.00	
				$0.00	
				$0.00	
		No Tax – URI is Tax Exempt – RI Tax Exempt 189		$0.00	
		Shipping Cost		$0.00	
			Total	$55.28	A & J Distributors
					Abcam, Inc.
					Additions Exhibit Systems
					Advanced Educational T

Figure 58: Order Form for Racks and Gears

MCISE Capstone Order Request Form

4103 | 03/29/17

McMaster Carr

https://www.mcmaster.com/#

401-874-2524

Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
51 Lower College Road, 230 Pastore Hall, Kingston RI 02881

mceoffice@egr.

Team # Team Number MPA #:

Project Sponsor: Name of Sponsor

Project Name: Title of Project

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	Part Number	Description	Unit $	Subtotal
1	1327K66	Rotary Shaft - 12L14 Carbon Steel, 1/4" Diameter, 12" Long 12L14 Carbon Steel, 1/4" Diameter, 12" Long	$7.72	$7.72
1	1327K93	Rotary Shaft Rotary Shaft - 12L14 Carbon Steel, 1/8" Diameter, 3" Long 12L14 Carbon Steel, 1/8" Diameter, 3" Long	$2.93	$2.93
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
		No Tax – URI is Tax Exempt – RI Tax Exempt 189		$0.00
		Shipping Cost		$0.00
			Total	$10.65

A & J Distributors
Abcam, Inc.
Additions Exhibit System

Figure 59: Order Form for Rotary Shafts

MCISE Capstone Order Request Form

4103 | 03/01/17

Amazon
PO Box 81226
Seattle, WA, 98108

Fax Number:
XXX-XXX-XXXX

401-874-2524

Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
92 Upper College Road, 203 Wales Hall, Kingston RI 02881

mceoffice@ec

Team # 12 Michael Dana, Reid Elleman, Nick Harris

MPA #:

Project Sponsor: Professor B. Nassersharif

Project Name: HeroX Airflow Design Competition

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	Part Number	Description	Unit $	Subtotal
1	100-25x10-32	Midwest Ducts Rectangular Ductwork (32") - 25" x 10"	$28.23	$28.23
1	B00002ND67	Lasko 3733 20" Fan Box	$28.52	$28.52
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
		No Tax -- URI is Tax Exempt -- RI Tax Exempt 189		$0.00
1		Shipping Cost	$32.00	$32.00
			Total	$88.75

Note: The fan is order through Pirozhki

Account #

Professor:
(your name or person your preparing the order for)

PI Approval Signature **Date**

Capstone_Order_Form_Team12_No_1

Figure 60: Order Form 3-1-17

MCISE Capstone Order Request Form

4103 | 03/01/17
Amazon
PO Box 81226
Seattle, WA, 98108

Fax Number:
XXX-XXX-XXXX

401-874-2524

Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
92 Upper College Road, 203 Wales Hall, Kingston RI 02881

mceoffice@ec

Team # 12 Michael Dana, Reid Elleman, Nick Harris MPA #:

Project Sponsor: Professor B. Nassersharif

Project Name: HeroX Airflow Design Competition

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	Part Number	Description	Unit $	Subtotal
1	5V Laser	Diode Module Head WL Red 650nm 6mm 5V 5mW Pack of 10pcs	$2.88	$2.88
1	A382X5	AIRSUNNY three Legs 5 pairs Infrared Diode LED IR Emission an	$5.98	$5.98
1	PCELPN-53979535	Gikfun USB Nano V3.0 ATmega328 CH340G 5V 16M Micro-contro	$11.98	$11.98
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
		No Tax -- URI is Tax Exempt -- RI Tax Exempt 189		$0.00
1		Shipping Cost	$11.24	$11.24
			Total	$32.08

Account #

Professor:
(your name or person your preparing the order for)

PI Approval Signature **Date**

Capstone_Order_Form_Team12_No_2

Figure 61: Order Form No 1 3-1-17

MCISE Capstone Order Request Form

4103 | 03/01/17
McMaster Carr
200 New Canton Way
Robbinsville, NJ 08691

Fax Number:
XXX-XXX-XXXX

401-874-2524

Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
92 Upper College Road, 203 Wales Hall, Kingston RI 02881

mceoffice@e(

Team # 12 Michael Dana, Reid Elleman, Nick Harris **MPA #:**

Project Sponsor: Name of Sponsor Professor B. Nassersharif

Project Name: Title of Project HeroX Airflow Design Competition

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	**Part Number**	**Description**	**Unit $**	**Subtotal**
2	57655K19	ear - 14-1/2 Deg Pressure Angle Press-Fit Mnt, 48 Pitch, 36 Teeth	$7.93	$15.86
2	57655K61	48 Pitch Rack for Plastic Gear - 14-1/2 Deg Pressure Angle	$5.82	$11.64
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
		No Tax -- URI is Tax Exempt -- RI Tax Exempt 189		$0.00
		Shipping Cost		$0.00
			Total	$27.50

Account #

Professor:
(your name or person your preparing the order for)

PI Approval Signature **Date**

Capstone_Order_Form_Team12_No_3

Figure 62: Order Form No 2 3-1-17

MCISE Capstone Order Request Form

4103 | 03/01/17

Grainger
PO Box 81226
Seattle, WA, 98108

Fax Number:
XXX-XXX-XXXX

401-874-2524

Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
92 Upper College Road, 203 Wales Hall, Kingston RI 02881

mceoffice@ec

Team # 12 Michael Dana, Reid Elleman, Nick Harris

MPA #:

Project Sponsor: Professor B. Nassersharif

Project Name: HeroX Airflow Design Competition

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	Part Number	Description		Unit $	Subtotal
1	5JLK8		DAYTON	$4.39	$4.39
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
		No Tax -- URI is Tax Exempt -- RI Tax Exempt 189			$0.00
1		Shipping Cost		$10.48	$10.48
				Total	$14.87

Account #

Professor:
(your name or person your preparing the order for)

PI Approval Signature **Date**

Capstone_Order_Form_Team12_No_4

Figure 63: Order Form No 3 3-1-17

MCISE Capstone Order Request Form

4103
McMaster Carr
200 New Canton Way
Robbinsville, NJ 08691

Fax Number:
XXX-XXX-XXXX

04/12/17

401-874-2524

Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
92 Upper College Road, 203 Wales Hall, Kingston RI 02881

mceoffice@e(

Team # 12 Michael Dana, Reid Elleman, Nick Harris **MPA #:**

Project Sponsor: Name of Sponsor Professor B. Nassersharif

Project Name: Title of Project HeroX Airflow Design Competition

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	Part Number	Description	Unit $	Subtotal
2	60355K502	Ball Bearing	$6.65	$13.30
1	1327K104	12L14 Carbon Steel, 3/16" Diameter, 4" Long	$3.70	$3.70
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
		No Tax – URI is Tax Exempt -- RI Tax Exempt 189		$0.00
		Shipping Cost		$0.00
			Total	$17.00

Account #

Professor:
(your name or person your preparing the order for)

PI Approval Signature **Date**

Capstone_Order_Form_Team12_No_5

Figure 64: Order Form 4-12-17

MCISE Capstone Order Request Form

4103 **04/07/17**
McMaster Carr
200 New Canton Way
Robbinsville, NJ 08691

Fax Number:
XXX-XXX-XXXX

401-874-2524

Capstone Design
URI Department of Mechanical, Industrial & Systems Engineering
92 Upper College Road, 203 Wales Hall, Kingston RI 02881

mceoffice@e(

Team # 12 Michael Dana, Reid Elleman, Nick Harris **MPA #:**

Project Sponsor: Name of Sponsor Professor B. Nassersharif

Project Name: Title of Project HeroX Airflow Design Competition

Forward this form electronically to: Professor Nassersharif
Email: bn@uri.edu

Quantity	Part Number	Description	Unit $	Subtotal
4	57655K52	·ar - 14-1/2 Deg Pressure Angle Press-Fit Mnt, 24 Pitch, 18 Teeth	$6.18	$24.72
4	57655K63	24 Pitch Rack for Plastic Gear - 14-1/2 Deg Pressure Angle	$7.64	$30.56
1	60355K501	Trade No. R2, for 1/8" Shaft Diameter, 3/8" OD	$5.94	$5.94
1	1327K66	Rotary Shaft - 12L14 Carbon Steel, 1/4" Diameter, 12" Long	$7.72	$7.72
1	1327K93	Rotary Shaft - 12L14 Carbon Steel, 1/8" Diameter, 3" Long	$2.93	$2.93
1	94510A260	M8 x 1.25 mm Thread Size, 1.25 mm Thick Flange	$4.62	$4.62
1	17545K64	4" Diameter, 10 Blade	$3.44	$3.44
				$0.00
				$0.00
				$0.00
		No Tax – URI is Tax Exempt -- RI Tax Exempt 189		$0.00
		Shipping Cost		$0.00
			Total	$79.93

