PENN STATE UNIVERSITY

Cordless Handheld Vacuum Project

Team 8

Section 007

5/5/2015

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1.0 Team Contract- Team Magic 8 Ball

1. **Team Members**
    a. Michael Chahin- mic5468@psu.edu
    b. Cameron Gibbel- cmg5664@psu.edu
    c. Alex Stefanelli- ajs6197@psu.edu

2. **Mission Statement and Objective**
Our team's goal is to redesign a hand drill into a vacuum cleaner. Throughout the semester, we aim to improve our skill and knowledge of the design development process. We strive to do as well as we can academically, ideally earning an "A" grade.

3. **Meetings**
    a. Location
        i. We will meet in Eastview Terrace and its surrounding area (i.e. Redifer commons)
    b. Time
        i. Tuesdays and Sundays at 7:00 pm.
        ii. Alternative times may be agreed on at any point
    c. Attendance
        i. Each member will arrive on time to the pre-determined meeting
        ii. If a member plans to be late, they must notify the rest of the team
    d. Procedure
        i. An agenda, prepared by Cameron, will be constructed prior to the meeting, which will comprise of the discussion topics
        ii. During the meeting, all members will remain civil and on task
        iii. When necessary, group work will be done
        iv. At the conclusion of each meeting, when applicable, work will be assigned
        v. Meeting minutes will be recorded by Alex

4. **Communication**
    a. Most communication will be done using the "GroupMe" texting application
        i. If a member can't be contacted through the "GroupMe," calling and email is another acceptable form of communication
    b. All electronic information will be stored online in a Dropbox

5. **Performance Expectations**
    a. All group members must agree on the distribution of the work
    b. Work will be completed on time
    c. All work must be reviewed by all members of the team

6. **Decision Making**
    a. A majority vote will be used in making decisions
        i. The minority will be given time to express their opinion

7. Consequences and Accountability

a. Attendance Violation
   i. Attendance violation occurs when the offender has failed to notify the team of their absence/tardiness, arrived late, and/or skipped three meetings.
   ii. This violation will result in a poor evaluation of the offender at the end of the semester (4% points will be deducted)
   iii. Continuation of an attendance violation will result in firing of the offender from the team once all evaluation points are deducted

b. Late Work Violation
   i. Late work violation occurs if the offender has failed to turn in their work three times on the pre-determined due date
   ii. This violation will result in a poor evaluation of the offender at the end of the semester (4% points will be deducted)
   iii. Continuation of late work will result in firing the offender from the team once all evaluation points are deducted

8. Conflict Resolution

a. If a conflict arises, teammates will openly discuss the issue in a meeting and offer possible solutions and a warning
b. If the conflict continues, a final warning will be given (i.e. an ultimatum)
c. If conflict still continues, the team member responsible for the conflict will be reported to the professor
d. If the conflict can't be solved with the professor, the student will be fired from the team

9. Skills, Roles, and work Styles

a. Michael Chahin
   i. Strengths
      1. Hard Worker
      2. Good with engineering software
   ii. Weaknesses
      1. Technical writing
      2. Picky with details

b. Cameron Gibbel
   i. Strengths
      1. Writing skills
      2. Experience with tools
   ii. Weaknesses
      1. Easily distracted
      2. Not detail-oriented

c. Alex Stefanelli
   i. Strengths
      1. Good with hand tools
      2. Dependable
   ii. Weaknesses

1. Inexperienced with fabrication
2. Tends to over-think

X

Michael Chahin

X

Cameron Gibbel

X

Alex Stefanelli

2.0 Letter of Intent

February 3, 2015

Dr. Hacker and Dr. Hoskins

Instructor

Dear Dr. Hacker and Dr. Hoskins,

This letter confirms our intent to participate in the assigned vacuum design competition.

Objective

The objective is to construct a handheld vacuum cleaner powered by the motor from a cordless drill.

Design Requirements

The vacuum will be powered using the DC motor extracted from an 18V cordless drill. The corresponding NiCd battery pack, battery pack connector, and battery charger must also be used. These components may not be altered in any way, however any other parts of the drill may be used at the team's discretion. The vacuum must be handheld and cordless. No existing vacuum parts may be used. At least one part must be fabricated using rapid prototyping, water jet, CNC, or casting methods. There will be a $30 budget for the project's materials and components that are needed (materials and components will be purchased through McMaster-Carr and Jameco).

Performance

The suction flow rate under free operating conditions, stagnation vacuum pressure when the intake is blocked, and the expected battery life under free operating conditions will be calculated theoretically and then tested for verification. The performance of the vacuum will be measured by its ability to pick up uncooked rice in a 10-second period.

Design Process

We will begin the design process by dissecting and testing the cordless drill. We will then begin designing the vacuum around the motor, using sketches and/or CAD software, after external research has been performed. Our development process will consider cost, manufacturability, assembly, availability of outsourced parts, functionality, reliability, and ease of use. Once the design is finished, we will manufacture an alpha (functional) prototype. This prototype will be tested, and improved to a beta (demonstration) prototype. The beta prototype will be finalized and used for evaluation. All of the prototypes we design will be created in the Learning Factory located on Penn State's campus. We will submit weekly progress reports and memos to document our design process. The workload will be assigned evenly among the three team members, and completed in correspondence with the semester schedule. A preliminary schedule of our project can be found in figure 1 of the Appendix.

Sincerely,

Michael Chahin,

Cameron Gibbel, and

Alexander Stefanelli

3.0 Customer Needs

In order to design a product to best satisfy customers, we needed discover what they find important in a handheld vacuum cleaner. This could be done many ways: interviews, focus groups, observing consumers use the product, or surveys. Our team found that utilizing a survey would be both time efficient and cost effective due to our budget and schedule constraints. We used Google forms to create a survey that could be sent out to potential customers. The survey was advertised on Facebook in order obtain a variety of opinions from different backgrounds.

The survey created consisted of six questions: customers' age, gender, occupation, frequency of handheld vacuum usage (ranging from never to daily), most important component when purchasing a handheld vacuum, and any additional comments/features they wanted to share (see Table 1 in the appendix). The survey received a total of 43 responses in a matter of one week. We determined that the customer most importantly wants a handheld vacuum to function as advertised, meaning it will clean a mess up without problems. Additionally, it was observed that customers also want a handheld vacuum that is easy to use. This is justified from the data collected in the survey. A breakdown of what the customers want can be found in the appendix.

The majority of those surveyed were students in college ranging from ages 18 to 26. There were also adults with full time jobs (lawyer, accountant, and engineer) and some stay home parents with ages ranging from 27 to 55. Overall, the average age of those surveyed (not excluding outliers) was 25.3. The survey showed that most people either used a handheld vacuum at least once a week or never used one. Our team attempted to send the survey out to the general public because they will be purchasing a handheld vacuum. We desired input from all ages and backgrounds in order to obtain broad spectrum of opinions.

By targeting mostly college students and younger aged customers, we intended on marketing a handheld vacuum cleaner for small spaces. An added bonus of focusing on younger consumers would be the establishment of brand loyalty. Delivering a quality product to a young group of customers will encourage them to keep buying products from us for many years to come.

According to the answers obtained from the survey, functionality was the most important aspect when purchasing a handheld vacuum. Some of those who were surveyed also desired a handheld vacuum that was relatively easy to use and cheap. On the other hand, none of those surveyed thought that aesthetic appeal was the most important factor when purchasing a handheld vacuum. All of these things can be considered primary needs. We were able to obtain secondary needs from the last question asked on the survey. Some of these secondary needs included reliability, quietness, suction strength, durability, and added attachments for specific usage (i.e. for cleaning dog hair).

For a more detailed look at who was surveyed and the breakdown of answers, see the Appendix. Table 1 explicitly shows what each person surveyed answered.

4.0 External Search and Benchmarking

Each member of our team performed their own external research on the various types of handheld vacuums offered on the market. There are many ways to perform external research, such as interviewing lead users, observe users, consult experts, search patents, and search published literature. Due to our time constraint and budget, our team was only able to individually search patents related to vacuums and search published literature. We searched through reviews, trade magazines, technical journals, and many websites that had handheld vacuums as products. We found that there are many types of handheld vacuum cleaners. The main types were bagged, bagless, and cyclonic vacuums. Through our external research, each member of the team was able to understand what types of products that our handheld vacuum would be competing against.

Market Segments

There are many different segments of the market that our handheld vacuum could compete in. Most of the segments that we were able to research were related to demographics. For example, there are some handheld vacuums geared towards students in college, small apartments, car usage only, and for cleaning pet hair. Each one of these segments of the market has a handheld vacuum tailored to a certain need. Some of the handheld vacuums will have attachments while other didn't. For instance, a handheld vacuum designed for cleaning pet hair was different than one that was designed for general use and quick cleaning. Consumers are able to purchase handheld vacuums online or in store. After analyzing our customer needs survey, our team came to the conclusion that our handheld vacuum would compete in the market of handheld vacuums for college students and their dorms/apartments. However, it is possible that our product will branch out into other segments of the market.

Competing Products

There are many different handheld vacuums in the market that our handheld vacuum will need to compete with. Each member of our team performed external research on a model likely to compete with ours.

Black & Decker Handheld Vacuum (Source: www.blackanddecker.com)

One model that our handheld vacuum could compete with is a Black & Decker 20V MAX Lithium Pivot Vacuum. When a customer purchases this vacuum, they will get the handheld vacuum itself, a washable filter, pre-filter, on board brush, on board crevice tool, and a charging base/stand. The price of the handheld vacuum was pretty consistent around $79.99. The Black & Decker handheld vacuum had many specifications. The charging time of its 20V lithium ion battery is between 2-4 hours with its battery life being around 15 minutes of constant use. The vacuum's net weight is 3 pounds and its overall length is 18 inches with a cleaning path of 6.8 inches. It has a removable and washable dirt cup with a 15 ounce capacity for dirt.

Some of the key features of this product include a pivoting design, high performance motor, translucent bagless dirt bowl, and an extendable crevice tool. Additionally, the Black & Decker vacuum has a foldable nozzle to clean areas above your head. Overall, the customer reviews for this particular handheld vacuum were quite favorable. Many reviewers claimed that it requires very little storage space, is easy to clean and empty, has strong suction with fade power (suction doesn't weaken overtime, it just cuts out) and was easy to replace the battery. Moreover, customers found that the handheld vacuum was versatile because of its folding nozzle allowing them to clean tall places. The Black & Decker vacuum also had a few negative reviews, like the lack of ability to clean pet hair on carpet and its inability to be a floor cleaner like a stick vacuum. In the end, the Black & Decker vacuum will be a strong competitor against our design.

Dirt Devil Accucharge 15.6V Cordless Bagless Handheld Vacuum (Source: www.DirtDevil.com)

The Dirt Devil Accucharge 15.6V Cordless Bagless Handheld Vacuum is another competitor to our product. This particular vacuum has a retail price of $69.99, and features an advanced and efficient charging system. The charge of the battery is monitored, and the power delivery is reduced to a trickle when full to conserve energy. This qualifies the charging system for Energy Star efficiency specifications. The 15.6V battery takes 6 hours to fully charge, and owner reviews report a usage time of roughly 20 minutes. The vacuum has two attachments that offer versatile cleaning capabilities. There is a retractable brush and a foldable crevice tool to accommodate multiple cleaning conditions. The dirt collection portion of the vacuum is bagless. The collected dirt can be emptied by detaching half of the casing. This exposes the filter, which can be removed for cleaning. Customer reviews compliment the vacuum's suction power and ease of cleaning. The biggest complaint is that the usage time drastically decreases after roughly 18 months. Reviewers experience usage times of 2 minutes or less on a full charge. Many consumers highly recommend this vacuum, and it will be a significant competitor.

Eureka EasyClean Hand Vac 71B (Source: www.eureka.com)

The third handheld vacuum cleaner competitor we researched is the Eureka EasyClean Hand Vac 71B. This model costs $49.99 on the Eureka website. Unlike the other two handheld vacuums researched, this vacuum has a power cord, one 20 ft long which can wrap around the vacuum cleaner for convenient storage. The model has two motors: one powers the revolving brush while another operates suction. The roller has an adjustable guard visor for carpeted floors, stairs, or vertical surfaces. The EasyClean Hand Vac also features a stretchable hose, commonly found on full-size vacuum cleaners, and includes an add-on nozzle for crevices. This model has a bagless filter and instead has a collection cup. The cup is transparent to let users know when it is nearing or at capacity. The customer reviews on Amazon.com for this model were generally very positive. Users praised the power of the vacuum, its durability, and the large capacity of its dirt-collecting cup. However, many customers brought up its weight as a negative; at 4.8 pounds, they felt this model was slightly too heavy for comfort. It still had a 4.4/5 rating, though, from over 5,000 customers.

Patents

Included in our external research is information related to patents that are relevant to handheld vacuums and vacuums in general. The patents listed here are only a few of the hundreds that you can find online by simply going to the US Patent website or searching on Google.

One patent relevant to our vacuum is the “High-efficiency particulate arrestance (HEPA) Filter” (US6428610B1). A HEPA filter is an air filter that must remove (from the air that passes through) 99.97% of particles that have a size of 0.3 µm or larger. The inventors were Peter Tsai and Sanjiv R. Malkan of the University of Tennessee Research Corporation. This particular patent was filed on January 18th, 2000 and was published on August 6th 2002. Another relevant patent is the “Impeller for Vacuum Cleaner with Tapered Blades” (US5573369A). This is an impeller with blades having a leading edge that is tapered downward. Tapering of the top edge and trailing edge provides less noise and better durability without diminishing air performance. The inventor was Wei Du of the Scott Fetzer Company. This patent was filed on November 8th, 1995 and was published in November 12th 1996. A patent relevant to our design could also be the “Vacuum Cleaner Filter Bag Assembly” (US4084948A). The assembly includes an elongated, rigid, hollow tube coupled at one end to the exhaust of the vacuum cleaner. The inventor was Charles H. MacFarland of the Scott Fetzer Company. The patent was filed on December 15th 1976 and was published on April 18th, 1978. A patent named “Handheld Vacuum Cleaner”. This patent (US20100088841A1) was filed on September 21, 2007, published on April 15, 2010, and credited to Henrik Holm, Roger Karlsson, and Oskar Fjellman of AB Electrolux. The invention included in this patent can be applied to many handheld vacuums. The patented idea is the design and interconnection of the several casing elements that can accommodate several different vacuum components. There’s a patent for “Dirt Cup Filter with Pre-Filtration Cap” (US20040261382A1). This patent was filed on June 4, 2004 by Russell L. Baldinger and Danny Lamer. It was published on December 30, 2004. The patent involves a removable dirt filtration assembly with gas impermeable lids. The stream is able to exit through the filtration medium without any dirt escaping with it. “Handheld Pet Hair Vacuum Cleaner” (US20090229070A1) is a patent for a handheld vacuum cleaner designed specifically for cleaning pet hair. It was credited to Douglas J. Madema, Timothy S. Parker, and Tom Minh Nguyen of BISSELL Homecare, Inc. This patent was filed on March 13, 2009 and published on September 17, 2009. The patented product is a handheld vacuum cleaner with a plurality of attachments designed to remove pet hair from tight spaces and crevices. This solves the problems of pet hair not being picked up by a vacuum, and also prevents pet hair from sticking to normal attachments.

5.0 Cordless Drill Testing and Dissection

Note: All figures referenced are within this section, not the appendix like the other sections.

Project Overview

The goal of the project is to construct a handheld vacuum cleaner powered by the motor from a cordless drill. In order to successfully do this, our team must fully understand how our drill works by performing tests and a dissection.

Objective

Our objective is to explore the design, operation, and manufacturing characteristics of our handheld cordless drill. We seek to benchmark the product to obtain information on design improvement and competitive information.

Dissection Analysis

1) When the drill is running, there is a slight vibration that is felt in the handle. The source of the vibration is clearly from the motor running. The vibration is small enough that if you were to be using the drill, it would not be disruptive. Whenever the drill is initially started up, you can see a little spark where the motor is. Additionally, during startup, there is a slight whine coming from the motor. The drill's noise will vary depending on what level the clutch is on.

2) In our case both turning the chuck slowly and with a quick snap did not work. In order to remove the chuck, our team needed to hold onto it while reversing the drill. In theory, a quick snap should work because it will cause the chuck to slip from the shaft connected to the motor. Turning the chuck slowly will only turn the shaft in the motor.

3) To see the internal layout of the drill, see the "Pictures of Dissected Drill" section (Figures 4 and 5).

4) The drill uses three different types of gears, sun, planetary, and ring. The overall gear ratio of the drill is 1:24 (found by multiplying the individual gear ratios). There are two gear reduction stages with gear ratios 1:4 and 1:6. The gear ratio for each reduction stage was found using the equation:

$$Gear\ Ratio = \frac{S}{(R+S)}$$

where S and R are the number of teeth on the sun and ring gear respectively. The gear ratios were verified using the equation:

$$R = 2P + S$$

where P is the number of teeth of the planetary gear. Using the overall gear ratio, we were able to find the max motor torque to be 13.33 oz-in or 0.0694 lb*ft. Furthermore, we found that the max motor RPM is 24648 RPM. The inner gear ring allows slip, letting the internal spring compress and causing the clicking sound. Another gearing alternative that could be used is a one stage gear system. A one stage gear system would definitely cut down on costs, but possibly impede performance. Using two stages of gears allows for better performance internally, but will be more expensive.

5) The bearings used in the drill are ball bearings (16 total). These types of bearings were most likely chosen because to reduce rotational friction and support radial and axial loads. The load experienced can be transmitted through the balls.

6) The type of motor used is a DC motor (the drill comes with an AC/DC wall adapter for charging). This type of motor may have been chosen because most types of DC motors are used to produce rotary motion. Also, a DC motor can have its speed controlled over a wide range, using a variable supply voltage or by changing the strength of current in its field windings. The drill has variable speed and can be reversed using the reverse switch on the drill (reversed electrically).

7) The drill is cooled down using a fan located near the backend of the housing. The heat is generated through vibration and friction from the gears and the vibrations from the motor. Additionally, the heat is also given off by the wires internally. The air flow travels

through the motor (not the gear train) and outside the vent on the housing. The flow is most likely generated naturally with temperature gradients.

8) There are a total of 104 parts in the drill. As a rough estimate, it seems like about 80% of the total number of parts can be purchased from vendors. It is possible that some parts can be eliminated or combined. For example, the LED could be removed because it was not very bright and would not be significant if you are working in the dark. Also, the gears could all be combined into one stage to bring down costs.

9) One particular feature that made the drill hard to assemble was how precise the housing was. When our team was putting the drill back together, our biggest struggle was fitting all the parts (once all connected) back into the housing without clipping a wire. Using screws was a good design of the drill because it made dissecting it and reassembling it quite easy. There are some features that could be changed to improve the ease of assembly. For instance, there could be mini clips inside the housing to hold onto the wires so they do not get so tangled up. Additionally, if the housing had more "wiggle room" the drill components would be able to fit much easier when assembling it. Finally, when our team was disassembling the drill, the ball bearings almost went over the place. We observed many other teams struggle with the same problem. A great feature would be some sort of containment for the ball bearings that does not allow them to go all over the place with the possibility of getting lost.

Pictures of Dissected Drill

This section contains pictures taken during the dissection of the drill. Moreover, all the parts will be labeled and described.

Figure 1: Assembled Drill Prior to Dissection

Figure 2: Detached Battery

Figure 3: Drill with Detached Chuck

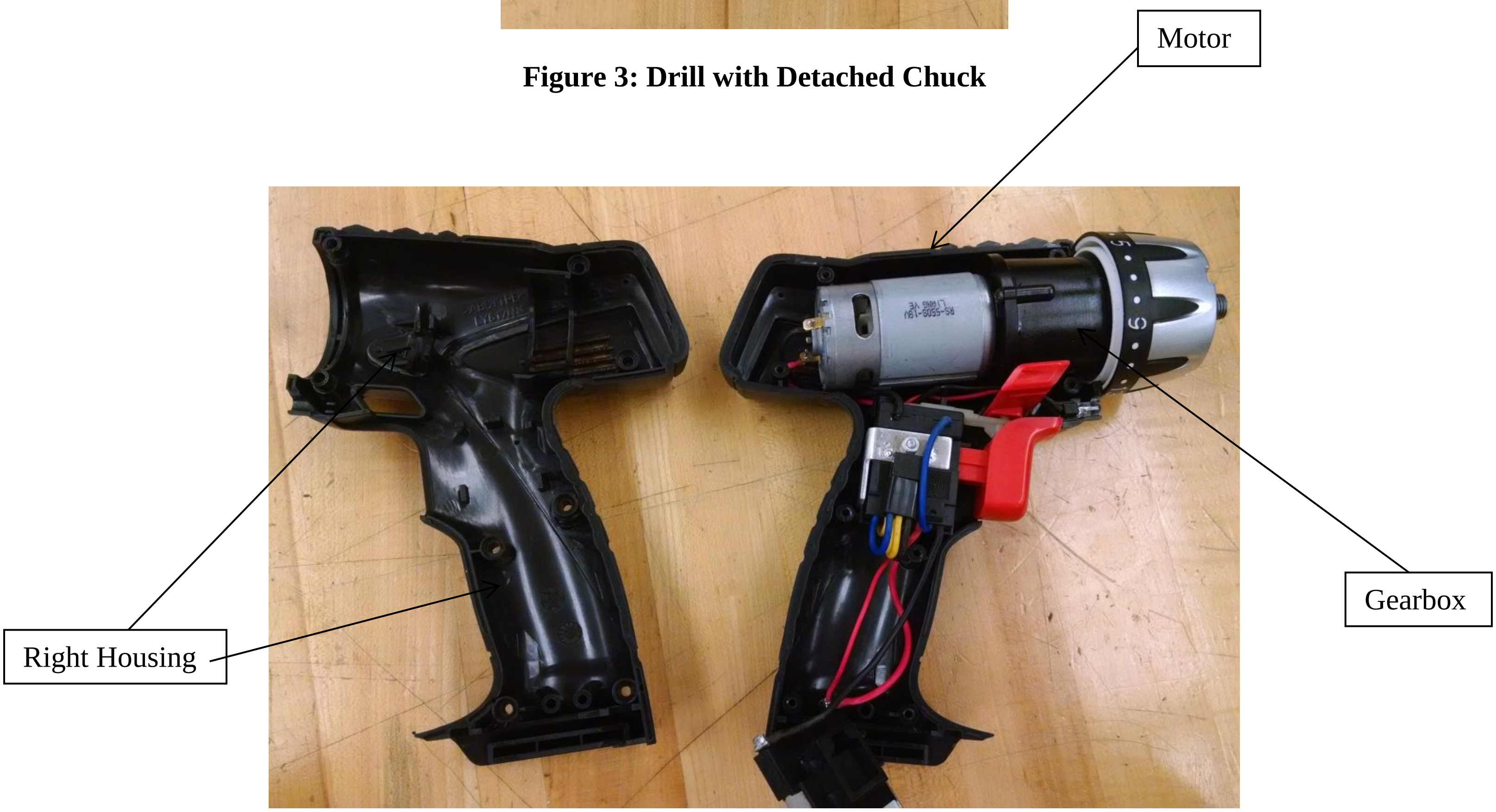

Figure 4: Internal Layout of Drill and Housing

Figure 5: Internal Layout of Drill (Left Housing)

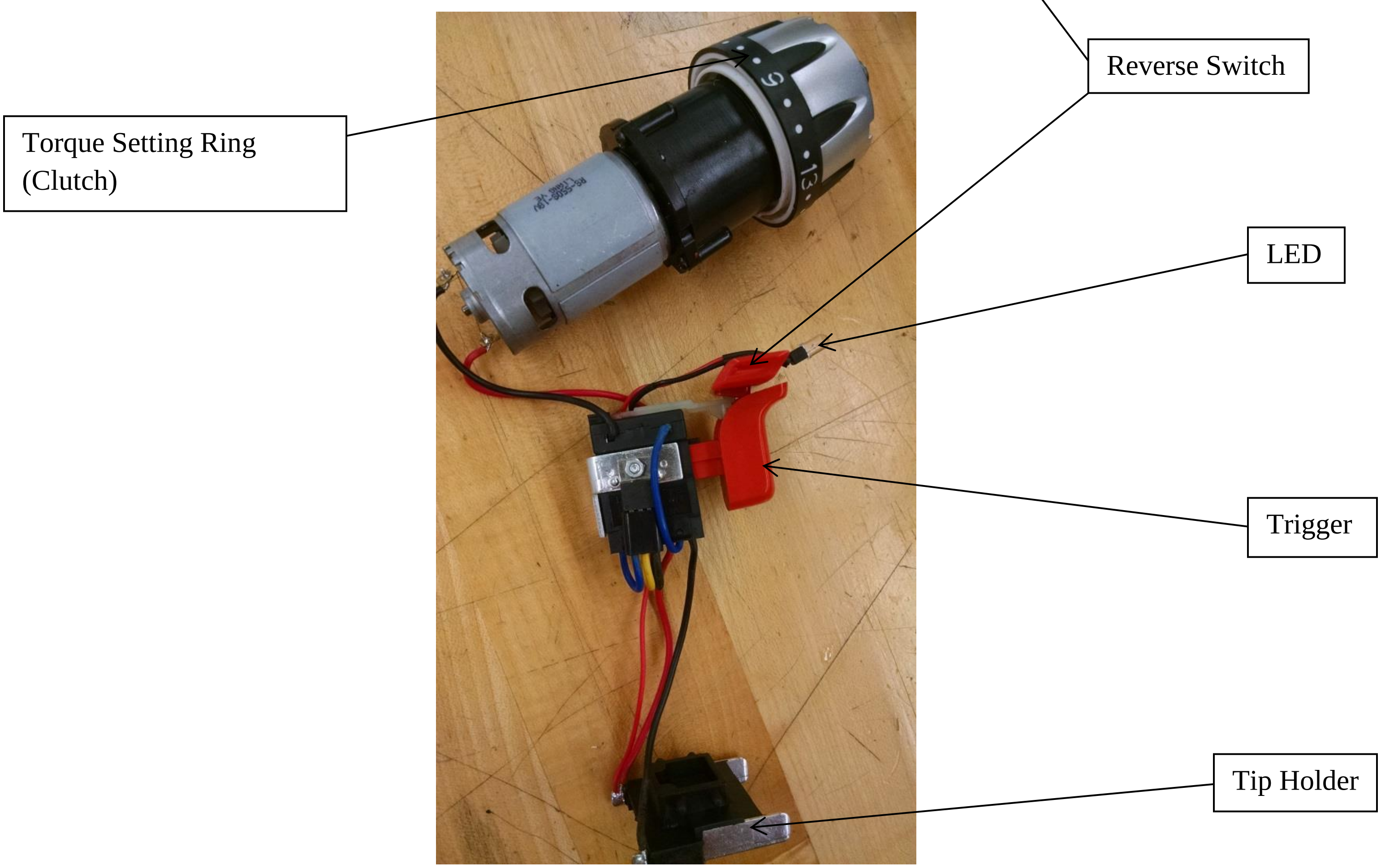

Figure 6: Internal Components of Drill (Side 1)

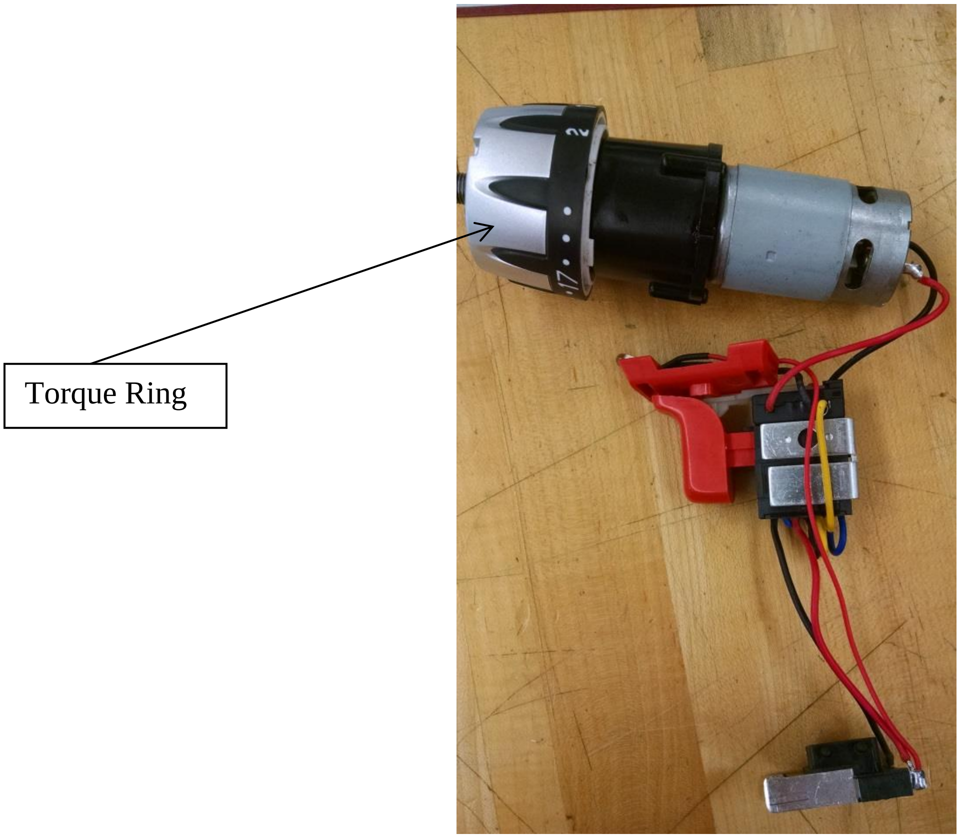

Figure 7: Internal Component of Drill (Side 2)