Account #

Professor:
(your name or person your preparing the order for)

PI Approval Signature **Date**

Shaft and Bearing order form

Figure 65: Order Form 4-7-17

22.4 Appendix D: Merv Rating Chart

MERV RATING CHART

Standard 52.5 Minimum Efficiency Reporting Value	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
20	n/a	n/a	< 0.30 pm particle size	Cleanrooms	≥99.999% eff. On .10-.20 pm Particles
19	n/a	n/a	Virus (unattached)	Radioactive Materials	Particles
18	n/a	n/a	Carbon Dust	Pharmaceutical Man.	Particulates
17	n/a	n/a	All Combustion smoke	Carcinogenetic Materials	≥99.97% eff. On .30 pm Particles
16	n/a	n/a	.30-1.0 pm Particle Size	General Surgery	**Bag Filter**- Nonsupported
15	>95%	n/a	All Bacteria	Hospital Inpatient Care	microfine fiberglass or
14	90-95%	>98%	Most Tobacco Smoke	Smoking Lunges	synthetic media, 12-36 in. deep, 6-12 pockets
					Box Filter- Rigid Style Cartridge Filters 6 to 12" deep m ay use
13	89-90%	>98%	Proplet Nuceli (Sneeze)	Superior Commercial Buildings	lofted or paper media.
12	70-75%	>95%	1.0-3.0 pm Particle Size	Superior Residential	**Bag Filter**- Nonsupported
			Legionella		microfine fiberglass or synthetic media, 12-36 in. deep, 6-12 pockets
11	60-65%	>95%	Humidifier Dust	Better Commercial Buildings	
			Lead Dust		**Box Filter**- Rigid Style Cartridge Filters 6 to 12" deep m ay use lofted or paper media.
10	50-55%	>95%	Milled Flour		
			Auto Emissions	Hospital Laboratories	
9	40-45%	>90%	Welding Fumes		
8	30-35%	>90%	3.0-10.0 pm Particle Size	Commercial Buildings	**Pleated Filters**- Disposable, extended surface area, thick with cotton-polyester blend media, cardboard frame
			Mold Spores		
7	25-30%	>90%	Hair Spray	Better Residential	**Cartridge Filters**- Graded density viscous coated cube or pocket filters, synthetic media
			Fabric Protector		
6	<20%	85-90%	Dusting Aids	Industrial Workplace	**Throwaway**- Disposable synthetic panel filter.
			Cement Dust		
5	<20%	80-85%	Pudding Mix	Paint Booth Inlet	
4	<20%	75-80%	>10.0 pm Particle Size	Minimal Filtration	**Throwaway**- Disposable fiberglass or synthetic panel filter.
			Pollen		
3	<20%	70-75%	Dust Mites	Residential	**Washable**- Aluminum Mesh
			Sanding Dust		
2	<20%	65-70%	Spray Paint Dust		
			Textile Fibers	Window A/C Units	**Electrostatic**- Self charging woven panel filter.
1	<20%	<65%	Carpet Fibers		

Figure 66: Merv Rating Chart

22.5 Appendix E: CAD Drawings

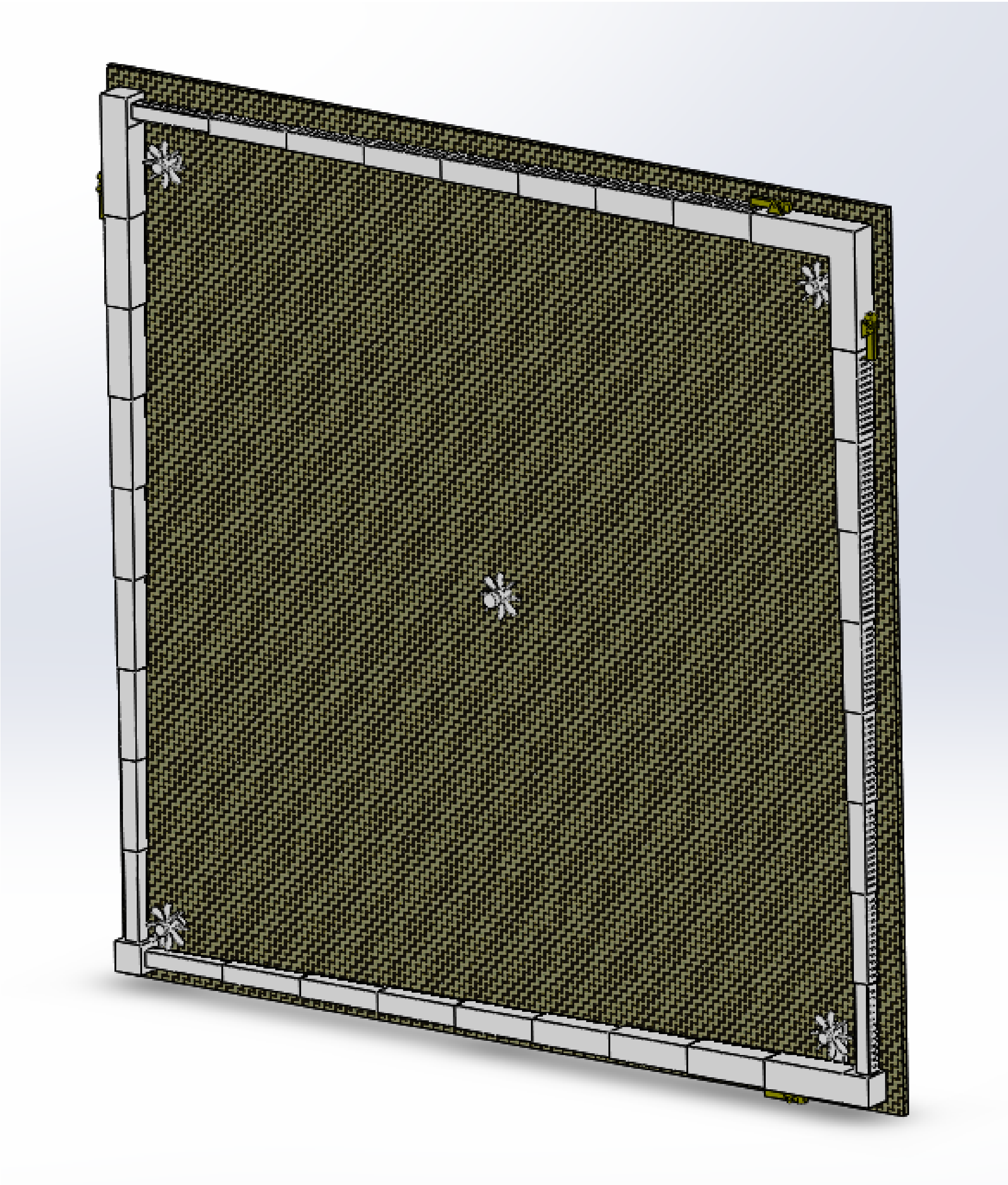


Figure 67: Fan Filter Matrix Assembly

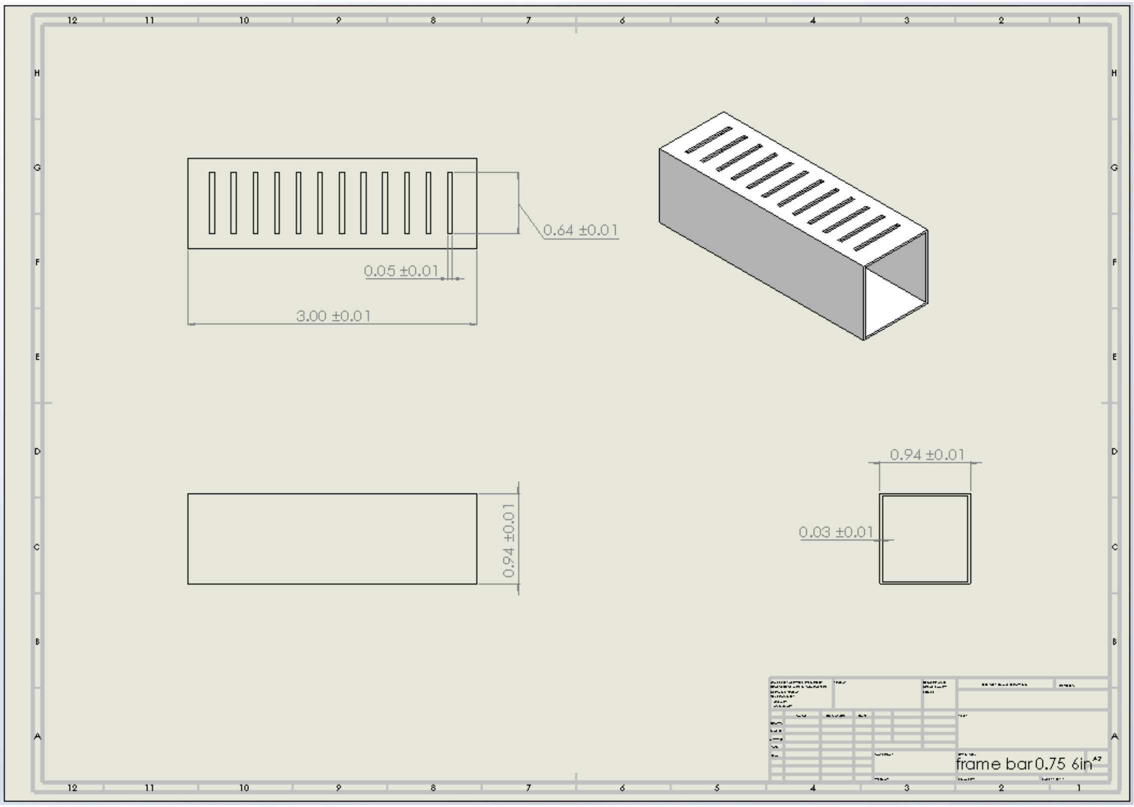


Figure 68: Frame part 1

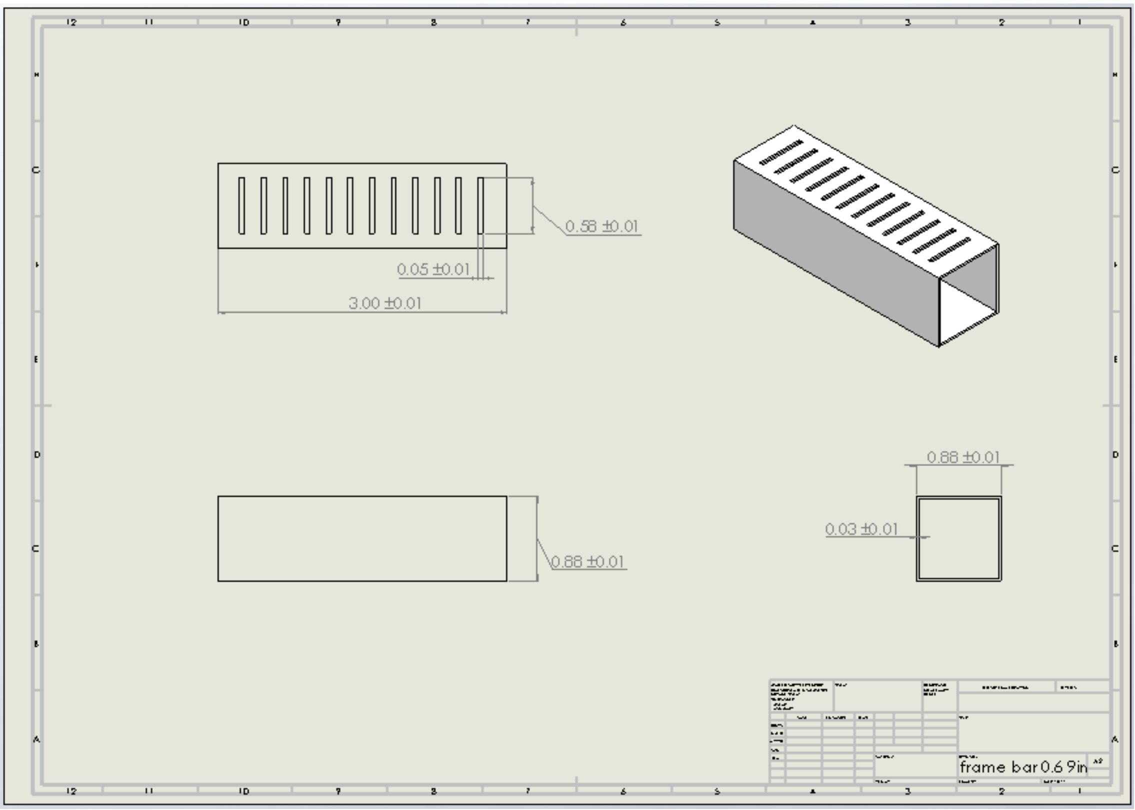


Figure 69: Frame part 2

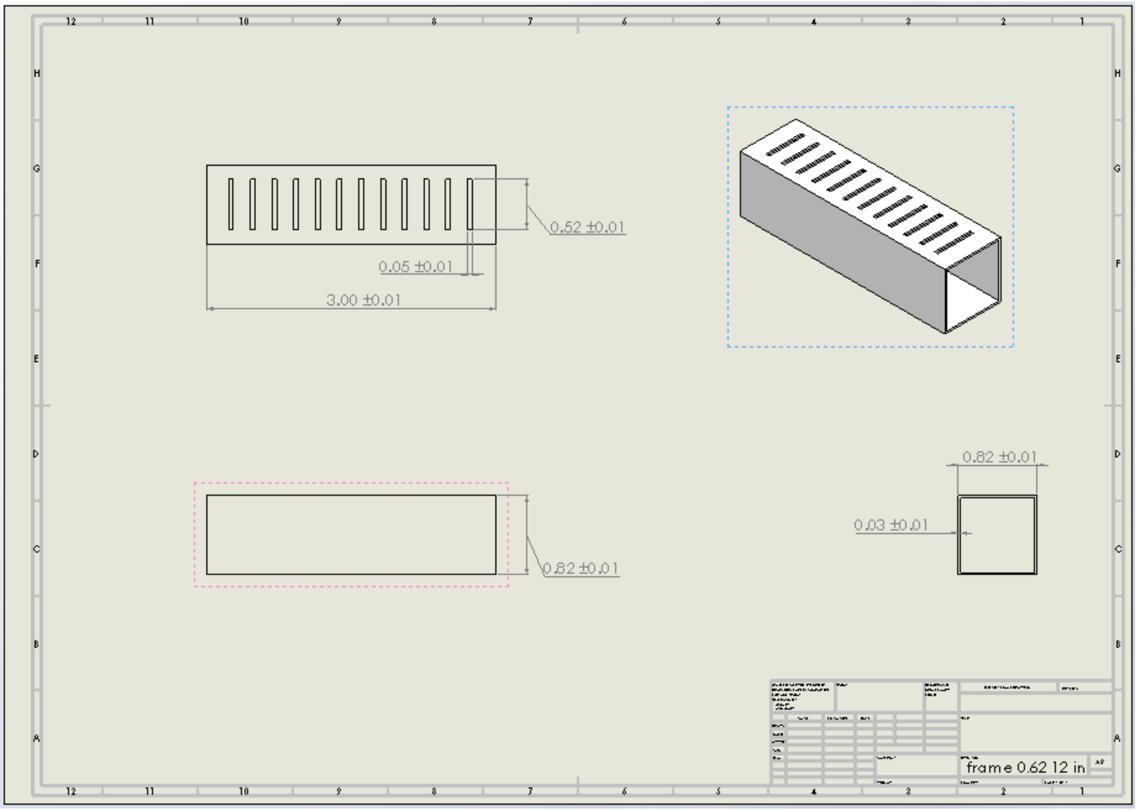