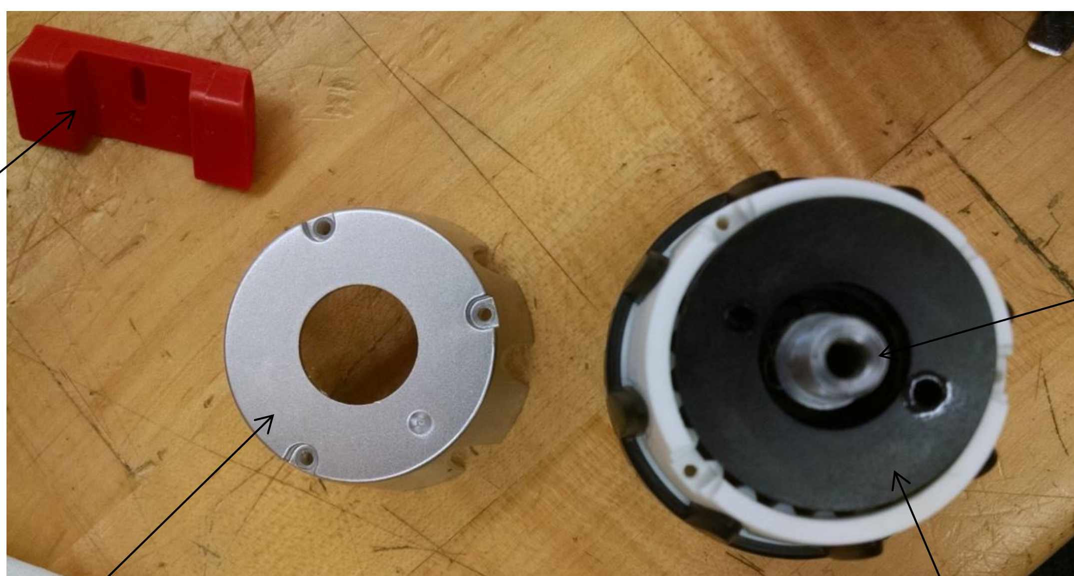

Figure 8: Gearbox Prior to Disassembly with Torque Ring

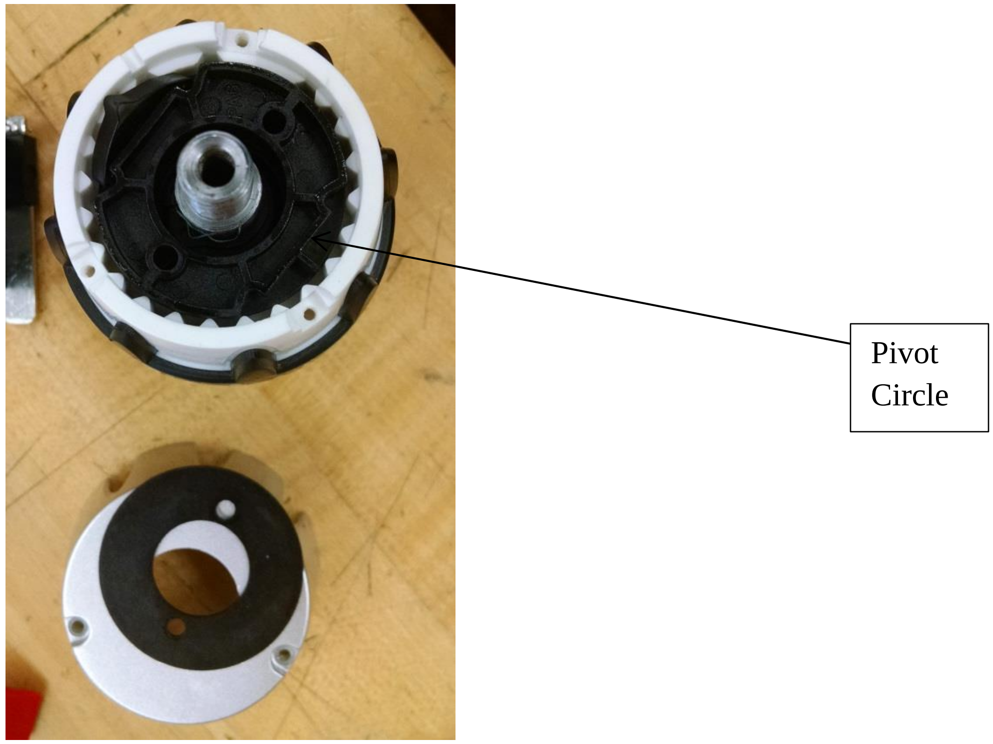

Figure 9: Gearbox with Removed Cover and Torque Ring

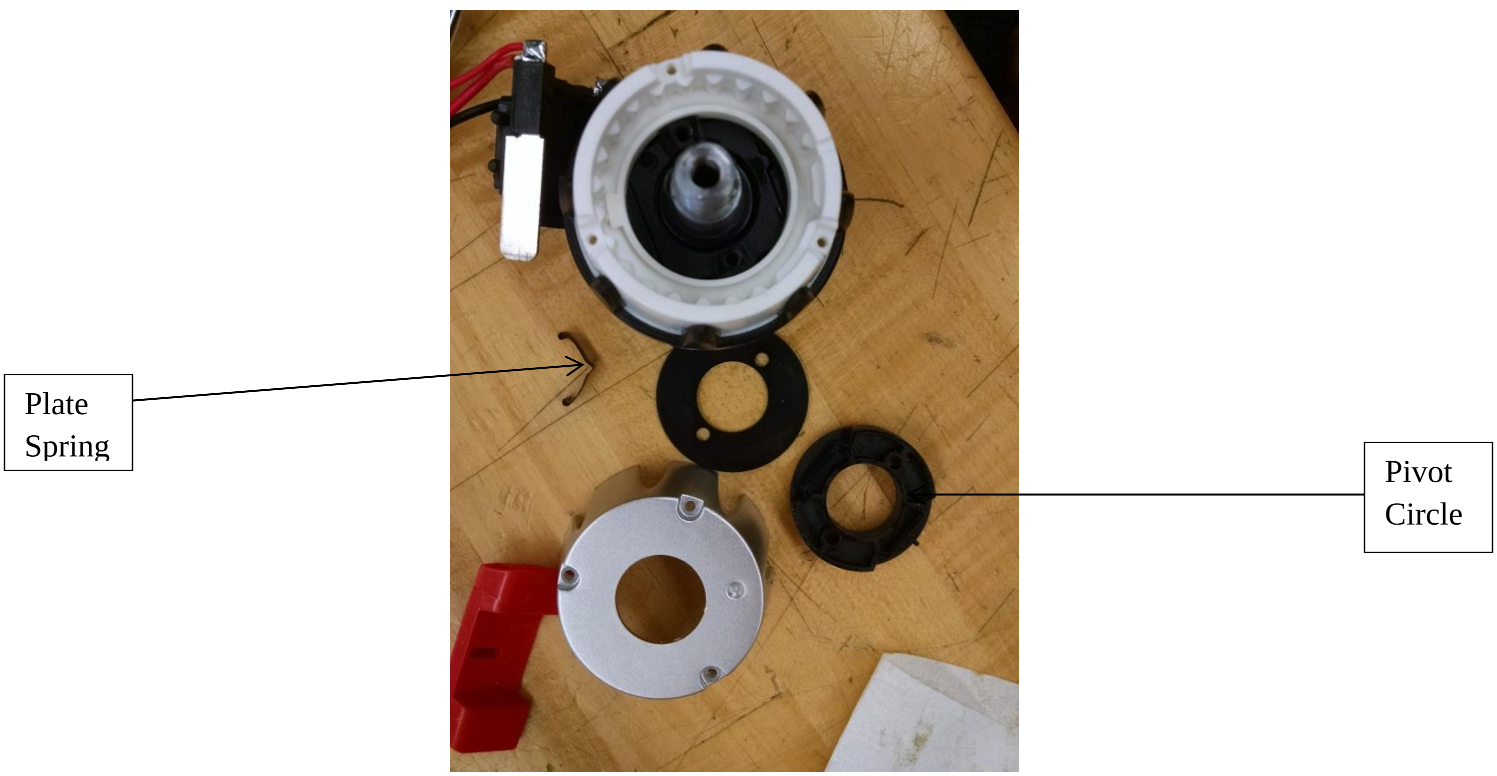

Figure 10: Gearbox Disassembled Continued

Figure 11: Gearbox Disassembled Continued

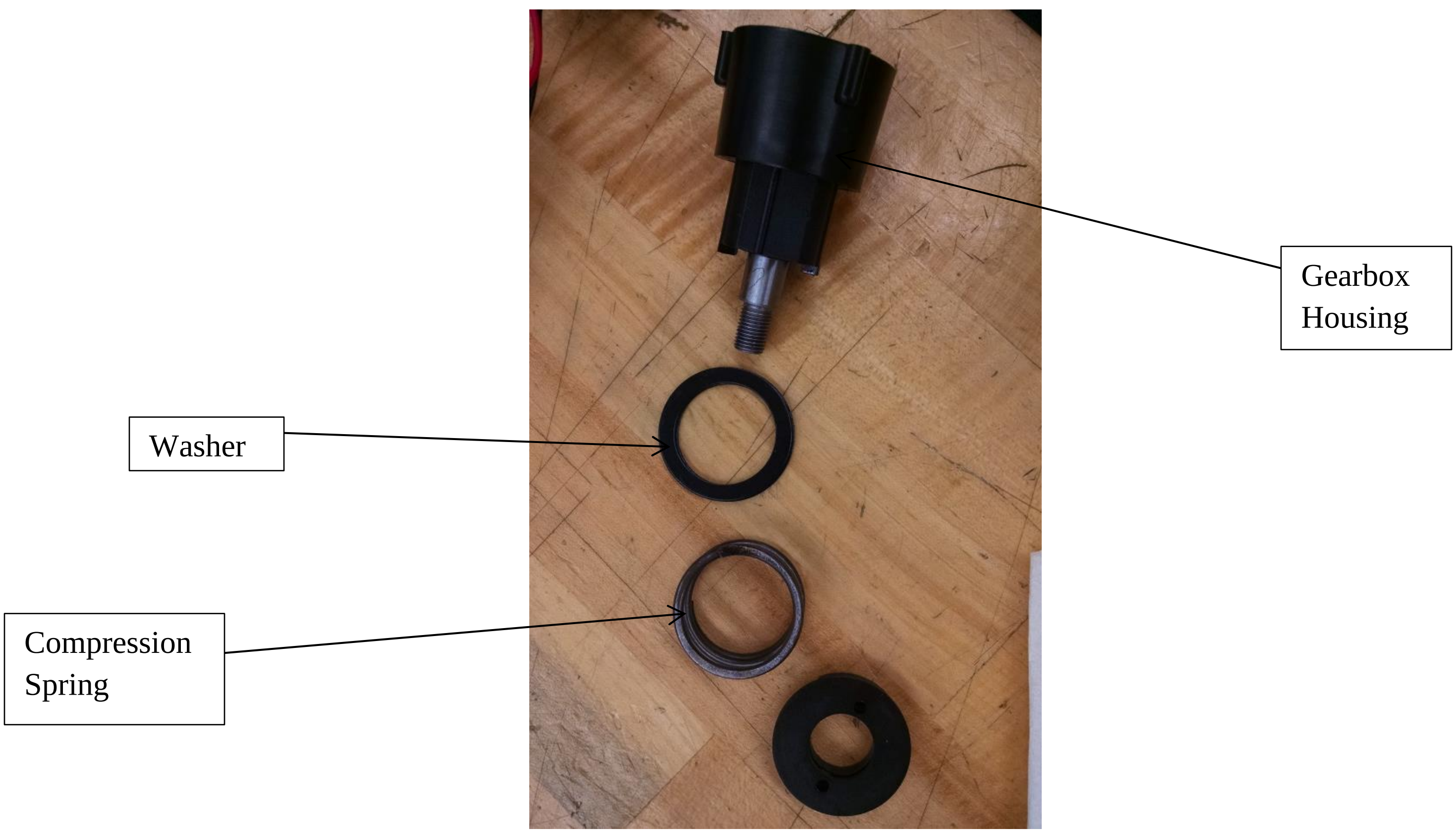

Figure 12: Gearbox Components

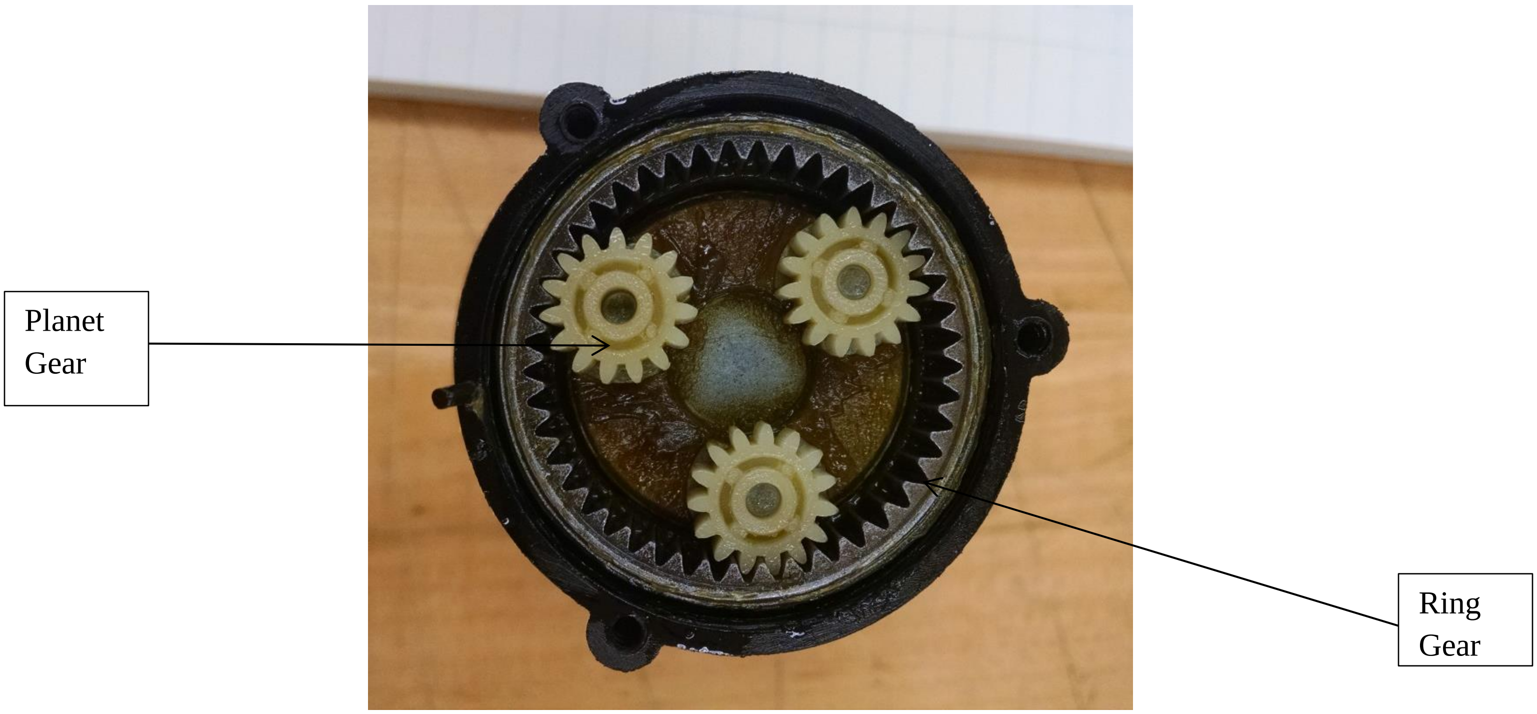

Figure 13: Assembled Gear Stages

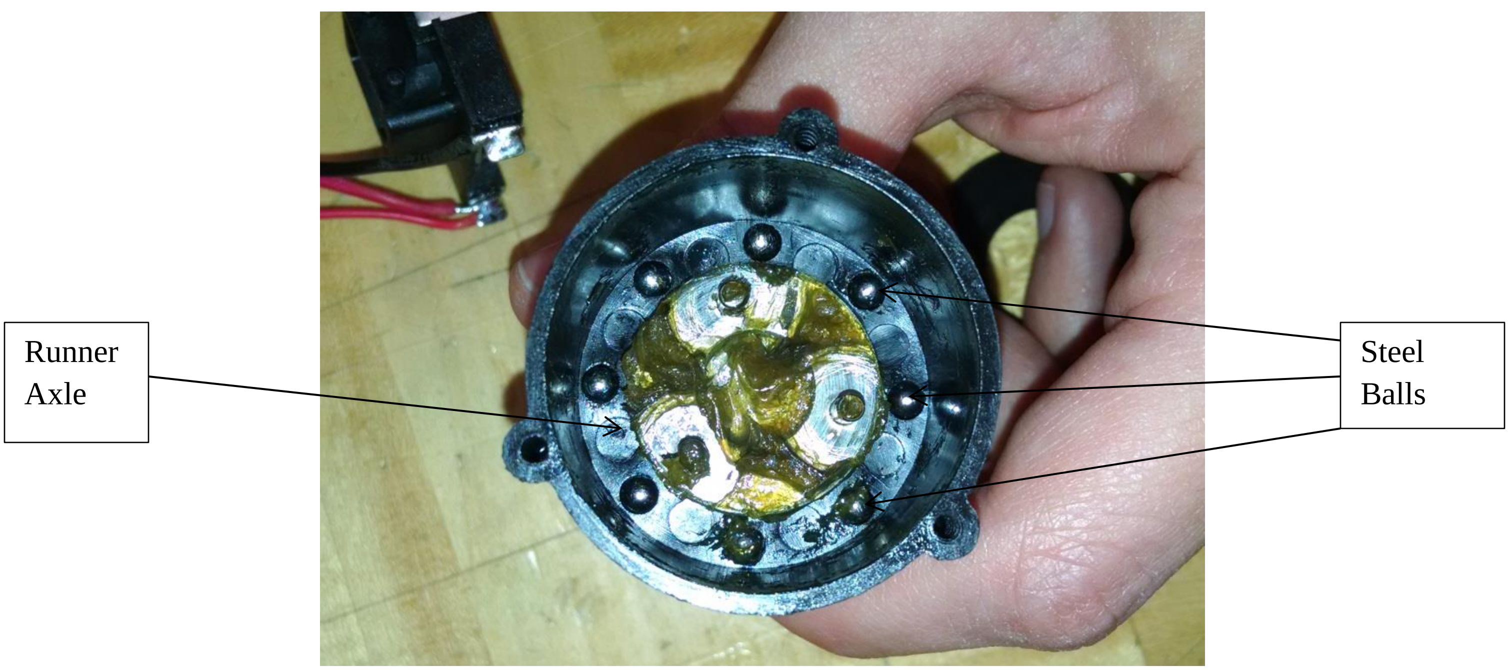

Figure 14: Assembled Bearings and Washer Setup

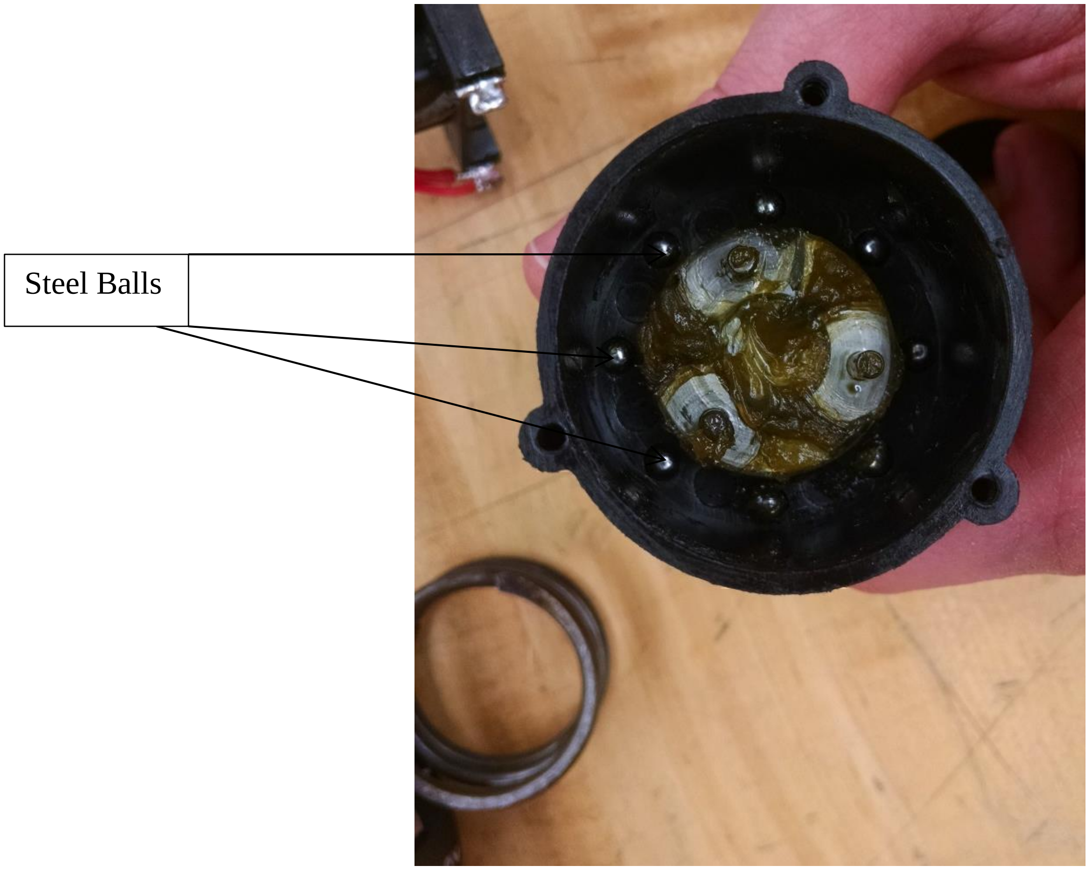

Figure 15: Ball Bearings in Housing

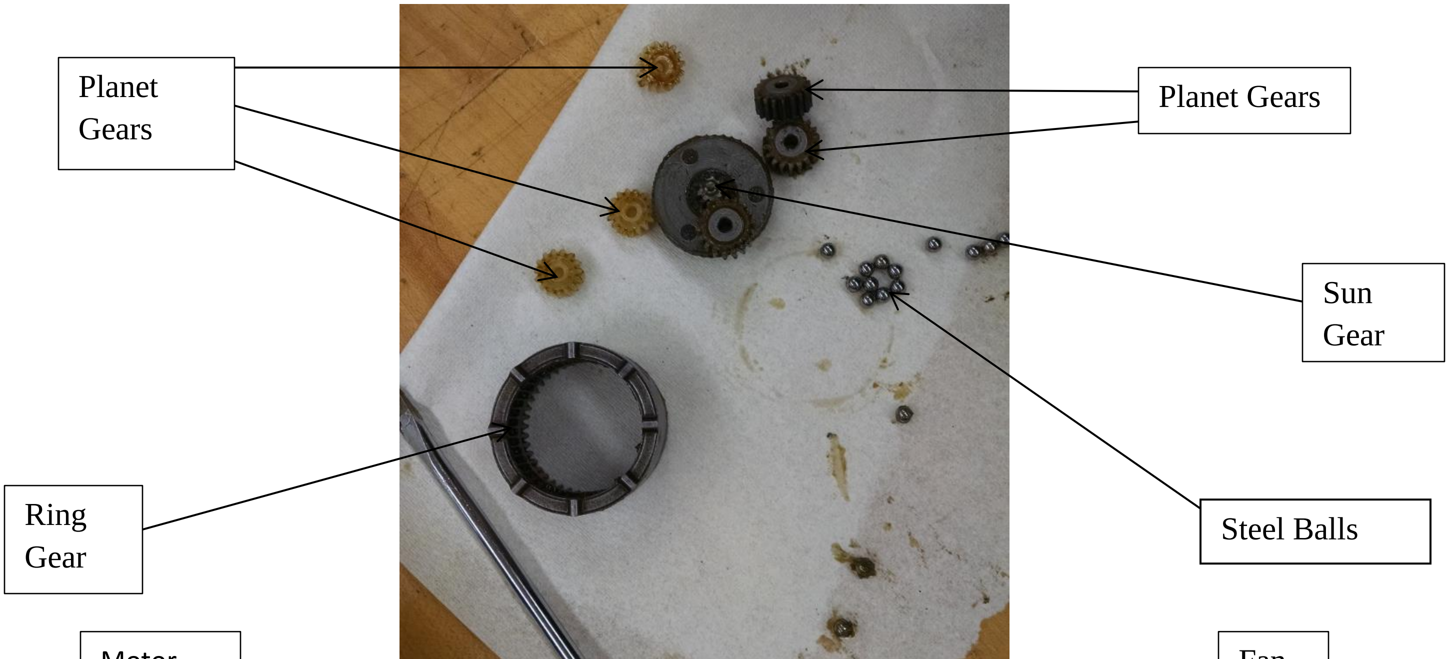

Figure 16: Disassembled Gear Housing and Ball Bearings

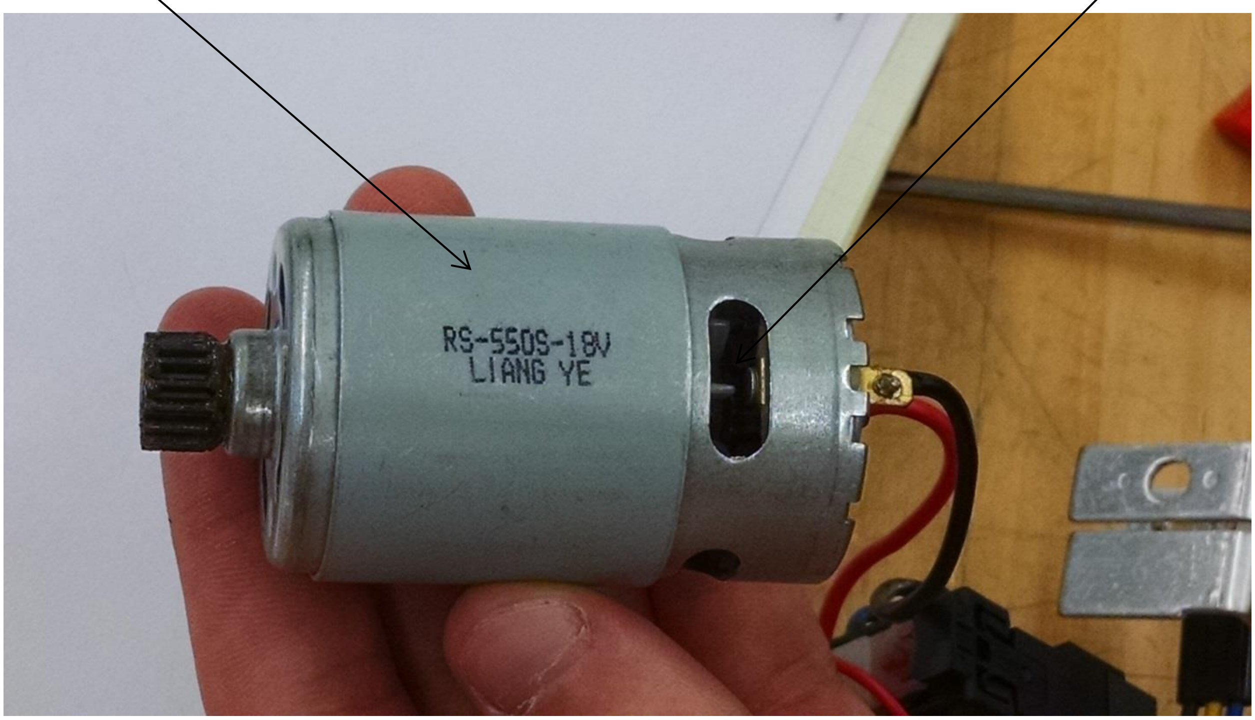

Figure 17: Drill Motor and Fan

Performance Evaluation

A dynamometer and various test instrumentation was used to measure the performance of our drill at several speeds. The test instrumentation consisted of two multimeters and their wires to