Figure 70: Frame part 3

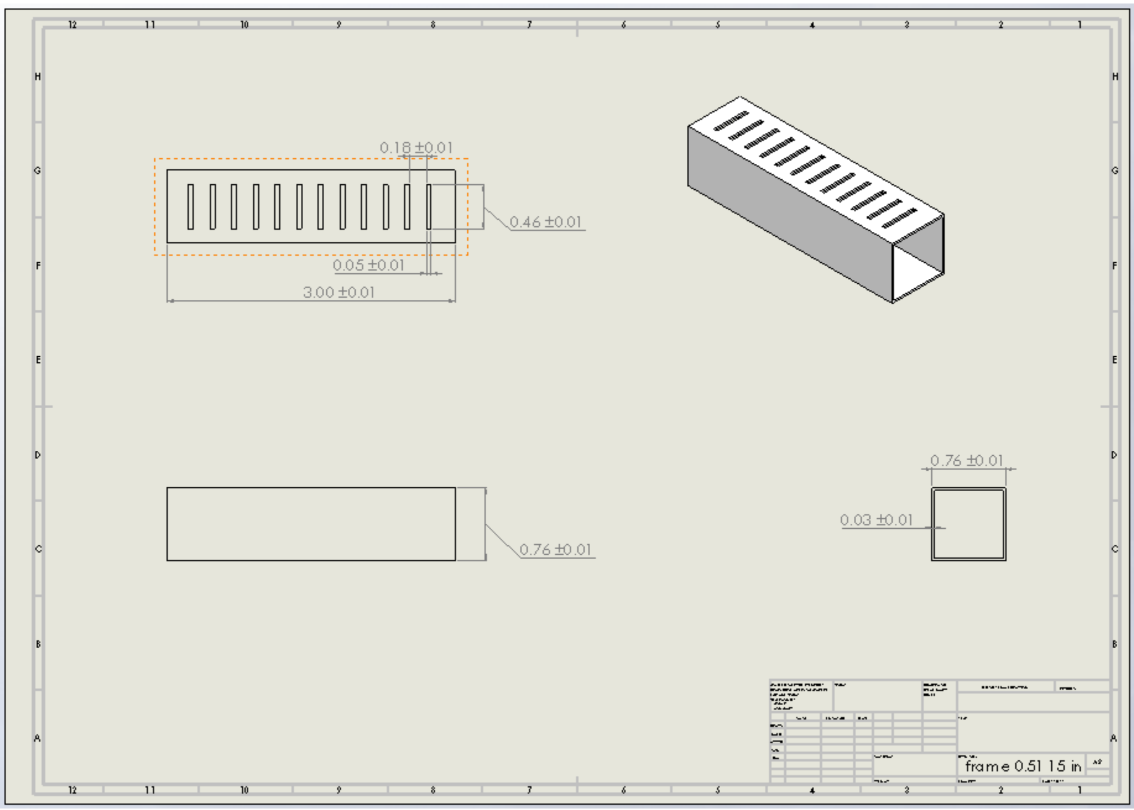


Figure 71: Frame part 4

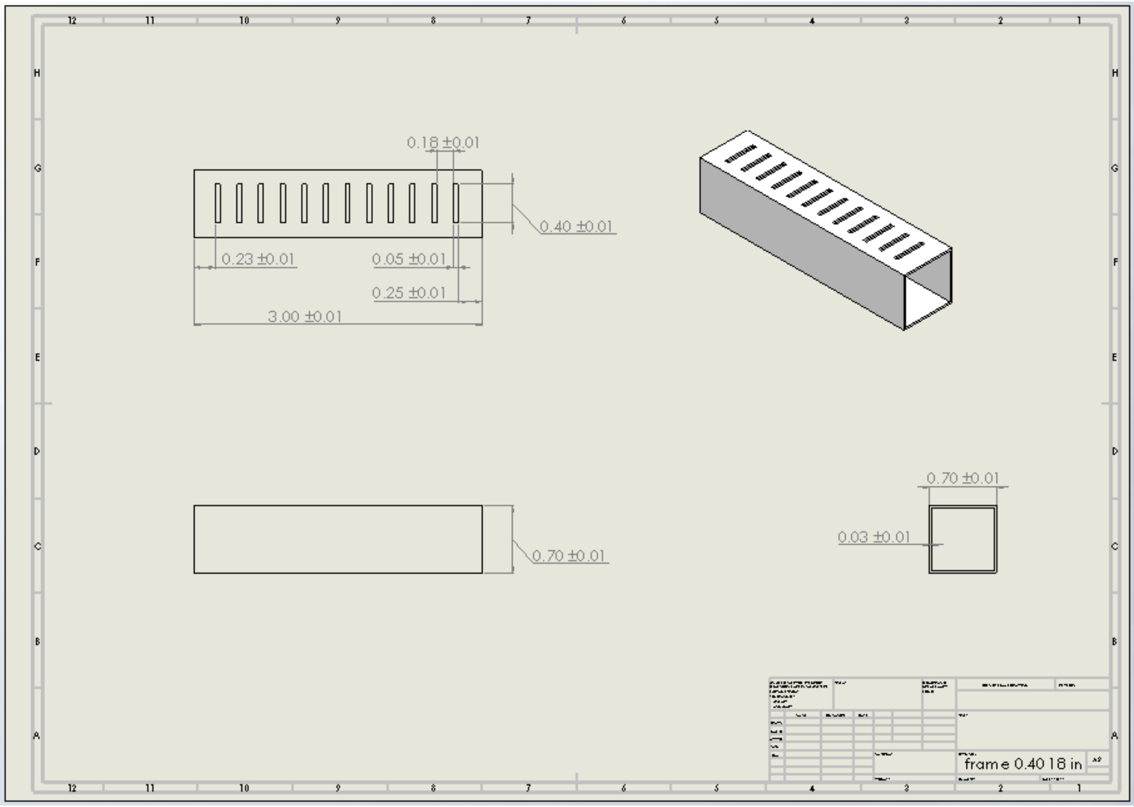


Figure 72: Frame part 5

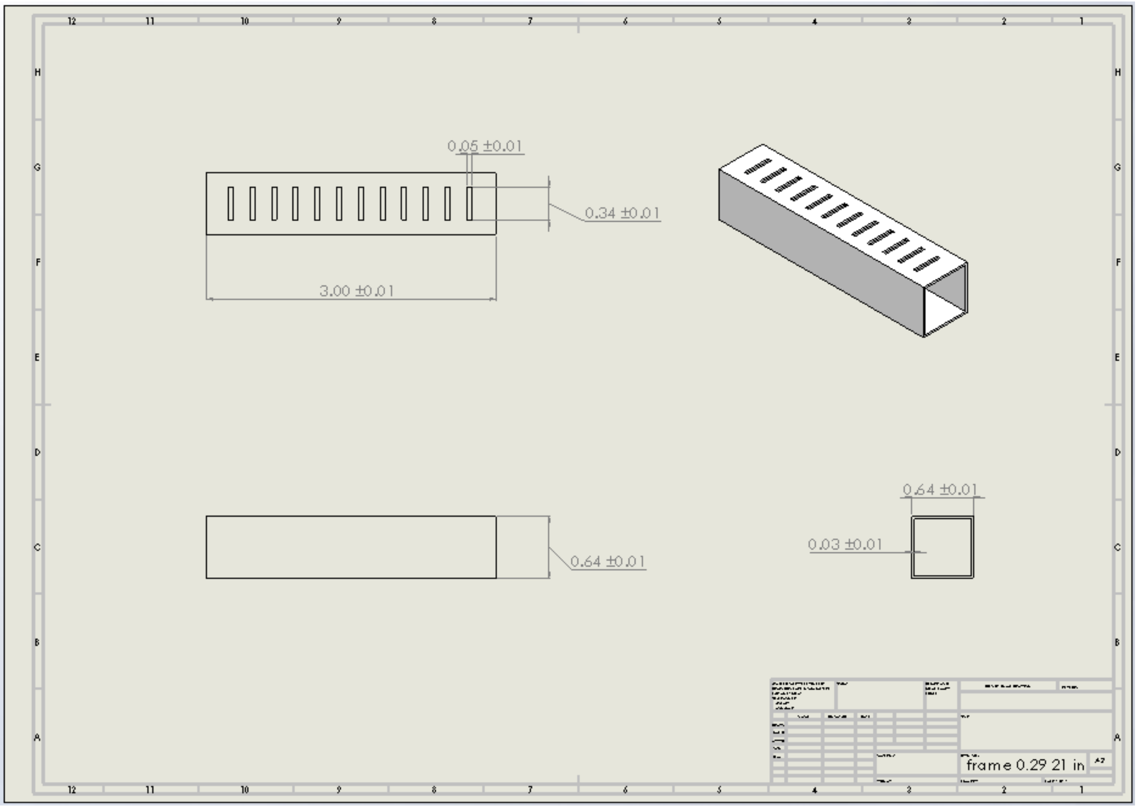


Figure 73: Frame part 6

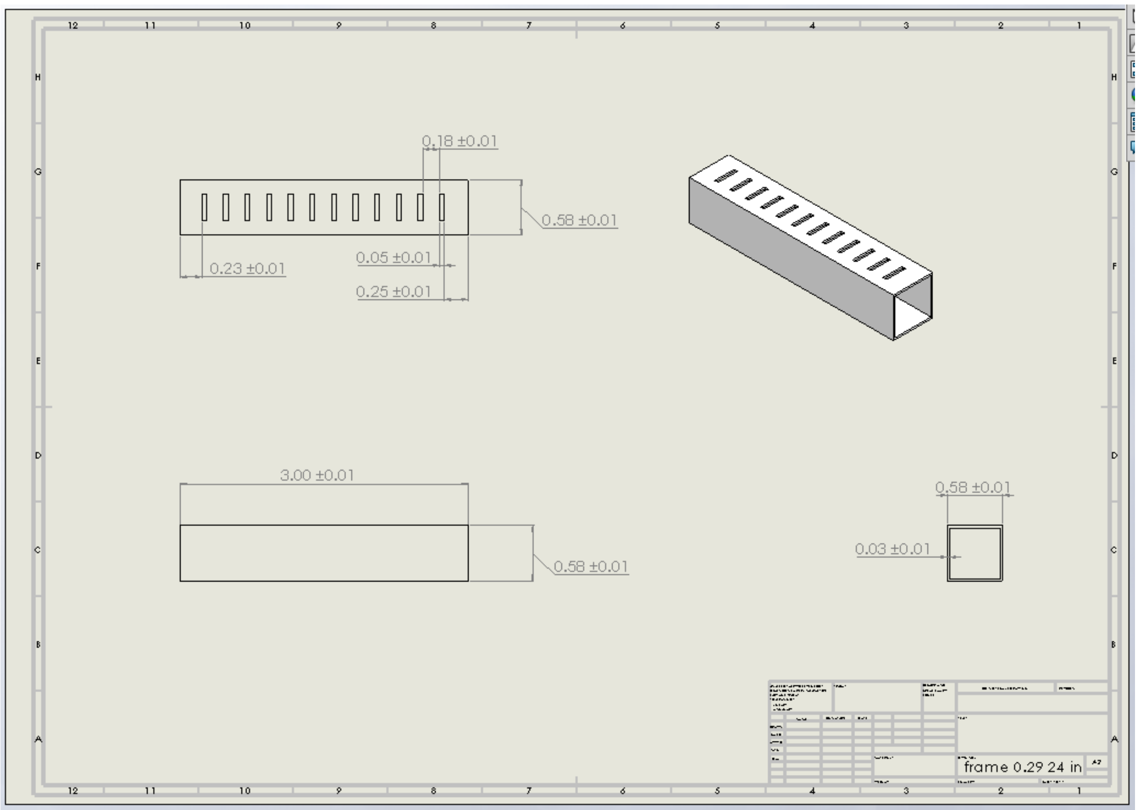


Figure 74: Frame part 7

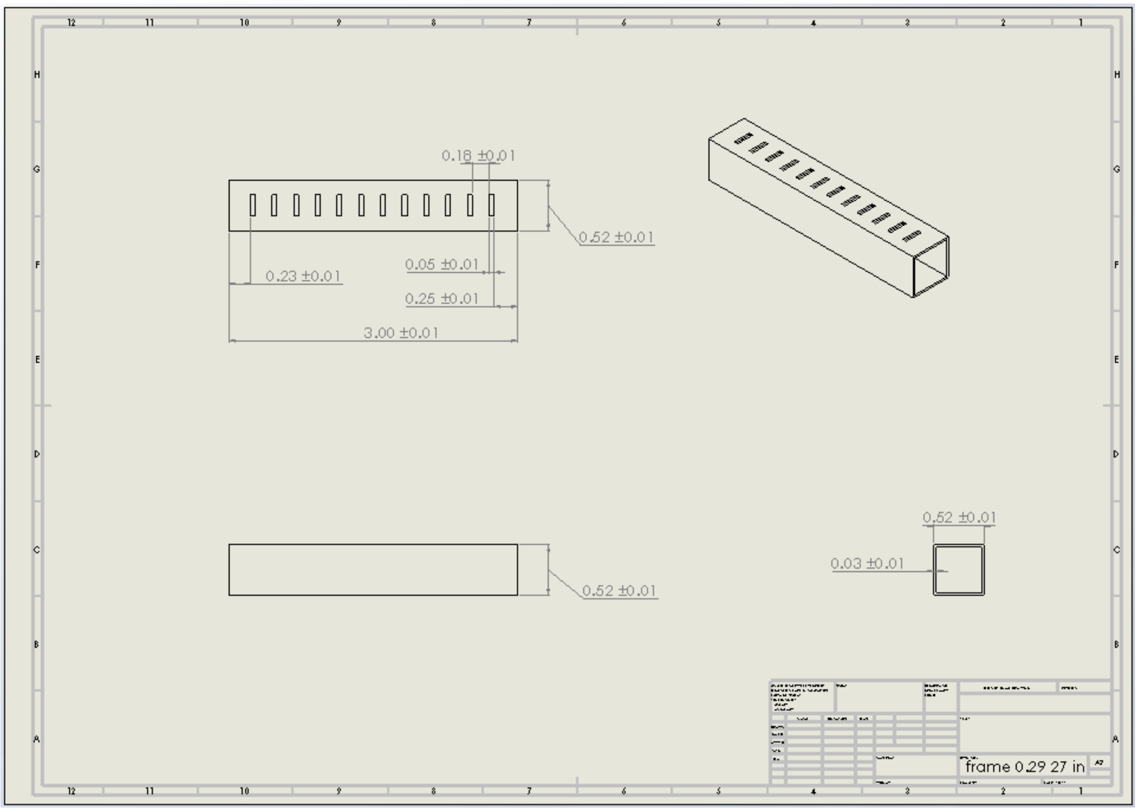


Figure 75: Frame part 8

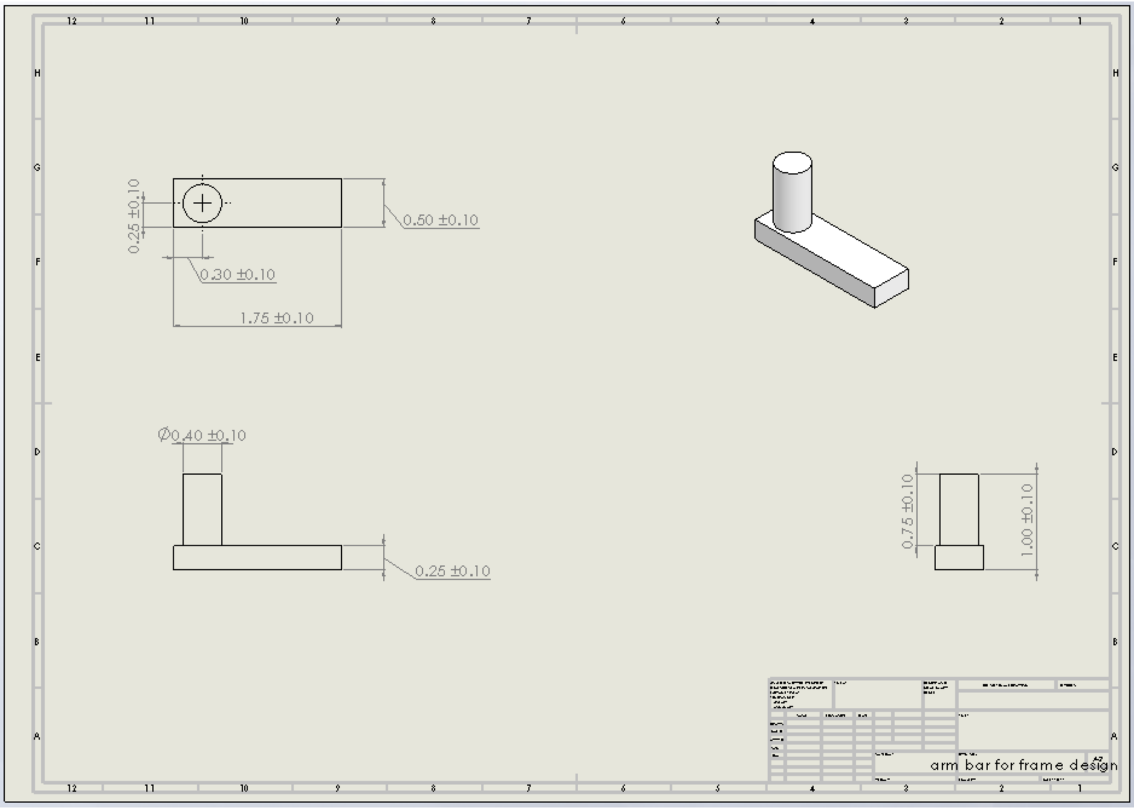


Figure 76: Arm Bar for Connection between Frame and Impeller

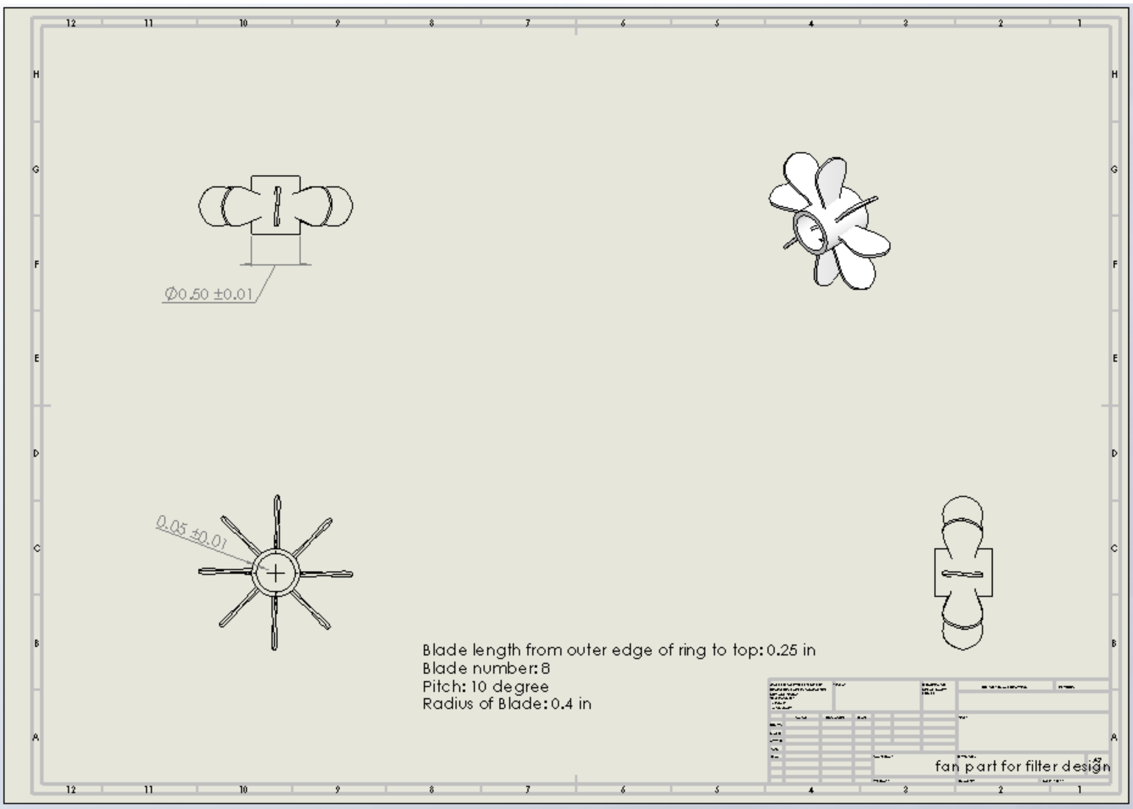


Figure 77: Fan Filter Matrix's Impeller

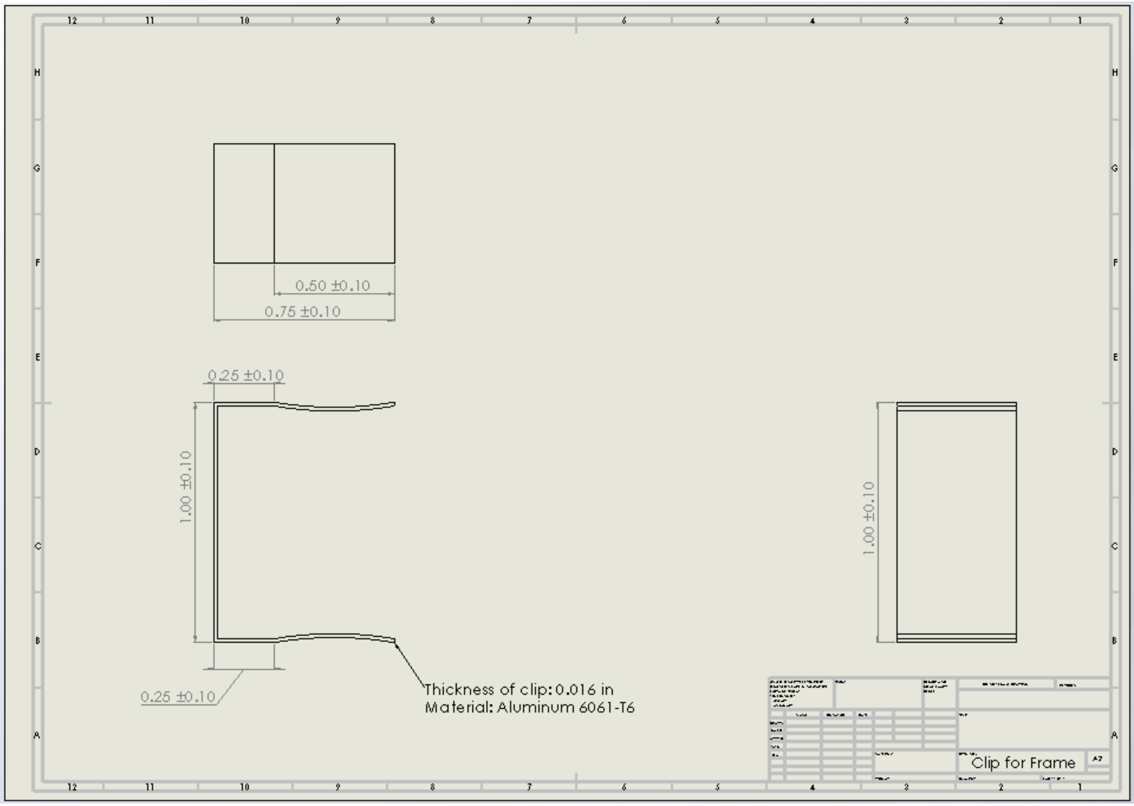


Figure 78: Clip to attach Merv 8 mesh to frame