measure the current and voltage of the drill. See figure 18-20 below of the experimental setup. Table 1 shows all the data obtained from the performance evaluation.

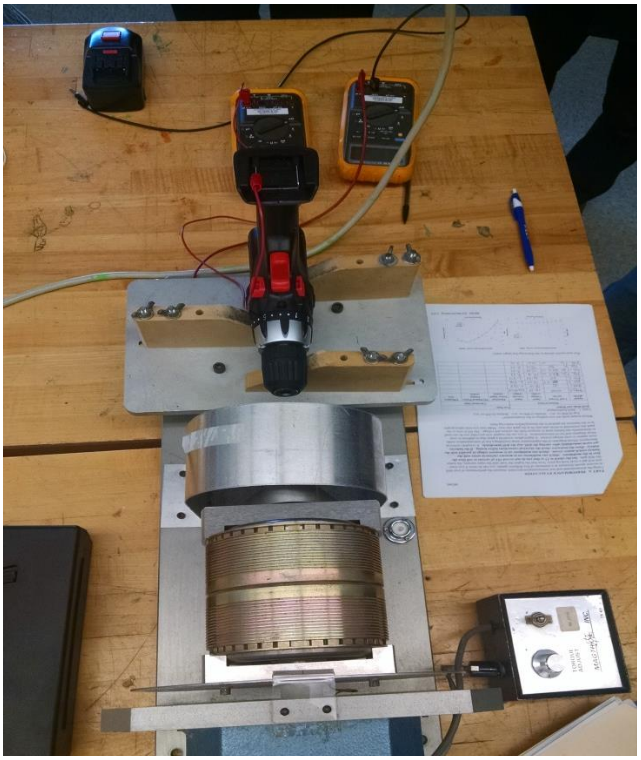

Figure 18: View 1 of Performance Evaluation Setup

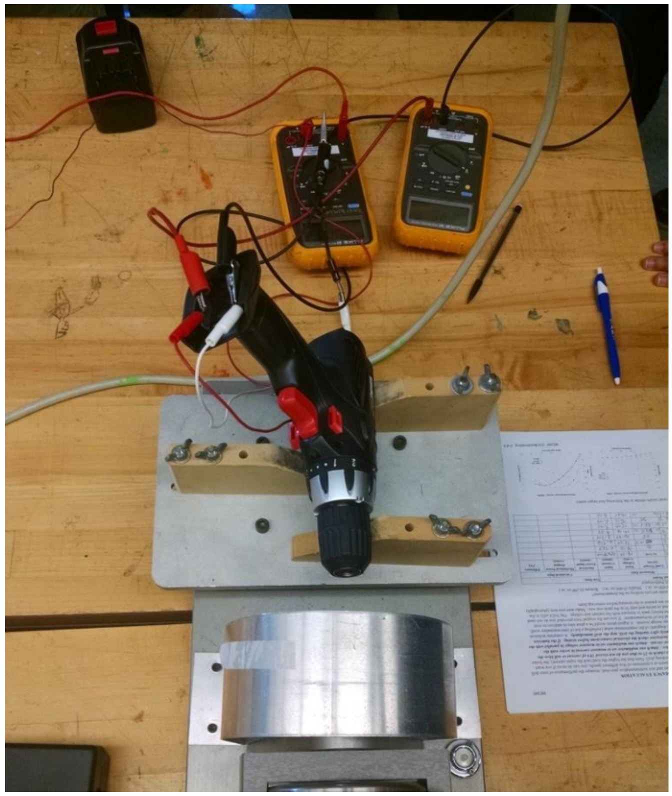

Figure 19: View 2 of Performance Evaluation Setup

Table 1: Drill Performance

Middle (0-400 oz-in) torque scale used

Drill Make and Model: Drill Master 68239				**Test Date: February 5, 2015**		
Measured Data				**Calculated Data**		
Speed (RPM)	**Load Torque (oz-in)**	**Input Voltage (volts)**	**Input Current (amps)**	**Electrical Power Input (watts)**	**Mechanical Power Output (watts)**	**Efficiency (%)**
1027	no load	19.10	1.64	31.324	0	0
968.1	12.5	18.00	2.30	41.4	4.47	10.80
841.4	57.5	17.05	4.55	77.58	17.89	23.06
785.9	150	15.90	5.40	85.86	43.59	50.77

745.0	190	15.2	6.35	96.98	52.34	53.97
682.0	225	19.55	7.23	105.20	56.74	53.94
629.5	270	13.90	8.20	113.98	62.84	55.13
556.0	320	12.90	9.60	123.84	65.78	53.12