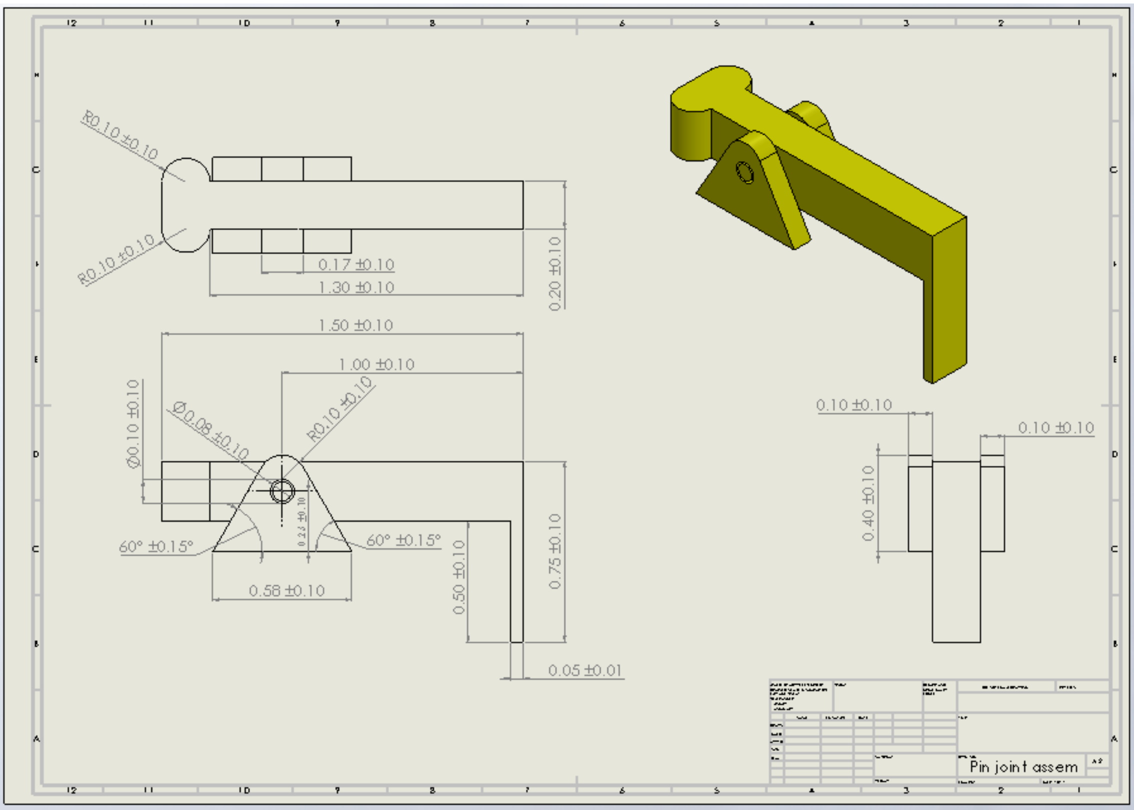


Figure 79: Pin joint attached to frame

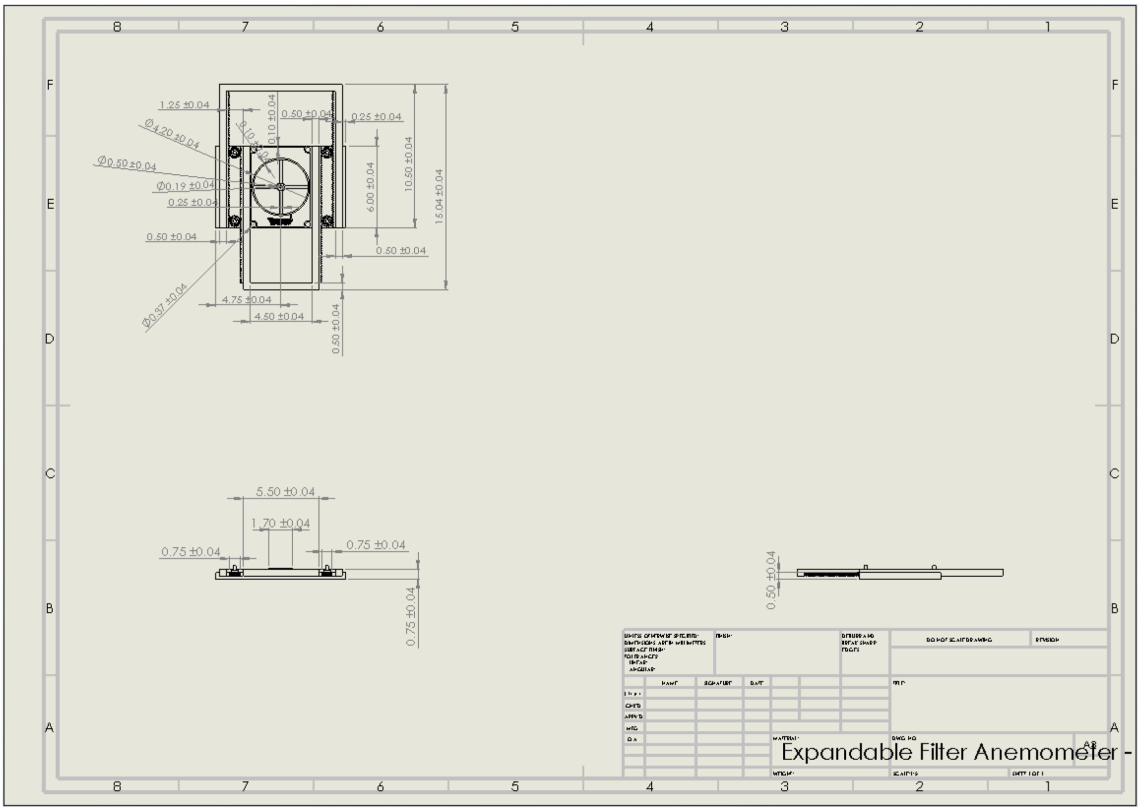


Figure 80: Bottom Plate Drawing

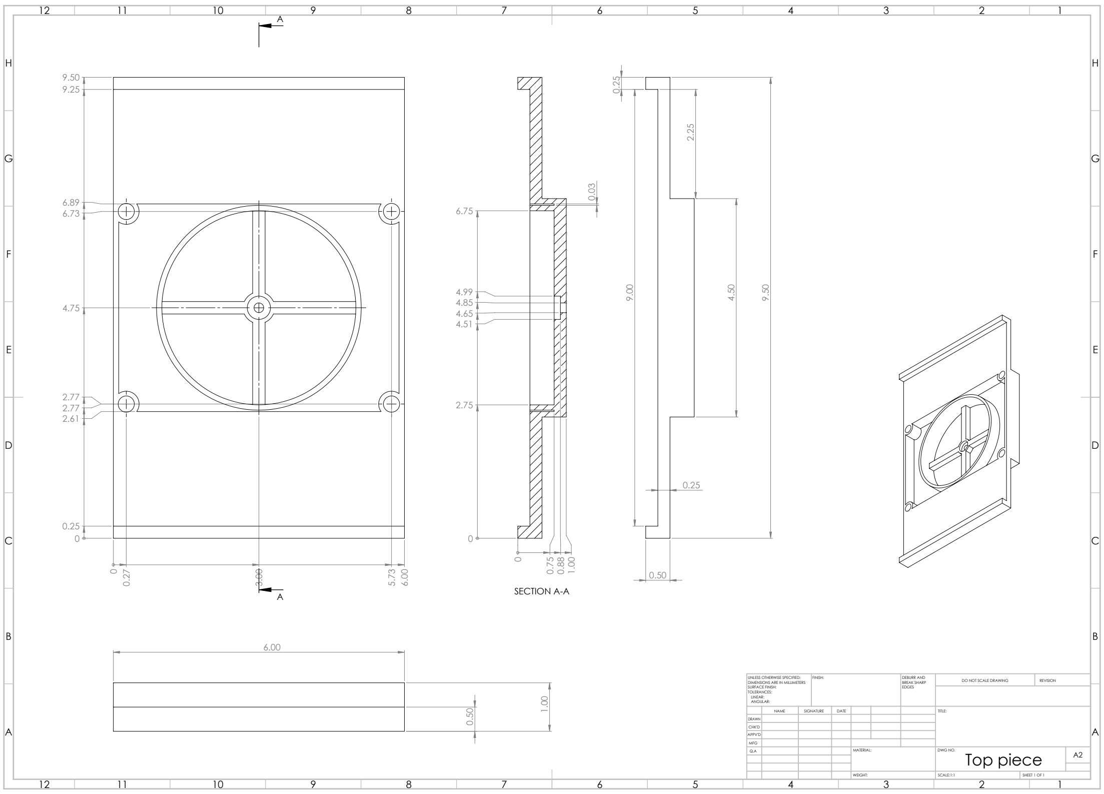


Figure 81: Top Plate Drawing

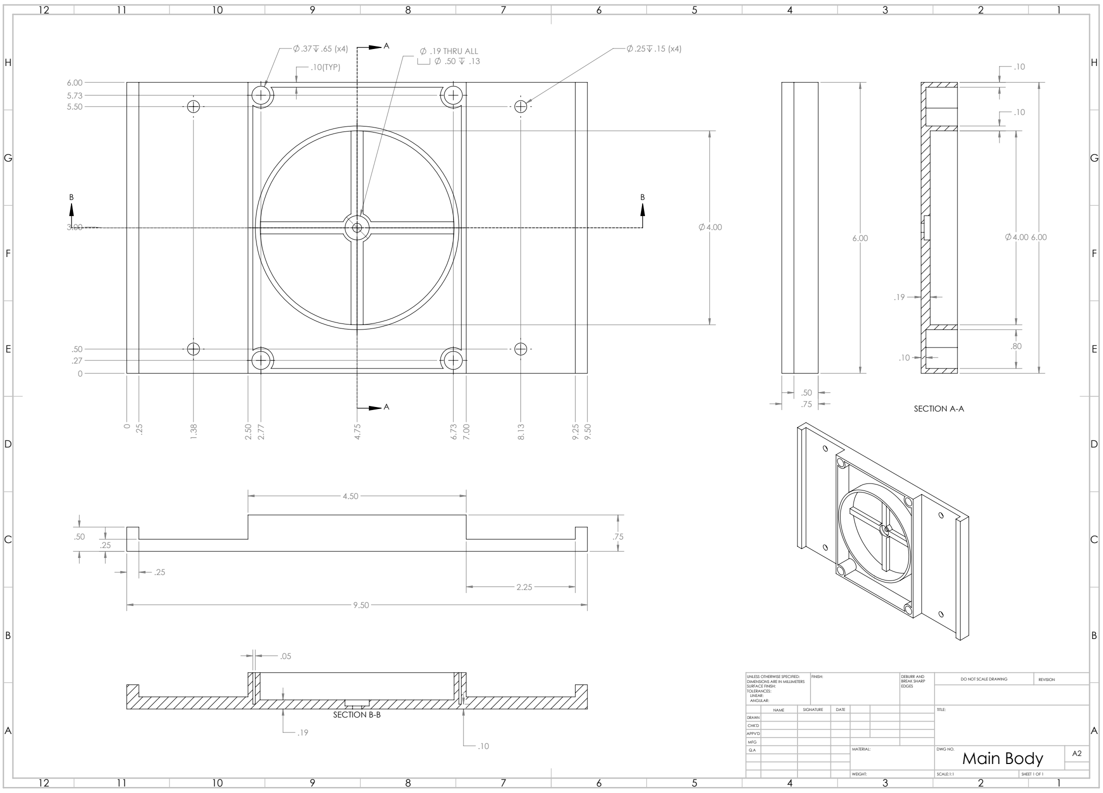


Figure 82: Main Body Drawing

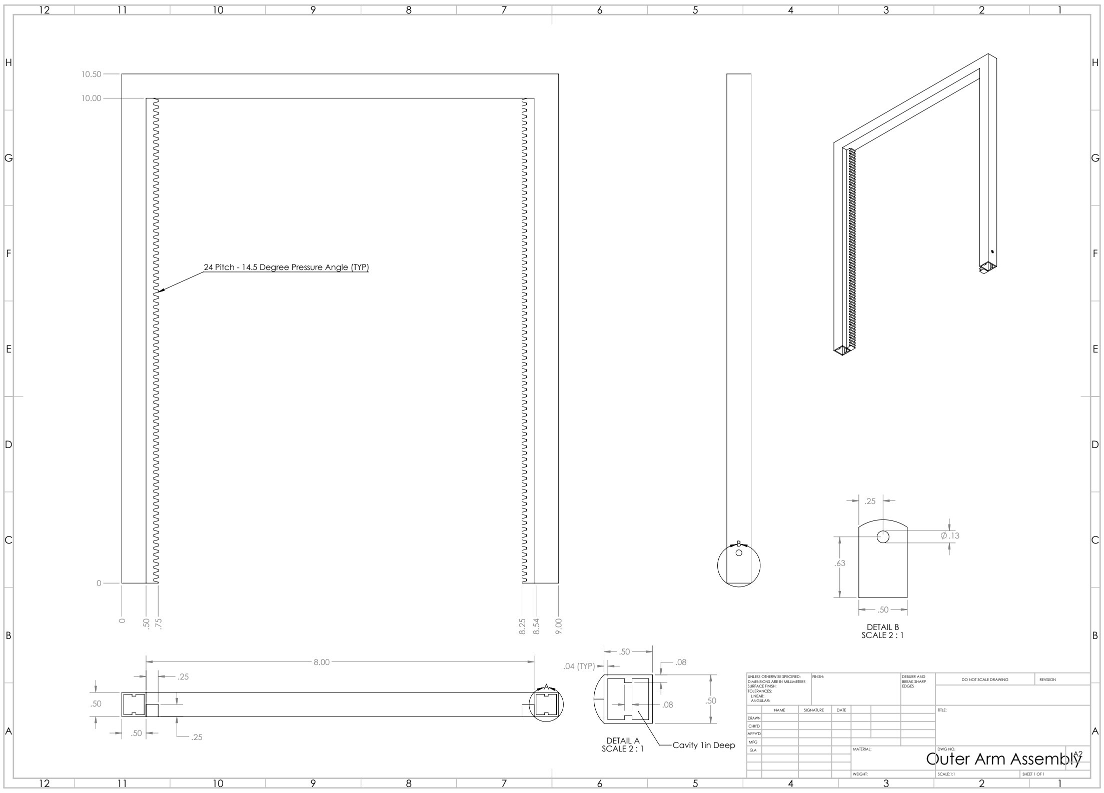