Data Plots Generated From Performance Evaluation

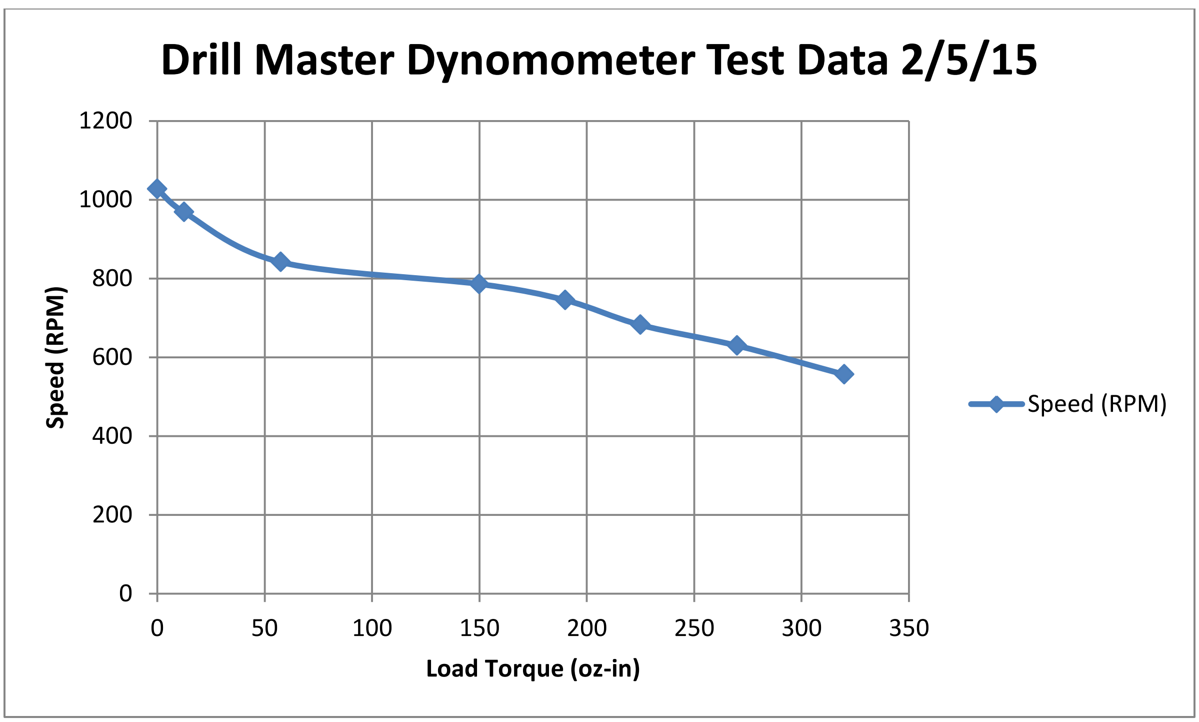

Figure 20: Speed vs. Load Torque

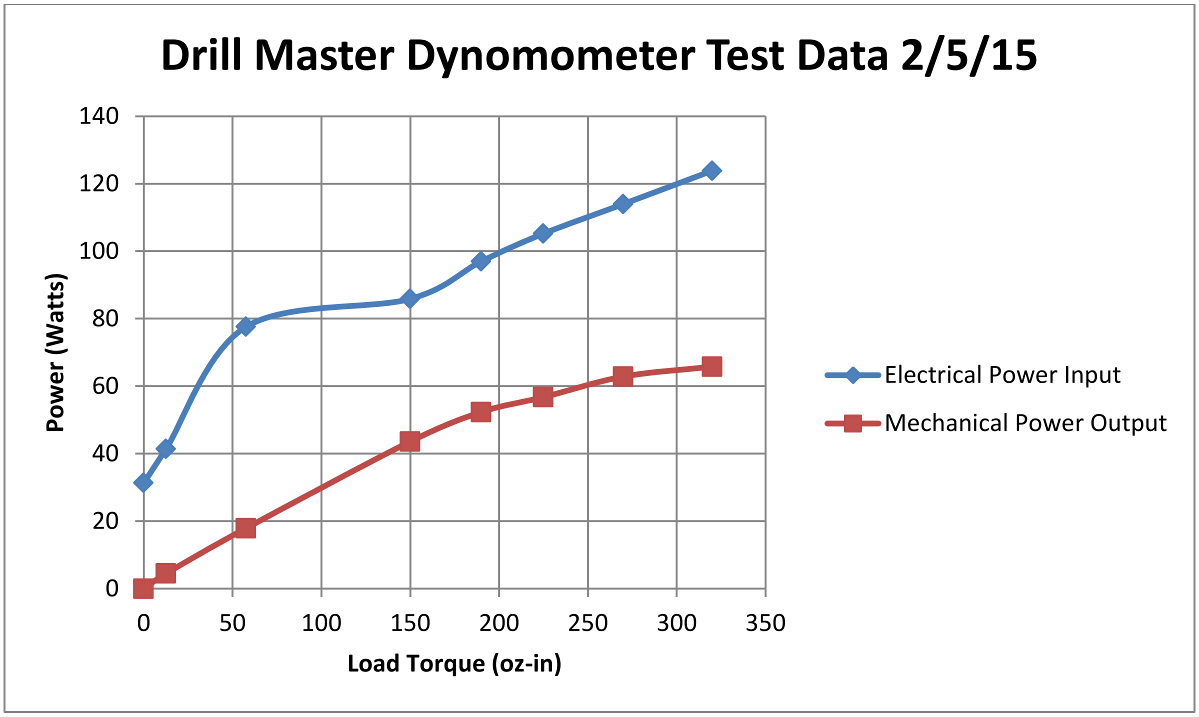

Figure 21: Power vs. Load Torque

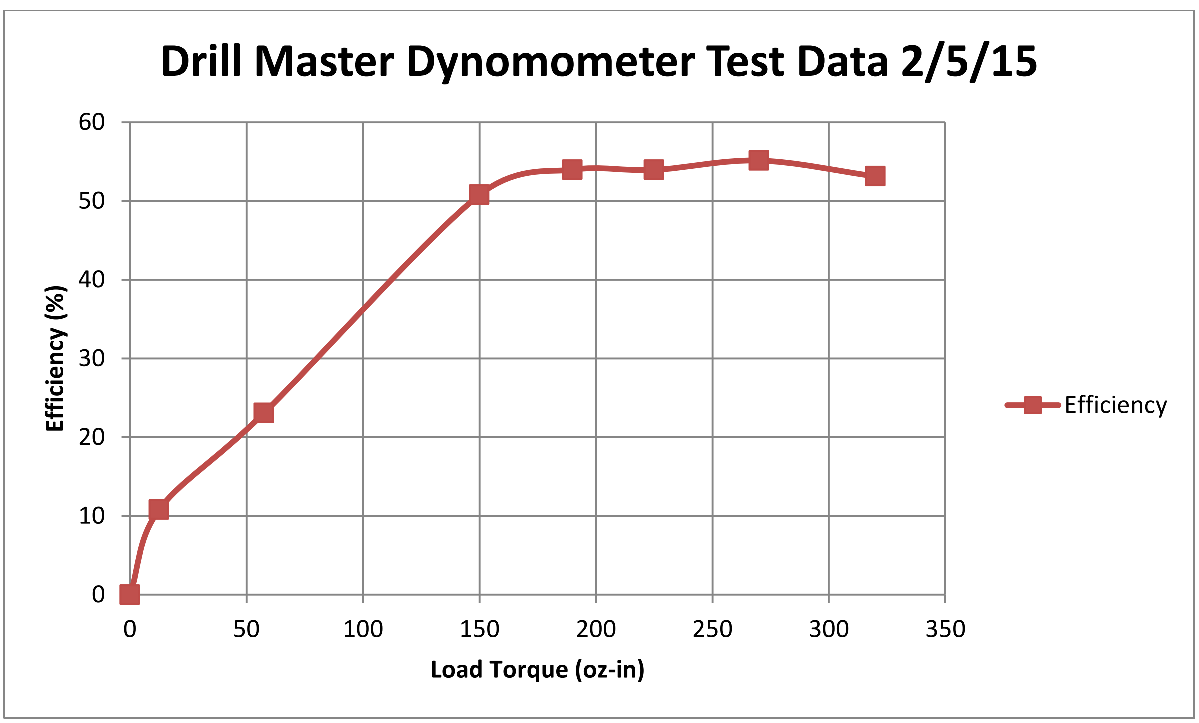

Figure 22: Efficiency vs. Load Torque

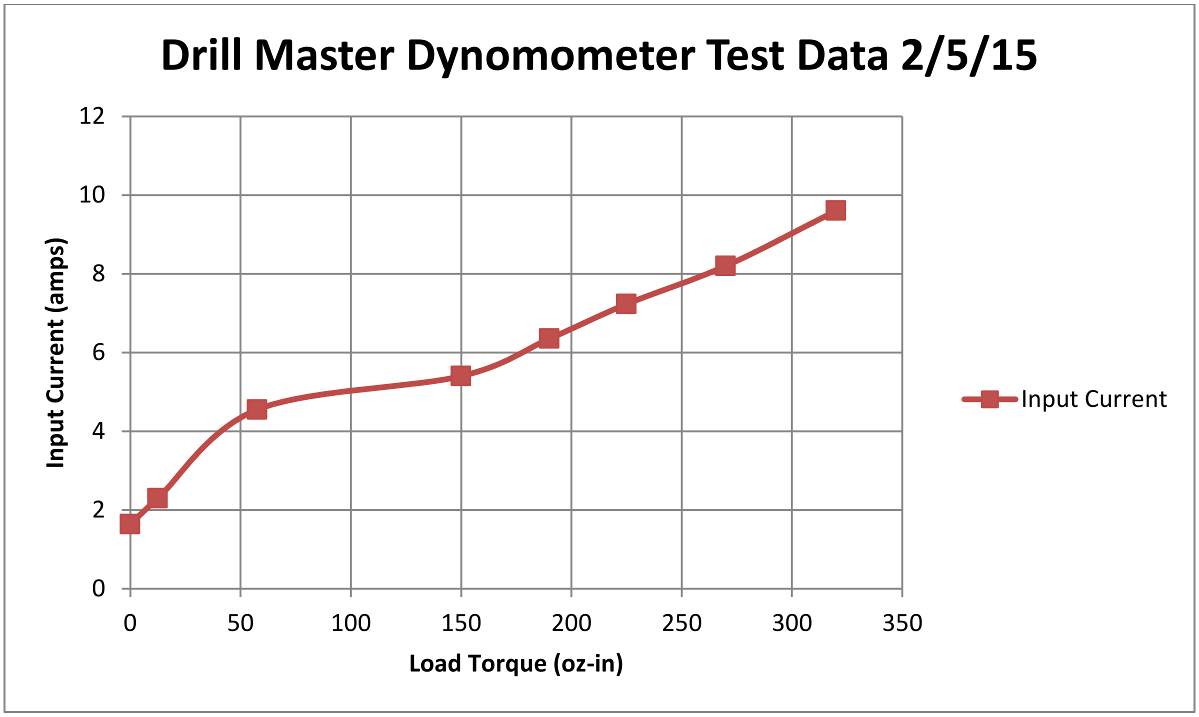

Figure 23: Input Current vs. Load Torque

Technical Features of the Drill

Table 2: Technical Features

	Cordless Drill
Manufacturer	Drill Master
Model	68239 18V Cordless Drill
Retail price ($)	20
Rated current (amps)	10 A
Rated speed at chuck (RPM)	0-900 RPM
Weight (lbs)	4.8
Variable speed (yes/no)	Yes
Bearing types (ball, roller, needle, bushing)	Ball Bearings

Motor type (ac, dc, universal?)	DC Motor
How is rotation reversed? (mechanically or electrically)	Electrically
Housing material(s)	ABS Plastic
Housing construction (2 piece clamshell, other?)	2 Piece Clamshell
Assembly complexity (1=complex, 5=simple)	4
Total number of parts	104
Overall speed reduction ratio	1:24
Number of gear reduction stages	2 Stages
Type of gears (spur, helical, worm, planetary….)	Sun, planetary, and ring gears
Warranty	90 days
Unique features (list below)	21 Clutch Settings
	Keyless Chuck
	Electric Brake

Conclusions and Reflection

Through the testing, dissection, and assembly of our drill, our team has been able to collect very valuable measurements and observations that will prove useful when designing our final handheld vacuum.

Our team was able to successfully record 8 sets of measurements during the performance evaluation testing. All of the testing went as planned with no significant problems. Any source of error in these measurements and calculations can be attributed to the fact that many of the instruments had fluctuating readings. It can be observed, that the speed of the drill decreases almost linearly as the load torque increase. Additionally, both the input and output power increase as the load torque increases. The efficiency of the drill continues to increase until it reaches a maximum point of around 53%. It makes sense that the drill does not reach 100% (it is impossible) because of the energy lost through heat generated from friction and vibrations in the drill. Please refer to the "Data Plots Generated From Performance Evaluation" section to view the figures derived from the data collected.

While performing the dissection of the drill, we were able to obtain technical information that helped us understand how the drill works and what each component does. This will be important when we design our handheld vacuum since we must use components from the drill. Furthermore, we feel that dissecting and assembling the drill was a good exercise to prepare for actually creating the vacuum.

6.0 Design Specifications

Specifications

Our team settled on thirteen different design specifications for our handheld vacuum cleaner.

- Durability: the sturdiness and build quality of the vacuum. Customers do not want and will not buy a product that easily breaks.
- Easy Disposal: People buys vacuum cleaners to pick up messes, not cause them. The vacuum cleaner should dispose of its collected dirt efficiently.
- Maintenance: The cleaner should dissemble easily for users to clean.
- Suction Rate: how quickly the cleaner picks up dirt. Consumers want to spend as little time cleaning as possible.
- Reliability: Customers want to feel assured the vacuum and all its parts will function properly when they want to use it.
- Longevity: how long the vacuum works. Consumers want to stretch their dollar, and want a cleaner that will last for several years before needing to be replaced.
- Versatility: People use vacuum cleaners on several different surfaces. Attachments targeted to the different surfaces would make cleaning easier for users.
- Battery Life: how long the cleaner lasts on a charge. Users want their vacuums to finish the job in a single charge.
- Weight: Users want a handheld vacuum cleaner that has a comfortable weight to it that does not become cumbersome.
- Noise: the quieter, the better for consumers.
- Price: Consumers want a reasonable price for their cleaners.
- Ease of Use: Users do not want a complicated interface on their vacuums; the cleaner should operate with just a few steps.
- Capacity: Whether with a bag or a collecting compartment, the vacuum should be able to hold enough dirt for a cleaning job.

Criteria

To select design concepts, five different criteria— aesthetics, cost, ease of use, functionality, and weight—were selected based on the specifications, customer survey, and external research on existing products in the market. Aesthetics are the visual and ergonomic attractiveness of the product. Cost is the price of the parts to produce the cleaner and, in turn, the price the consumer will buy it at. Ease of use relates to how well users can operate all aspects of the vacuum. Functionality is a measurement of the vacuum cleaner’s performance. Weight is simply the heaviness of the product.

Calculating Weighted Values

The Analytical Hierarchy Process method was used to determine the weighted importance of the criteria. Comparative values were selected by the team based on the results of the customer needs survey and existing product reviews found during external research. See Appendix for Features Comparison table.

Sub-systems

See Appendix for Black-box diagram of sub-systems.

7.0 Concept Generation

Design Alternative 1

Overall, this design aims to keep as much of the drill as intact and unaltered as possible. The only part that is truly removed is the chuck. The material of the housing will be made out of PVC and acrylic. The original battery from the drill will be used as the power source and instead of using an on/off switch, the trigger will be used. Also, the original motor, motor shaft, motor fan, handle, and housing will be untouched. For the most part, the internal wiring and components will be left alone. The switch to reverse the motor will be removed to ensure the user doesn't accidentally hit it while operating the vacuum. As seen in figure 4, all of the additions to the drill will be made on the front, possibly making it very front heavy. For that reason, a counterweight will be added to the back of the vacuum (either on the handle or battery) to balance it out, making the vacuum easy to use.

Figure 6 shows a model of the centrifugal fan that will be used in the vacuum. This fan will have radial blades because they are the least sensitive to solid build-up on the blades. A tradeoff to this is that they have a greater noise output. From external research, this type of fan is common in vacuums. This fan was chosen because the fluid is able to enter axially and leave radially. For this particular design, using an axial pump would not possibly work. The entire centrifugal pump (housing, fan, etc.) will be attached directly to the motor shaft via the filtration system housing.

Figure 5 shows the dual-filtration system and its housing. The entire housing that will contain the filters and the centrifugal pump will be made out of PVC pipe. The centrifugal fan will be located near the back of the housing, with a high-efficiency particulate arrestance (HEPA) filter in front of it to prevent any dirt particulates or rice from hitting it. The HEPA filter even traps fine particles such as pollen and dust mite feces. To be effective, the vacuum must be designed so that all the air drawn into the machine is expelled through the filter, with none of the air leaking past it. If this cannot be done, a different filter will be used that is efficient enough in preventing rice from reaching the fan. Prior to the HEPA filter will be a gap of space and a bigger sized filter that will allow particles up to the size of rice to pass through and stay in the gap (see figure 5 for the gap). Overall, the filtration system housing will be big enough to perfectly fit the centrifugal pump. The design is intended so that the pump is efficient. With a large filtration housing, the pump will not be effective and will result weak suction.

The gap within the filtration housing is intended to trap the rice between the two filters so that it can fall down through the opening at the bottom of the housing. The design requires that a section of the filtration housing be cutout at the bottom so an acrylic collection system can be attached via clips or Velcro. The cutout will allow the rice to fall into the attached collection system. Even though the collection container is made of acrylic, it can be considered the "bag" of this vacuum since all of the rice and debris will be collected there. The user will be able to attach and reattach the "bag" so that the contents can be emptied. The "bag" is clear so that the user can see how full it is. The size and shape of the collection system all depends on the shape and size of the filtration system housing.

Design Alternative 2

This design uses the existing drill housing, but makes some modifications. The electric motor is moved from the top of the housing to the handle portion. This is so that the top portion of the housing can be used as the inlet for dirt particles. The output shaft of the motor will power the 2-stage gearbox from the drill and a final output shaft will power the impeller. The impeller will be located at the top of the housing, opposite the entrance. The entrance will be an opening that is widened to increase the surface area of suction. A grate will cover the impeller to allow air flow, but prevent dirt from damaging the blades. After the dirt passes the impeller, it will go through a funnel shaped portion, where it is dropped into the collection area. The funnel shape is to prevent backflow of dirt into the upper portion of the vacuum. The collection area will be detachable at the top of the funnel. At the bottom of the collection area, the battery will be inserted. This means the battery must be removed in order to remove the dirt container. The motor will be controlled using the trigger that came with the drill.

The relocation of the motor will require a new mounting structure to support it. The new support will mimic the support used in the top portion of the housing that originally supported the motor. The detachable collection area will have a twist-on and twist-off function for ease of use. The internal wiring will be kept organized by attaching it to the housing when able. The impeller will be manufactured using a rapid prototyping method. The grate material will be purchased and bent to fit the shape of the housing to protect the impeller. The final output shaft of the motor will be purchased. Unused parts of the drill will be discarded. This includes the chuck and motor reversal. A diagram of the vacuum can be seen in Figure 7.

Design Alternative 3

This design emulates a popular design of handheld vacuum cleaners on the market in order to appeal to consumers' sense of familiarity. It has a different body than the drill. It still uses the drill's battery, trigger, and motor complex (motor, fan, and shaft). The trigger is moved to a position that can be gripped in an ergonomically comfortable manner while in operation. The battery's placed almost directly under the handle with the motor complex faced vertically beside the battery. The design's center of gravity should be approximately at the motor. Attached to the motor shaft is a pairs of straight bevel gears in order to transfer the torque 90°. Another shaft is attached to the one gear, which is attached to the vacuum's impeller. Two exhaust vents are on the vacuum's body, one each for the motor fan and another for the impeller. A HEPA filter is adjacent to the impeller. A detachable collection container will have a nozzle shaft up top, the shaft leading up to the filter. The entrance, where the dirt is collected, is at the bottom of this nozzle shaft. Figure 8 shows a side view of the model's cross section.

The collection cup is made of acrylic. The material's translucency will allow users to know when the cup if full. It is attached to the body of the vacuum via Velcro straps. A HEPA filter will prevent any debris from getting to the impeller's compartment. The impeller will either be made of PVC or 3D-printed material, whichever is more time and cost-efficient. Air will enter through filter and vent out the side of the body in the impeller's compartment. (See figure 6 for a front-view sketch of the impeller.) The bevel gears will most likely need to be 3D printed. The remainder of the body will need to be constructed of PVC, and it must house the new positions of the motor complex, battery, and trigger. This design is aesthetically pleasing and should be well-balanced for easy use. A main drawback is the complexity of its new body which would need to be constructed.

Our Concept Generation Process

The four steps our team used in the concept generation phase were clarifying the problem, searching externally, searching internally, and reflecting on the solutions and the process. The very first thing we did was decompose our problem functionally to represent it as a single black box operating on material, energy, and signal flows. The black box represents the overall function of the product (see appendix). We used our data collected from our customer needs survey to assist in the decomposition.

Next, our team performed internal search by using personal and team knowledge to generate solution concepts. Our team focused on using a brainstorming method, the Post-It-Note method. Since the concept generation process is not strictly one way, we could search internally again using other methods such as gallery, idea trigger, 6-3-5, and TRIZ. Our brainstorming method used both individual and group time periods of generating concepts. Each member brainstormed ideas alone and wrote them on separate post-it-notes. Next, the ideas were grouped by common themes and a header card was created for each group of ideas. Finally, using the multi-voting technique, our team was able to prioritize the list. Table 3 in the appendix shows our team's ideas and which ones were voted on. Some things that made brainstorming helpful were the ability to make analogies and use related and unrelated stimuli. The process of the multi-voting technique our team used was:

1) Count the number of items on the list and divide by three. This is the number of votes each person has. (Round fractions off to the lower number). There was a total of 16 post-its for our team
2) Each person uses his/her votes to select the items he/she wants to keep. While each person can vote for any item, it is a good idea to limit the number of votes any one item can receive from a single person to three. Note: the team can decide if they want to allow more or less multiple voting.
3) List alternatives in their new prioritized order
4) Critically discuss the top alternatives in order to reach consensus. Eliminate those that are outside the control of the team Table 3 shows which post-it note ideas (via a *) that we decided were important and needed to be incorporated in our vacuum.

Finally, our team reflected on the solutions we came up with throughout the entire concept generation process. Each individual member of the team took everything we did and generated feasible design alternatives with the important subsystems. Our designs were explained previously in the memo, with their corresponding diagrams in the appendix.

8.0 Concept Selection

In order to analyze the three design alternatives created in the concept generation phase, our team used decision matrices for each of the major system elements and the overall configuration of each design. We used a +1/-1 ranking system to rank the major systems of each design. This will allow our team to determine which aspects from the three alternative designs should be used in the final design. Next, we used the AHP method to calculate weights for the overall configuration scoring matrix. (see Appendix for all decision matrices, including the AHP matrix).

Using all of our prior external/internal research, as well as customer needs analyses, our team was able to assign rankings and weights to each respective matrix. Additionally, we considered the results of our three system element decision matrices while rating the respective systems in our overall configuration matrix to give an added dimension of interdependence.

All of the decision matrices take a lot of factors into account that make each numerical result significant and logical. The common criteria between the three major system element decision matrices included ease of production, predicted cost, and maintenance. Our team found that these three criteria were valuable to the overall design of our handheld vacuum during both production and use. Through our analysis, we found the criteria that holds the greatest weight is the design of the fan since this is the most important component of our handheld vacuum. This is logical because during our customer needs survey, functionality was found to be the most important factor. Conversely, the least important factor was aesthetics, resulting in the lowest weight. This also directly corresponds to our customer needs survey.

In the end, design 1 ranked first, with design 3 ranking second and design 2 ranking third. Looking at table 8 in the appendix, it can be observed that each of the design alternatives received similar scores, only varying by roughly 0.2. Our team decided that we would take components from each design alternative and factor them into our final design. The following design is not necessarily the final design because this process is iterative, and will likely be modified as we move on further into the production phase. Our results that we will receive in future testing will most likely determine what will be changed (i.e. size of the fan).

Overall, the final design will be modeled after design alternative 1 (see figure 4 in appendix). One major difference will be that the filtration system will not be a dual system. Instead, we will use a filter that is good enough to only let in rice (which is the overall goal of the handheld vacuum). We will be using a centrifugal fan with straight radial blades, attached directly to output shaft. The chuck will be removed completely and not used in the vacuum.

The nozzle of the vacuum will be made of a flexible hose type material in order to allow the collection system to be upright during operation. Our team found that the best material for the collection system is acrylic because it is transparent, allowing the user to see how full it is. Furthermore, our team has access to raw acrylic for at the Learning Factory. We intend the collection system to be attached to the housing via Velcro for ease of attachment. It was decided that the battery would remain the power source and the trigger would be utilized, instead of an on/off switch. See figures 11 through 25 for Solidworks models of the centrifugal fan and housing that will be attached to the drill.

9.0 Theoretical Analysis

To ensure the design of our handheld vacuum cleaner has ample power and volumetric flow rate to successfully suck up rice, we performed theoretical analyses. For the calculations, we used the values of rotational speed and power found during the drill benchmarking performed earlier in the semester.

The equations used to calculate the pump specific speed are listed below (equations 1-4):

$$Q = v\pi \frac{D^2}{4} \qquad (1)$$

$$SP_{fan} = \frac{8.52P\eta_f}{Q} \qquad (2)$$

$$H = \frac{SP_{fan}}{\gamma_{air}} \qquad (3)$$

$$N_{SP} = \frac{\omega \dot{V}^{1/2}}{(gH)^{3/4}} \qquad (4)$$

where:
Q, or $\dot{V}$, is volumetric flow rate;
v is air velocity;
D is diameter of the inlet;
SP_{fan} is static pressure of fan;
η_f is efficiency of fan
P is power;
γ_{air} is specific weight of air at room temperature (11.82 N/m^3)
N_{SP} is pump specific speed;
ω is angular velocity;
g is acceleration due to gravity (9.807 m/s^2); and
H is head loss.