Figure 83: Outer Arm Drawing

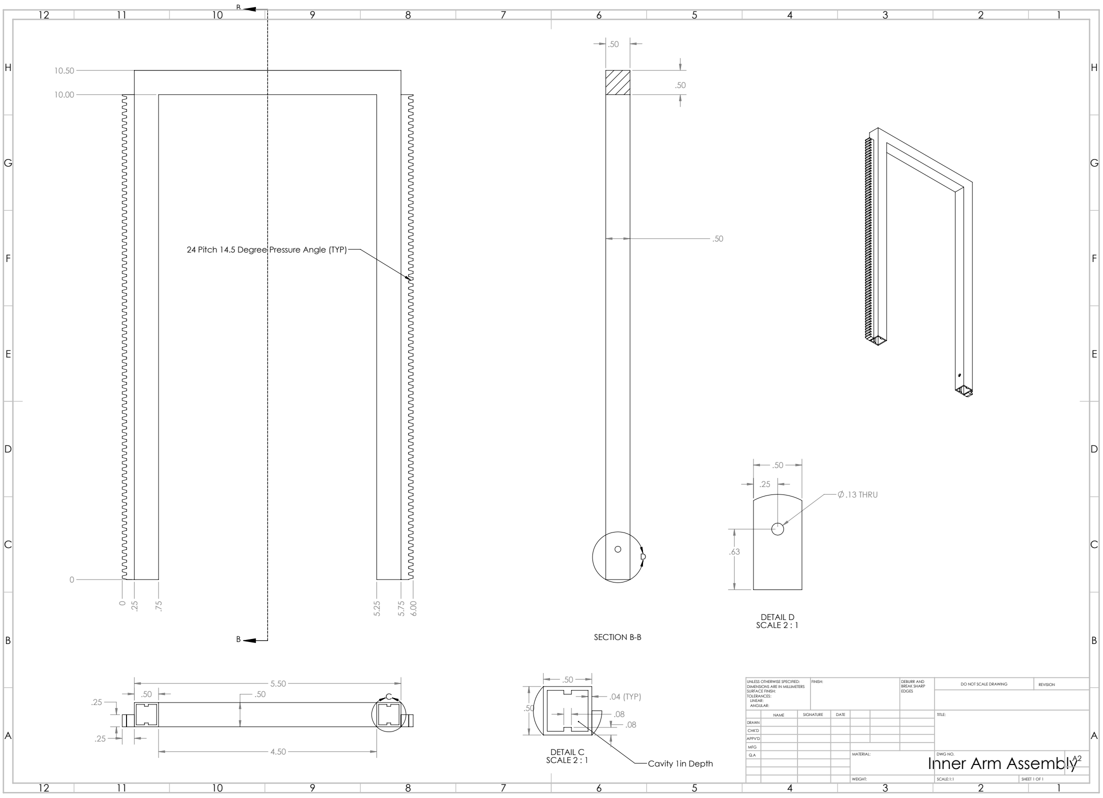


Figure 84: Inner Arm Drawing

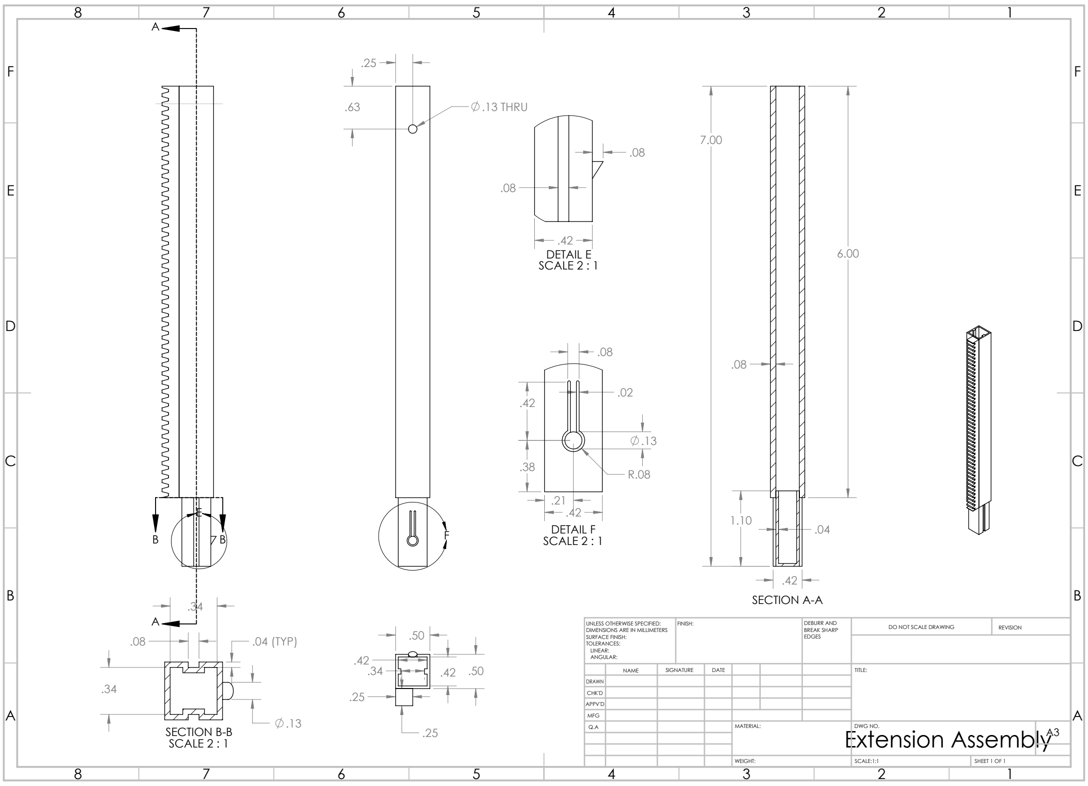


Figure 85: Extension Drawing

22.6 Appendix F: Testing Data

Test Results		
Light Sensor	Success	< 5mA from Battery
Frequency Sensor	Success	Accurate 0-10 kHz
Expanding Arms	Success	8-14 in
Air Speed	Success	+/- 1% of commercial anemometer
Battery Life	Success	Over 2 hr sustained use
Set up time	Success	~5 mins
Disassembly time	Success	~5 mins
Reading from RPM to FPM	Success	Reads FPM
Robustness	Success	Passed drop test from 2 ft
Maximum Air speed	Success	0-2000 CFM (1440FPM)

Table 10: Test Matrix