Table 8 should be referenced for all of the calculations performed. The air velocity of the handheld vacuum was chosen based on average velocities found through external reserach. Using the air velocity and equation 1, the flow rate is obtained. The flow rate is needed to calculate the static pressure of the system, as seen in equation 2. Once the static pressure is found, the head loss can be calculated using equation 3 (the specific weight of air was assumed to be at room temperature, 20 degrees Celsius). Equation 3 was found online using *www.engineeringtoolbox.com*. The handheld vacuum experiences head loss due to the friction the impeller experiences. The head loss can be increased if there are a greater number of blades on the impeller and/or the blades are relatively thick. Finally, once the head loss is calculated, it can be input into equation 4 to find the pump specific speed. It should be noted that the angular velocity was obtained from our benchmarking drill dissection/assembly. The final design intends on removing the gear reduction stages, therefore increasing our angular velocity data by a factor of 24, which is incorporated in these calculations.

According to our results, our impeller should be designed as a centrifugal fan (this agrees with our original design). This can be seen using figure 14-73 in *Fluid Mechanics: Fundamentals and Applications* textbook written by Cimbala and Cengel. Additionally, using scaling laws, and figures found in *Fluid Mechanics: Fundamentals and Applications* textbook, we found that the best orifice size for our nozzle is roughly 0.5 inches. These results found in the testing analysis will shape our final design when it comes to actually rapid prototyping an impeller and nozzle. In conclusion, theoretically, our impeller should supply sufficient flow rate and static pressure to successfully provide suction to pick up rice.

10.0 First Prototype Evaluation

For images of our alpha prototype, please refer to the Appendix.

Materials
After much consideration, our team came to the conclusion that using a 3D printer would be best in printing our components for the vacuum. All of the parts are made of PLA plastic, by the Makerbots supplied by the Reber building. Compared to ABS, PLA demonstrates much less part warping. It is also much stronger and more rigid than ABS plastic. PLA is created from processing any number of plant products including corn, potatoes or sugar-beets, PLA is considered a more 'earth friendly' plastic compared to petroleum based ABS.

Construction Process
As stated previously, all of the parts were printed using a 3D printer. There are many reasons why we chose to construct all parts from a 3D printer; they were created for rapid prototyping reasons. Penn State has a free and quick 3D printing service provided to mechanical engineering students in Reber building. It was very time-efficient because we were able to send STL files of our parts to operators of the printers, which allowed our team to work on other material while our prototype was being printed, a big benefit to our busy schedules. Another reason 3D printing was used: it is the most accurate representation of what our final design will look like. Using cups, cardboard, or any other material will be unrealistic. 3D printing our parts is better aesthetically than using other materials.

Our team 3D printed five components for our handheld vacuum. The parts printed were the nozzle, housing, impeller, front impeller plate, and a collection bin (see appendix for figures 26 through 41). In order to attach parts to each other, our team decided to simply use super glue since this is only an alpha prototype that does not need to be functional. Not all of our components will be completely assembled (i.e. the housing will not be attached to the main body of the drill). The nozzle was glued to the housing and the front plate was glued to the blades of the impeller. We removed the chuck of the drill and directly attached the impeller to the rotating shaft. Internally, our team has yet to remove the gear reduction stages. This will be done for our next beta prototype since it will need to be functional. The collection bin is not permanently attached to the housing since it will be removable. Due to the limitations of the free 3D printing, a slot for the collection bin and holes for the exhaust of the impeller were not created. Using a sharpie, we have indicated where such slots would be located. Additionally, we used a piece of paper with holes in it to model our filter. The final filter obviously won’t be made out of paper; it will most likely be a screen from a window or something similar. After consideration, we concluded that this alpha prototype is a scaled down version of what the final will look like. Our team did not anticipate the amount of rice we would have to collect, therefore the housing and nozzle will be bigger for the final design. Finally, to aid in collecting the rice, we have considered placing a hinged flapped that will open and close when the pressure difference is and is not present; hence whether the vacuum is on or not. This will allow some of the rice to be collected in the main housing if the collection bin becomes full.

Performance
Since this is only an alpha prototype, no testing was performed to see how our vacuum works. The next step would be to create a beta prototype, which will allow our team to successfully test our design. For these reasons, no results can be reported at this time.

Overall, our team can't determine what aspects of our vacuum did and did not work well due to the limitations of an alpha prototype. However, from working with the 3D printers, our team decided that our final design will use an impeller fabricated by one of the higher end 3D printers located in the Learning Factory. Our prototype helped our team realize that at its current size, the vacuum would be unsuccessful in sucking up rice in a sufficient manner. Even if this prototype was fully functional, it would be very limited in the amount of rice it could collect. This means our final design will need to utilize bigger parts in order to be successful.

Improving the Prototype
Constructing a beta prototype being our next step means we must greatly focus on improving our initial prototype. With our current design of the impeller, there is no existence of an inlet for air to enter. We will focus on the Solidworks model in order to create this inlet. In addition, the Solidworks models of our collection bin, nozzle and housing will be edited in order to increase their size for the final design. The most important thing our team needs to look into is how to attach all of our components (impeller, housing, nozzle etc.) to our drill. We need to ensure that everything is sturdily attached while having an air tight seal so that we achieve the pressure drop that is needed for suction. Also, our team will need to find a way to remove the gear reduction stages without hindering the rotation of the shaft. Removing the gear reduction stages will allow our impeller to rotate at a high enough rpm to create airflow and a pressure difference.

In addition, we will be focusing on the collection system for our vacuum. Our future prototype will utilize a collection bin and hinged flap system in order to collect the maximum amount of rice possible. We plan on redesigning our collection bin completely so that it is permanently attached to the housing, unlike how it is for the alpha prototype. The collection bin will have an opening at the bottom where the contents can be emptied. This opening will be sealed with some sort of lid or cap that will utilize an O-ring or cork like design.

11.0 Component and Material Selection

Components and Materials

Deciding what components and materials should be used for our mass produced vacuum is a very important step in the product design process. There are many factors that need to be considered when making your selection.

For a mass produced variant of our handheld vacuum, all components and parts, besides the motor, filter, and wires, will be made using plastic injection molding. Injection molding is one of the fastest and most efficient ways to mass produce a product. Most polymers may be used, including all thermoplastics, some thermosets, and some elastomers. There are tens of thousands of different materials available for injection molding. The polymer used for the housing, nozzle, and collection bin of the vacuum will be polycarbonate. Polycarbonate has excellent physical properties, including high toughness and heat resistance. As well, it is resistant to chemicals. These properties will allow the housing, nozzle, and collection bin to have a long lifespan, allowing the consumer to get the most out of the vacuum. An added bonus to using polycarbonate is that it is transparent. This will allow users to see into the collection bin and know when to empty it.

The impeller will be a centrifugal fan made out of nylon plastic because of its high mechanical strength and resistance to wear and organic chemicals. Nylon has a very high heat deflection, meaning the heat produced by the motor won't affect it.

These changes for a mass produced product would slightly change our overall layout for the prototype. For example, using injection molding would allow us to design the vacuum to be three main pieces that snap together. The housing/nozzle would be two pieces to allow users to replace the filter. The third piece would be the collection bin that would be easily separated from the body of the vacuum in order to be emptied.

Common Off-The-Shelf (COTS) Components

Within our mass produced handheld vacuum, there will be numerous parts that can be easily accessed/purchased from off the shelf. It is crucial to determine which parts of a product can be purchased as COTS components. Many of the parts in the vacuum are considered standards, making them COTS components. For example, our vacuum will use a HEPA filter which can be easily purchased because HEPA filters are a very common component in today's world of vacuums. Moreover, to minimize some costs, the motor and its subcomponents (wires, housing, shaft, etc.) will be purchased as a COTS component. Finally, all other components including bolts, screws, fasteners, bearings, and washers will be purchased as COTS components. It would not be efficient to custom make any of these small parts.

Environmental Impact

As design engineers, assessing the potential environmental impacts (DFE) of our design is a very important step. When the vacuum is being mass produced, environmental impacts becomes a very influential factor in manufacturing. First off, our decision to use polycarbonate as the main polymer for injection molding was a smart move because it is 100% recyclable. Polymer waste is a huge issue when it comes to the environment, so our team wanted to choose the best method of producing the polycarbonate components. Plastic injection molding is an efficient method that does not waste any material. Prior to mass producing our vacuum, DFE goals are established using the methods found in “Product Design and Development” (chapter 12) for our materials being used. See table 9 in the appendix for the DFE goals. Moving forward with DFE, our team considered many questions related to the environmental impacts of each lifecycle stage found in table 9. See table 10 for the questions our team considered during the DFE process.

Drawings of Mass Produced Device

In the appendix (figures 42 through 45), you will find ANSI formatted drawings that are easily readable for the mass produced handheld vacuum. Each one of the drawings will have three view orthographic projections. All assemblies and parts drawings that are required to manufacture the vacuum in mass production quantities are included. No COTS parts or trivially simple parts, like screws, are included in the drawings. Figures 46 and 47 show what the components will theoretically look like when attached to each other.

12.0 Fabrication Process

When it comes to mass production, there are a countless number of methods that can be utilized. For a mass produced variant of our handheld vacuum, all components and parts, besides the motor, filter, and wires, will be made using plastic injection molding. Injection molding is one of the fastest and most efficient ways to mass produce a product. Most polymers may be used, including all thermoplastics, some thermosets, and some elastomers. Each individual part will have its own separate mold, meaning one mold will have multiple copies of the housing and another mold will have multiple copies of the impeller. This will be the same for the nozzle, collection bin, and the housing for the "drill" portion of the vacuum.

With injection molding, granular plastic will be fed by gravity from a hopper into a heated barrel. The granules will slowly move forward by a screw-type plunger. The plastic is then forced to a heated chamber where it is melted. As the plunger continues to advance, the melted plastic is forced through a nozzle that rests against the mold, allowing it to enter the mold cavity through a gate and runner system. The mold will be cold, which results in the plastic solidifying almost as soon as the mold is filled.

Within our mass produced handheld vacuum, there will be a variety of parts that can be easily accessed/purchased from off the shelf. These specific parts will not have to be fabricated and will be bought in bulk quantities. Small parts that can be easily purchased in bulk will include bolts, screws, fasteners, bearings, and washers. Furthermore, the HEPA filter and the motor and its subcomponents (wires, housing, shaft, etc.) will be purchased in bulk as well. The motor is able to be purchased and not fabricated because it is a component that is produced for the Drillmaster from Harbor Freight Tools.

Once all components of the handheld vacuum are produced, they will be all brought together in one place in order to be assembled. When it comes to assembling the handheld vacuum for mass production, it will be produced in a manual fashion. There will be workers on an assembly line, repeating the same step for one vacuum over and over again. In the first step, the impeller will be attached to the drill portion of our vacuum (the impeller will be directly attached to the shaft of the motor in the drill housing). Next, the HEPA filter will be attached to the inside of the housing on one end, via interference of the two components. Then, the nozzle will be attached to the other end, using a sealant. From there, the housing/nozzle portion will be attached to the drill, creating an airtight seal. Since the collection system is permanently attached to the housing, the final step is to install the plug at the bottom of the collection bin. Once all components have been assembled, the handheld vacuum will be packaged in a cardboard box, along with its battery and any attachments.

An updated assembly/exploded view of the final design for the handheld vacuum that will be mass produced can be found in the appendix (figures 46 through 50 in the appendix). All parts will be labeled for convenience.

Note: The battery and drill are not shown in these figures. The battery and drill would be unaltered (besides the removal of the gearbox). Our design (figures 46 and 47 in the appendix) is directly attached to the housing of the drill.

13.0 Safety

When any type of consumer product is produced, it must meet or exceed all relevant government consumer safety regulations. In the case for our handheld vacuum, the product must at least meet safety regulations for sale in the North American and European markets. There are many safety standards to consider, for which our product must comply. Our product must consider numerous components that satisfy these standards such as the wiring, toxicity of materials, and the stability of the impeller.

Firstly, the handheld vacuum will not have any electrical components exposed, like wiring, in order to prevent any kind of shock to the user while the product is functioning. The vacuum's housing will be sealed with screws in order to prevent any exposure. The battery is designed in a way such that it can be handled without any concerns (the leads to the battery will not be exposed).

As stated previously, there are certain safety standards that must be met in order to sell our handheld vacuum. One particular safety standard that will be met is UL 1017. This standard applies to motor-operated vacuum cleaners and blower cleaners, and to household use floor finishing machines to be employed in accordance with the Canadian Electrical Code Part I (CEC), C22.1, and the National Electrical Code (NEC), ANSI/NFPA 70. The requirements cover by UL 1017 can be applied to countless vacuums like household, coin, wet, dry and in our situation, portable handheld vacuums. The construction method outlined in the Fabrication memo for our mass produced vacuum complies completely with the construction clauses present in UL 1017. Specifically, the enclosures, mechanical assembly, corrosion protection, internal wiring and interconnecting cords, and electrical insulation is all constructed according to this standard.

Tests will also be done to our handheld vacuum according to various standards to ensure that the product is ready for consumers to use. In addition to UL 1017, our product will be tested according to IEC 60312-1. These standards outline how our vacuum will be tested, including factors such as the testing conditions/environment, normal loads, leakage current, rating, temperature, severe operating conditions, resistance to moisture, stability, and physical abuse. These are just some of the tests that will be done on our handheld vacuum to ensure it complies with the clauses outlined in these standards. Performing the tests outlined in UL 1017 and IEC 60312-1 are essential to selling our product in the North American and European markets. Without performing these tests, our product could potentially put consumers in danger. Finally, another example of a standard our vacuum will meet is the Active Standard ASTM F450 developed by subcommittee: F11.30. Meeting this standard will ensure that our product is able to withstand the anticipated stresses and strains that vacuum cleaners endure during normal use. Additionally, the hoses, housing, and nozzle on our product will exceed the standards set on how much they can handle torsional flex, hot/cold flex with aging, abrasion, crushing, and stretching.

Standards are not the only thing our handheld vacuum must meet. There are many statutes that must be followed when putting any type of consumer product on the market. These laws passed by Congress serve as Consumer Product Safety Commission's (CPSC) basis for protecting the public from unreasonable risks of injury or death from thousands of types of consumer products under the agency's jurisdiction. The laws that will be followed are the Consumer Product Safety Act (CPSA), Child Safety Protection Act (CSPA), and the Federal Hazardous Substances Act (FHSA). All of these laws ensure the safety of the consumer and will be followed so that our product does not harm anyone.

In the end, these are just a few of the standards and statutes that must be followed to allow our handheld vacuum to be sold in the North American and European markets. Even though we want our product to sell very well, we have to keep safety as our number one priority.

14.0 Economic Justification

When it comes to producing a product, there are countless factors that come into play when analyzing the unit production cost. For our handheld vacuum, parts, materials, tooling, labor, and overhead (marketing, development, etc.) costs will affect how much it will cost to produce. We have performed an analysis on how much it would cost to produce a volume of 100,000 units. The two main materials that are used in our handheld vacuum are impact modified polycarbonate and impact grade nylon 66. Both the housing and the collection bin will be made out of the polycarbonate while the impeller will be made out of nylon.

Referencing www.custompartnet.com, it was found that it would cost $2 per pound to purchase the polycarbonate and $1.81 per pound for the nylon. Using this resource, our team is able to calculate the costs for using injection molding for these two materials. Our calculation factored in the quantity (100,000 units), material envelope, max wall thickness, projected area, projected holes, volume, tolerances, surface roughness, and complexity of the parts being produced through injection molding. The total cost for injection molding the housing and collection bin out of polycarbonate will be $1,083,785 ($10.838 per part). On the other hand, the total cost for injection molding the impeller out of nylon came out to be $26,674 ($0.247 per part). These total costs include the cost for the raw material, production, and tooling. More detail can be found in the bill of materials table in the appendix.

In addition to parts that are produced through tooling processes, our team factored in common off the shelf parts into the analysis. These common off the shelf parts for our handheld vacuum include a HEPA filter, screws, bolts, fasteners, and washers. It would not be efficient and would result in significant costs to custom make any of these small parts. All common off the shelf parts will be purchased through McMaster-Carr. For example we will be purchasing 10-24 type 316 stainless steel (part number 91735A240) pan head machine screws. Another example would be the 316 stainless steel general purpose washers (part number 90107A127) that we will be purchasing. See the bill of materials table in the appendix for a more accurate representation of how much it will cost to purchase the common off the shelf parts for the handheld vacuum.

Also factored into our analysis of unit production cost is labor. The labor will include the time for a worker to assemble our handheld vacuum. The labor rate used in our analysis was $45/hour. The labor for the purchased drill includes disassembly, removal of gearbox, relocation of the motor, and reassembly. The labor for the housing and collection bin involves fastening the parts to the drill housing. The impeller labor involves securing the impeller to the output shaft of the motor. Finally, labor is required to attach nuts, bolts, and washers to secure all parts. The total assembly time for each vacuum is roughly 15.67 minutes. At $45/hour, the total cost of labor per unit is roughly $11.75.

The last thing we needed to include in our unit production cost would be overhead costs. Overhead includes things such as development and marketing costs. Both development and marketing are crucial to the success of this product. Development is important because it is needed to actually design the handheld vacuum. Marketing is obviously used to promote and sell our product when it finally hits the market in North America and Europe. Accurately estimating overhead costs for a product is generally difficult. Typically overhead charges are assigned by using overhead rate (burden rates). In the end, we were able to conclude that development would cost $750,000 per quarter and marketing would cost $150,000 per quarter. More information can be found in the NPV table in the appendix.

After all of our economic analysis, our team was able to calculate the unit production cost for our handheld vacuum. It was determined that it would cost $50.10 per unit. Compared to other companies who manufacture handheld vacuums, this production cost is on the higher end. The retail price for our handheld vacuum will be $100.20. This is exactly twice the cost of manufacturing the vacuum. Our team decided on this retail price because we wanted to make a profit, but did not want to have a handheld vacuum be extremely expensive for consumers to purchase. By comparison, the Hoover PortaPowered Handheld Vacuum retails for $119.00, which shows our vacuum's retail price is not unrealistic. The vendors we would sell our vacuum to would be retail stores such as Walmart, Target, and Lowes.

Based on the NPV, it was determined that developing and producing our handheld vacuum is good investment. This can be observed by looking at the NPV table found in the appendix. Additionally, since we are retailing our handheld vacuum at twice the production cost, we will be significantly profiting on sales.

As seen in the NPV, located in the appendix, there are many inputs that have to be factored in. The inputs include development, ramp-up cost, marketing/support, production cost, and sales revenue. Development is the actual designing of the handheld vacuum. It is all of the research that is put into producing the vacuum. Ramp-up cost is the increase in production that comes after securing deals with distributors and anticipating increased demand with product's release. Marketing/support cost is the money that goes into promoting our product to consumer in order to increase sales, which will result in increased profits. Production costs factor in how much it costs to perform the injection molding for our handheld vacuum. Finally, sales revenue is what we make off of the handheld vacuum when it is in the market. For a more quantifiable view of the NPV, see the appendix.

15.0 Industrial Design

When the handheld vacuum was designed for mass production, industrial design was a very important thing to consider. Our main goal was to design a product that looks good, performs well, and is easy to use, while still making a profit. Our team considered the quality of the user interface (including safety), aesthetic appeal, ability to maintain and repair, appropriate use of resources, and product differentiation.

According to our customer needs survey/analysis, the most important aspect users look for in a handheld vacuum is functionality. Even though aesthetics was not the number one thing customers looked for in a vacuum, it is still important to consider how the final design looks. Overall, every part on the vacuum is smooth and forms nice lines. There are not any random parts sticking out of the vacuum that distract the eye or take away from the overall look. The vacuum's design includes many different circular and cylindrical parts; the geometrical motif gives the product an inviting and modern look. The vacuum needs a professional aesthetic in order to catch the consumer's eye as soon as they see it, which in turn would give in an advantage in the market.

Bad ergonomics on a handheld vacuum can actually lead to permanent injury to a consumer's hand, and could possibly lead to litigation. Our design considers various human-machine interfaces including the battery pack, vacuum cleaner handle, and the collection system. To make the handheld vacuum as efficient as possible, human-machine interfaces are limited. Fewer actions equal less work for the user, giving them more time to do other things. Additionally, fewer actions lead to an overall safer product since users will not be messing around with any important components such as wiring. The only human interface functions required are the trigger control of fan speed, fan rotation direction, removal/installation of the battery, and removal/installation of the collecting bin. Each of these actions is very simple and requires little physical effort. All moving parts are concealed within the vacuum housing, which is not only safe for the user, but advantageous for the longevity of the product. All parts that are joined together are sealed, air-tight, and reinforced so that there is a high confidence that the vacuum will not break apart. In the end, our team concluded that if you are going to buy a handheld vacuum, you want to find one that will maximize comfort, safety, and efficiency.

The vacuum cleaner is designed so that the rechargeable battery can be removed by simply holding down a button and sliding the entire battery away from the vacuum. From there, all users have to do is plug the charger into the battery, and connect everything to an electrical source via an outlet. No parts of the vacuum need to be moved to access the power source, making the usability of our vacuum much better. Also, turning the vacuum on and off is easy to do by simply flipping a switch.

The handle of the vacuum is comfortable a sized so that users have good grip. The average hand size for males and females respectively are 7.4 and 6.77 inches (http://www.theaveragebody.com/average_hand_size.php referenced). Our drill was designed to guarantee the average user can use our product. Furthermore, there will be padding on the handle to help with comfort and to dampen vibrations users feel in there hand. This padding will be textured/shaped so that your fingers fit in a particular position, allowing greater control of the vacuum. Finally, the overall weight of our product will be light enough so that the average consumer can easily hold it up. The average male and female has hand strength of 137 and 81 lb. respectively. Our team ensured that our handheld vacuum could be lifted by someone with hand strength of 60lb, which mean the average consumer will easily be able to use our product.

16.0 Final Prototype and Evaluation

Materials Used
All materials used for the final prototype can be found in the Learning Factory on Penn State's campus or at Lowes. The main materials used for the final prototype are PVC, acrylic, high density polyethylene (HDPE), and PLA plastic. The entire drill housing and its motor are used in the final prototype, with the exception of the LED and gearbox.

The housing (main body) of the handheld vacuum is made out of a 2 inch PVC pipe, 2 to 3 inch adaptor, and a 4 inch diameter acrylic plate. The fabricated nozzle utilizes both PVC and PLA plastic printed on the Reber Makerbot. Our collection bin is made out of the HDPE plastic from the chocolate milk bottles you can find in any one of the convenient stores located on Penn State's campus. Lastly, the impeller was fabricated using the dimension printer's plastic, located in the Learning Factory. A better view of the materials used in our final prototype can be found in the appendix.

Construction Process
Overall, assembling our entire final prototype was challenging, however it was very rewarding in the end, constructing a fully functional handheld vacuum cleaner. The very first thing we had to do to construct our final prototype is fabricate our final design for our impeller. The impeller was modeled after an actual impeller that can be found in the Dirt Devil handheld vacuum. Once our team had the impeller modeled in Solidworks, an .stl file was submitted to the Learning Factory to be printed on the dimension printer. Our team concluded that the dimension printer would be the best option available to us because the Makerbot's print quality is not very good and the object printer would be too expensive to use. Our impeller cost our team exactly $14.80 to fabricate. With our impeller in hand, we attached it to the gear on the motor of the drill. Our impeller was designed to have a perfect interference, press fit with the gear (see the impeller figure in the appendix).

Before assembling any other components, everything was spray painted a glossy white in order to have an aesthetic appeal for consumers. The next step in the construction process was to build the housing of the handheld vacuum. In order to attach the adapter to the drill, we created an acrylic disc that fit around the drill housing and was secured using hot glue. The acrylic disc has the exact same diameter as the 2 to 3 inch adapter, which can be seen in the figures located in the appendix. Since our planned housing and nozzle were going to be a little heavy, our team laser cut acrylic support "beams" to help minimize the stress the hot glue would experience (see "Exhaust Holes with Impeller figure in the appendix). Prior to attaching the adapter to the acrylic disc, six, 0.5 inch exhaust holes (created using the drill press) were drilled (three on each side and symmetrical). A 4.5 inch long, 2 inch diameter PVC pipe was inserted into the adapter to complete the housing. A wire mesh was utilized as our filter and place on the end that would be attached to the adapter. The filter is in a dome shape and is attached using hot glue. At the bottom of the 2 inch PVC pipe is a 1 inch hole (created using a center drill), where the collection bin is connected to via an industrial 3M adhesive spray. The collection bin is a simple bottle with a hole in its cap for the rice to fall into (see figure of collection bin in the appendix below).

Finally, the last step in our construction process was attaching the entire nozzle to the housing. The nozzle comprises of a 2 to 1.5 inch adapter, 1.5 inch diameter PVC pipe, and a 3D printed nozzle. The 3D printed nozzle was printed with the exact same diameter as the PVC pipe in order to have the two components sit flush with each other and be hot glued together. The PVC and 3D printed components are then inserted into the adapter which is then attached to the rest of the housing. This final attachment concluded the construction of our handheld vacuum. An image of the final prototype assembled can be found in the appendix.

Differences from First Prototype

There are countless differences between our final prototype and our first two alpha prototypes. The one thing that did not change was the overall design for our impeller. To start off, the main difference is the materials used. In our first alpha prototype, all materials used were PLA plastic. The components were all printed using the Reber Makerbot. Our first prototype was not functional at all, or even truly assembled. Our goal for the first prototype was to get a sense of how our vacuum would look structurally. In the end, the design for the first alpha prototype was not used.

The second alpha prototype was also significantly different than our final prototype. Even though the second alpha prototype was functional, it was not a very viable solution since it was constructed out of a Gatorade bottle and a small PVC pipe as our "nozzle." The entire Gatorade model was the housing of our handheld vacuum. It was attached to the drill by cutting out the bottom of the bottle and slipping it over the drill. We were very lucky that the hole we cut and duct tape used made an airtight seal, allowing the impeller to function correctly. The collection bin and the filter were the only components that stayed the same from our second alpha prototype to our final prototype. In the end, there was no way that our second prototype could have been close to our final prototype since it was a fragile setup overall. Using sturdier material, like PVC, for our final design instead, proved to be the smart choice in constructing a functional handheld vacuum.

Prototype Positives and Negatives

For measured results, please refer to the future memo title "Performance." There are many things that worked well for our final prototype, but they were of course accompanied by some things that did not. The one thing our team agreed on that worked the best was our impeller. From the start, we knew we wanted to design an impeller that was modeled after an actual impeller found in handheld vacuums. Our team went for a simple design that proved to be very effective. Nothing fancy was needed for our impeller to function correctly. Our design for the impeller worked out perfectly because our final prototype supplies more suction than what is needed. Additionally, in combination with our impeller, the nozzle turned out to work great. Our nozzle design allows our handheld vacuum to pick up rice at a very high velocity. It was so effective, that grains of rice would actually hit our filter so fast that they would break up in to tinier pieces. Finally, as can be seen in the "Construction Process" section above, our team used hot glue many times. Hot glued proved to be a great sealant and adhesive.

Unfortunately, with our design, the housing and nozzle contributed to a lot of the weight that the acrylic disc would feel. Since we were using hot glue as our adhesive, we were worried about the shear forces from the weight ripping the housing off of the acrylic disc. We had to cut down the lengths (by cutting the PVC pipes) of our housing and nozzle significantly. Additionally, a last moment decision made was to add 8 support pieces made out of acrylic (see the Exhaust Holes and Impeller figure in the appendix). These 8 support components take away from our aesthetic appeal, and make the vacuum not look as sleek as it did before. All of the weight from the nozzle and housing also causes consumers to use two hands when handling the vacuum. Another negative is that when removing the battery from the drill, users must be careful of how they remove it. If a user isn't paying attention, they could accidentally hit the collection bin with the battery. This by all means does not mean it is difficult to remove the battery because there is plenty of clearance.

Plan of Improvement

Even though this is our final prototype for our project, there is always room for improvement. The main thing our team would focus on is the attachment of the housing to the drill. All other components such as the impeller, nozzle, and collection bin would stay the same. Our plan would be to laser cut the acrylic disc (that still fits over the drill) with a smaller diameter. We would make this diameter just small enough so that there would be a tight interference fit between the 2 to 3 inch adapter and the acrylic disc. This tight interference would create an airtight seal, all while avoiding the use of hot glue to be the adhesive to hold everything up. The interference fit would be much more resistant to shear forces caused by the weight of the housing than hot glue. Additionally, this interference fit would make the overall look of our handheld vacuum much more aesthetically pleasing, especially with the removal of the 8 support components.

Finally, once this next prototype was created and proved to function just as well, if not better, than our current final prototype, we would move on to mass production stage. This of course would be a huge step and much more research would have to be done. Most of the research would go into injection molding and the types of materials that the final product would use.

17.0 Performance

When it comes to performance, our team concluded that our final prototype for the handheld vacuum exceeds every minimum requirement necessary to suck up the rice. Experimental evaluation was performed in order to prove the airflow and stagnation vacuum pressure are sufficient to accomplish our goal of sucking up rice. Research showed the minimal air flow and vacuum pressure of a handheld vacuum are 1.87 cu. m/min and 10.0 kPa, respectively. After finishing construction at the Learning Factory, our team ran the vacuum while inspecting it for leaks. After determining it was airtight, we then ran a test with approximately one cup of rice; it picked the rice up quickly, indicating flow rate and pressure well above the minimum (see the appendix for a image taken from testing). Exact measurements can be taken using the tools available to us in the Learning Factory. A flow meter is used to measure the flow rate of air intake under free operating conditions. The stagnation pressure of the vacuum when the intake is blocked can be measured using a vacuum gage or manometer. Furthermore, no rice passed the vacuum's filter and exited the exhaust, another aspect of a marketable handheld vacuum cleaner to which our team complied.

To assess the performance of our design, one of our team members will use our vacuum to collect uncooked white rice. This will occur in a direct competition against the other teams in our class. Performance will be measured by the amount of rice collected in a certain amount of time. Uncooked white rice will be poured onto a table. One of our team members will operate our vacuum. At a verbal signal from a judge, we will activate our vacuum and the rice will be collected. Each test will be timed with a manual stopwatch to provide a quantitative performance metric. At the end of each 10-second test, the rice must be poured into a cup to demonstrate emptying the collection system. At the end of each 10-second test, the rice must be poured into a cup to demonstrate emptying the collection system. The rice will then be weighed to determine the amount collected. If our vacuum collects the most rice in our section, we will advance to compete against prototypes from the other class sections. If any rice exits through the exhaust, we will be disqualified and our prototype will be judged as unsafe. Adherence to competition constraints will be judged by the Rules Committee consisting of an elected member from each team. Non-compliance will result in disqualification.

Our final prototype is able to successfully function, will keeping in mind all of the design constraints put on us. The vacuum is cordless and handheld. Also, the original NiCd battery pack, battery pack connector, and the same DC electric motor from the 18V cordless drill is still used. No components in our final prototype were cannibalized from an existing vacuum. Additionally, our handheld vacuum contains two components that have been fabricated by using rapid prototyping. Our team was limited to a $30 reimbursement for all materials and components purchased through either McMaster-Carr or Jameco. Unfortunately, some personal money was spent on two adapters for our final prototype because by the time we put our order in through one of the suppliers, it would have been too late. On top of the $30 for components and materials, we were allotted $24 for 3D printing. Our final impeller design required that we spend $14.80 to use a dimension printer. All other items such as nuts and bolts, washers, common fasteners, etc. were obtained from the MNE Instrument Room in 23 Reber and the Learning Factory.

18.0 Final Poster Presentation

19.0 Appendix

What is your gender?

Female	25	58%
Male	18	42%
Other	0	0%

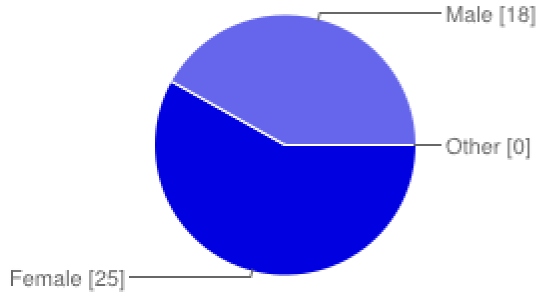

Figure 1: Gender Breakdown

How often do you use a handheld vacuum cleaner?

Daily	3	7%
At least once a week	14	33%
At least once a month	8	19%
At least once a year	4	9%
Never	14	33%

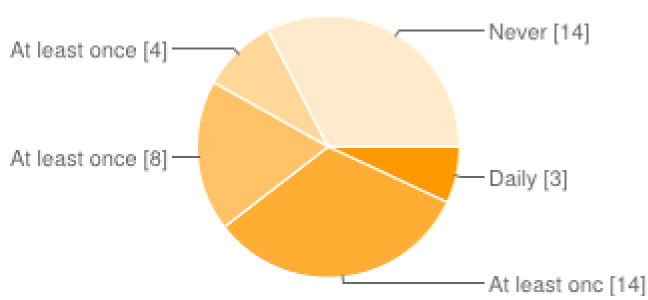

Figure 2: Breakdown of How Often Product Is Used

What is most important to you when purchasing a handheld vacuum cleaner?

Price	3	7 %
Ease of use	6	14 %
Aesthetic appeal	0	0 %
Functionality	33	77 %
Other	1	2 %

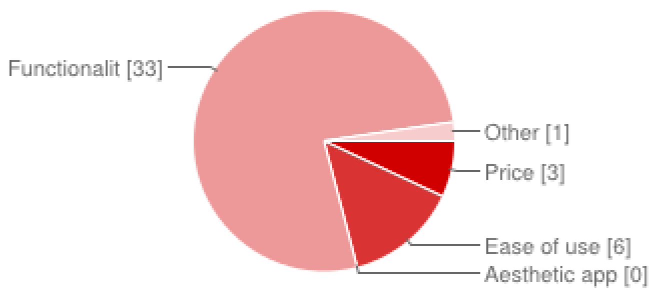

Figure 3: Breakdown of What Customers Want

Table 1: Survey Responses

What is your age?	What is your gender?	What is your occupation?	How often do you use a handheld vacuum cleaner?	What is most important to you when purchasing a handheld vacuum cleaner?	Are there any particular features you wish a handheld vacuum had?
21	Male	Student	At least once a week	Functionality	None
20	Female	Student	At least once a week	Functionality	None
20	Male	student	At least once a year	Ease of use	no wires!
26	Male	Student	Never	Functionality	A detachable container that I can easily remove to dispose of the stuff I vacuum up and then reattach it to the handheld vacuum. Easy to change filters would be nice too.
55	Female	Yoga instructor	At least once a week	Functionality	Good performance
20	Male	Student	Never	Functionality	None
26	Male	Student	Never	Functionality	None

20	Female	Student	Never	Price	None
20	Female	Student	At least once a week	Functionality	None
22	Male	Student	At least once a month	Functionality	None
20	Female	Student	Never	Price	None
55	Female	Stay home mother	At least once a week	Functionality	Make sure it is reliable
19	Female	Student	Daily	Functionality	Quickness of sucking
20	Male	Student	At least once a week	Functionality	None
34	Female	mother	Daily	Functionality	Simple to work
26	Female	student	Never	Functionality	It doesn't break easily
28	Female	Student	At least once a week	Functionality	None
20	Female	Student	At least once a month	Functionality	None
21	Female	Student	At least once a month	Ease of use	
22	Female	Student	At least once a month	Ease of use	None
21	Female	student	Never	Functionality	it would be nice if it had an attachment for getting into small crevices for dusting purposes
30	Male	Engineer	At least once a month	Functionality	Make sure the battery lasts
21	Male	Student	Daily	Functionality	None
21	Male	Student	At least once a year	Ease of use	If you watch Archer and know why he hates robots, then a solution to this problem.
21	Female	Student	At least once a week	Functionality	None
33	Female	Engineer	At least once a week	Functionality	none
27	Male	Accountant	At least once a month	Functionality	None
21	Male	Student	Never	Functionality	Reliability
19	Male	student	Never	Ease of use	Make sure it works
19	Male	Student	At least once a year	Functionality	none
18	Female	Student	At least once a week	Functionality	None
20	Female	Student	Never	Functionality	None
21	Male	student	Never	Functionality	none

21	Male	Student	Never	Functionality	I would like for it to be able to last a while, without losing and suction.
20	Female	Student	Never	Functionality	None
20	Female	Student	At least once a week	Functionality	An attachment to get dog hair off of blankets/furniture.
20	Female	Retail	At least once a month	Functionality	None
22	Female	Student	At least once a year	Ease of use	none
31	Female	Lawyer	At least once a month	Price	The vacuum should last a while before being replaced
29	Male	Engineer	Never	Functionality	None
55	Female	nurse	At least once a week	Functionality	good suction and lightweight
38	Female	N/A (Mother)	At least once a week	Quietness	None
25	Male	Student	At least once a week	Functionality	It would be nice if it was quiet

Table 2: AHP

Features Comparison (AHP)

Criteria	Aesthetics	Cost	Ease of Use	Functionality	Weight	***Total***	***Weighted***
Aesthetics	1.00	0.17	0.20	0.11	0.50	1.98	0.0344
Cost	6.00	1.00	0.33	0.14	0.50	7.98	0.1386
Ease of Use	5.00	3.00	1.00	0.25	0.20	9.45	0.1642
Functionality	9.00	7.00	4.00	1.00	7.00	28.00	0.4866
Weight	2.00	2.00	5.00	0.14	1.00	10.14	0.1763
					Σ	57.55	1

Design Alternative 1

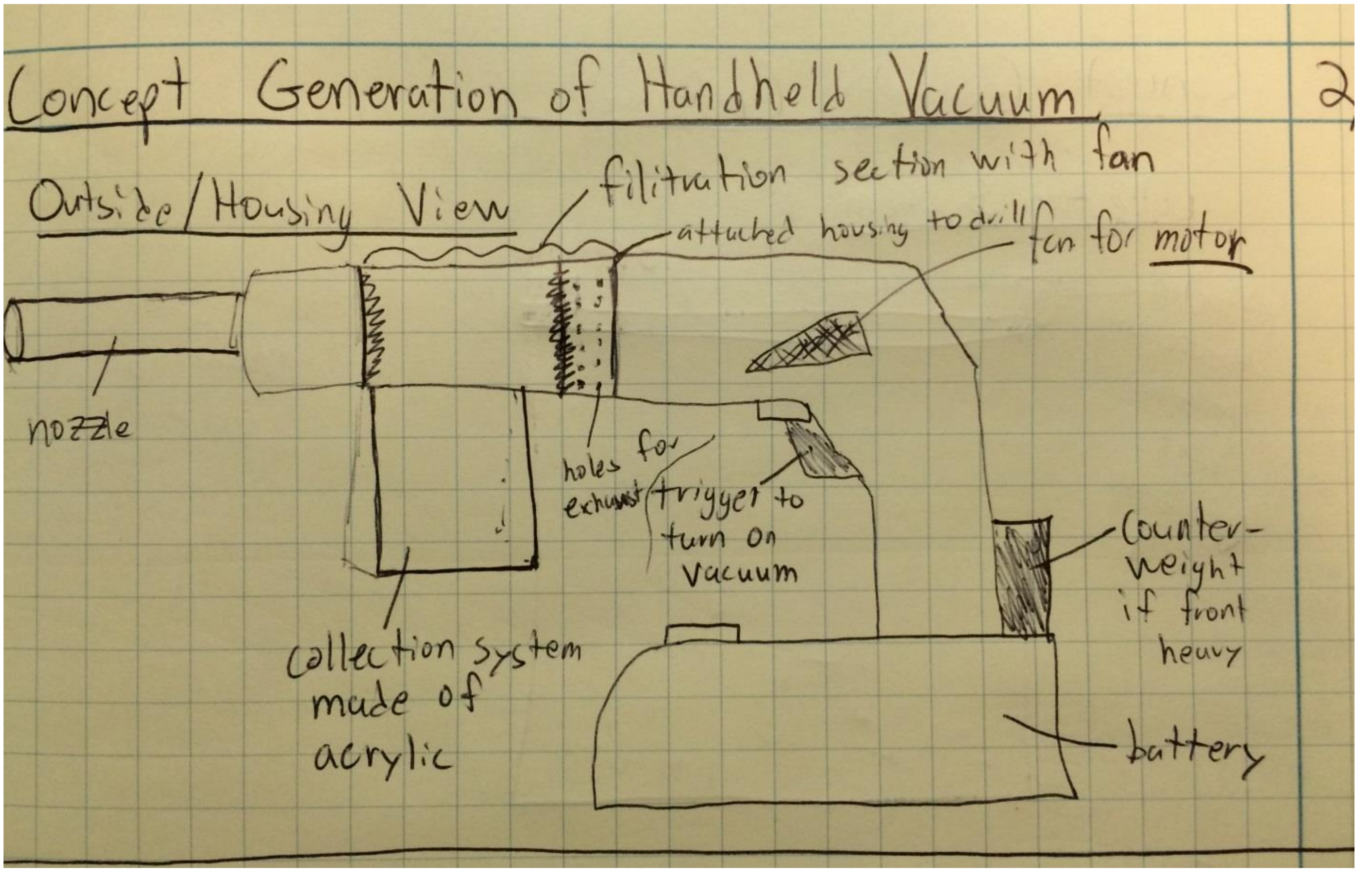

Figure 4: Design Alternative 1

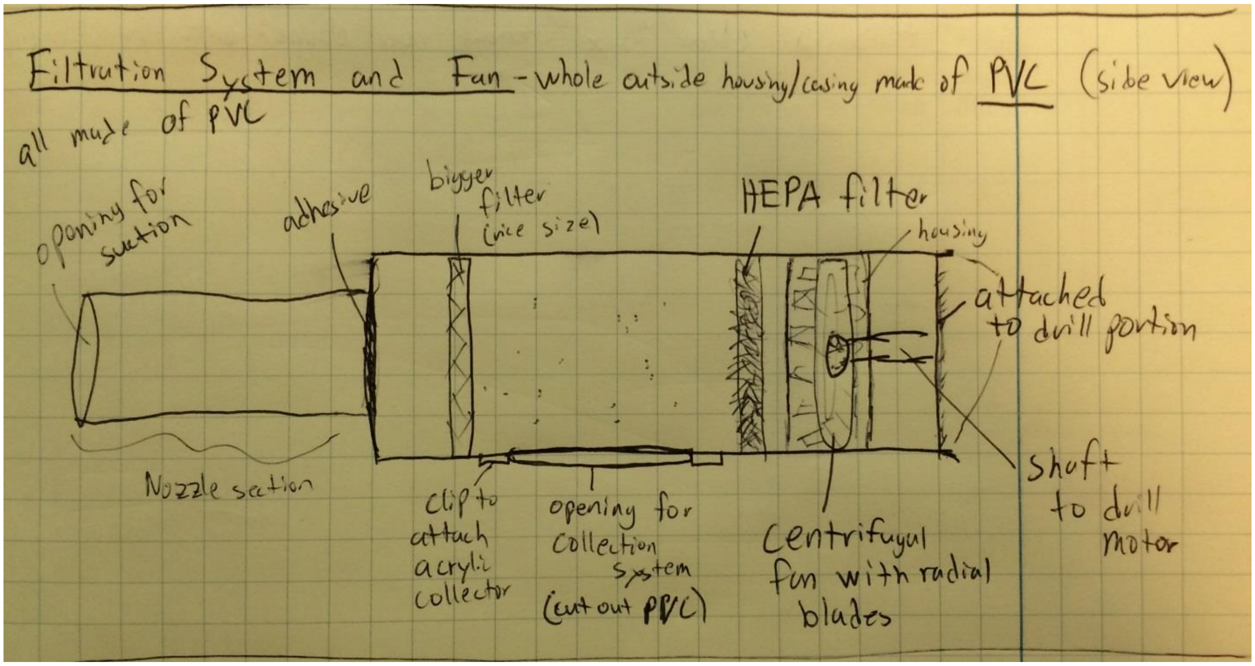

Figure 5: Filtration System and Fan Housing

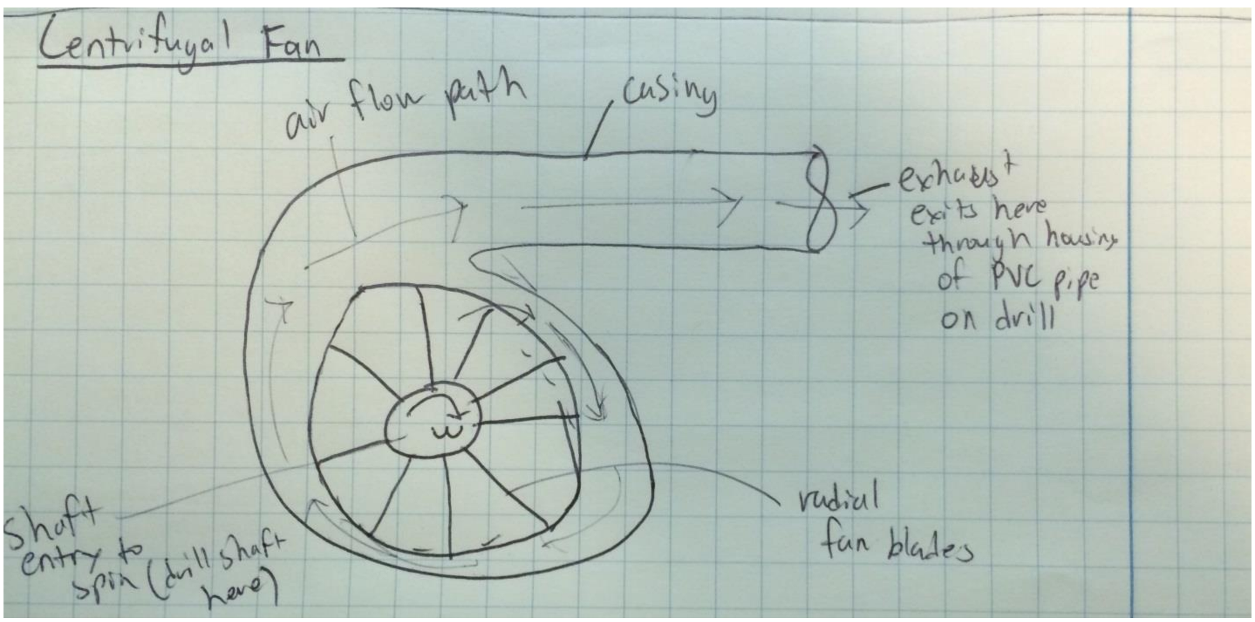

Figure 6: Centrifugal Fan

Design Alternative 2

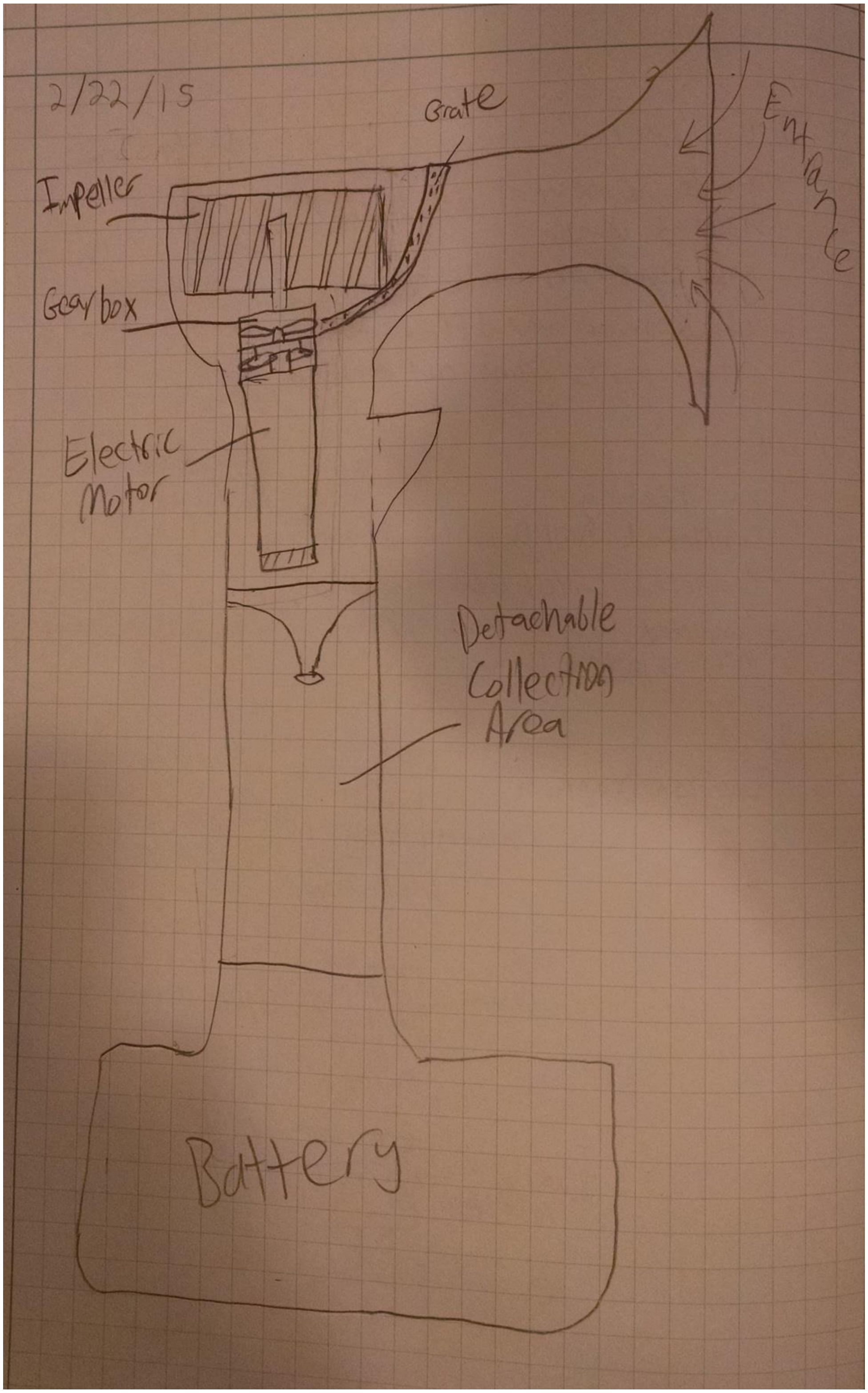

Figure 7: Design Alternative 2

Design Alternative 3

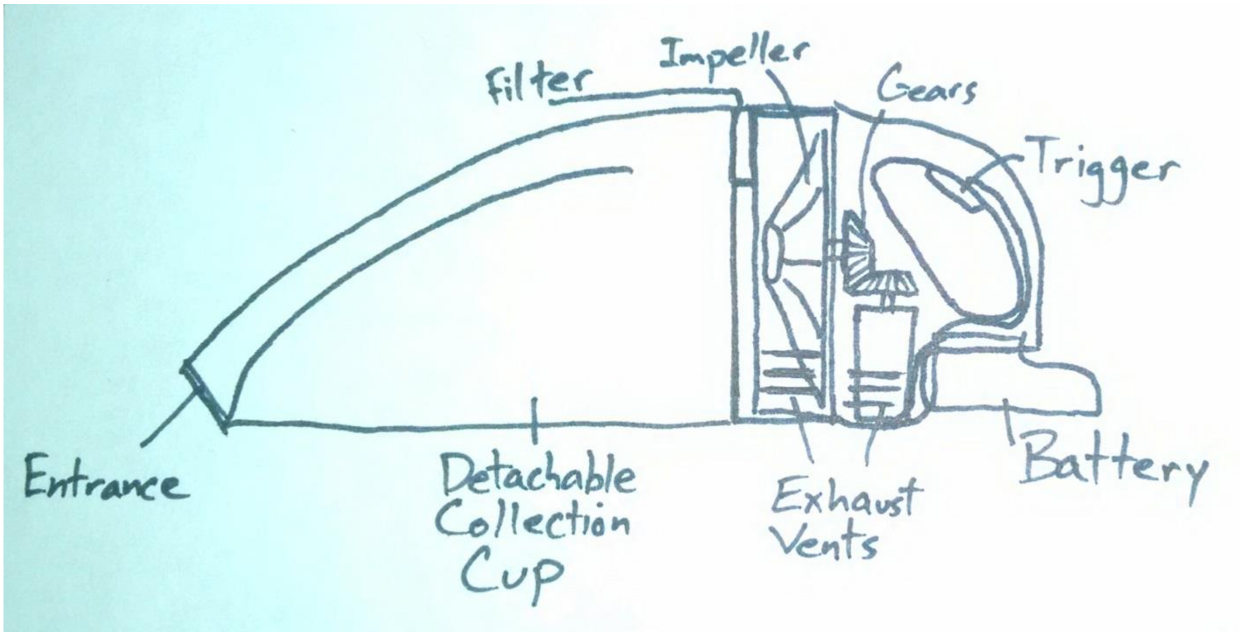

Figure 8: Design Alternative 3

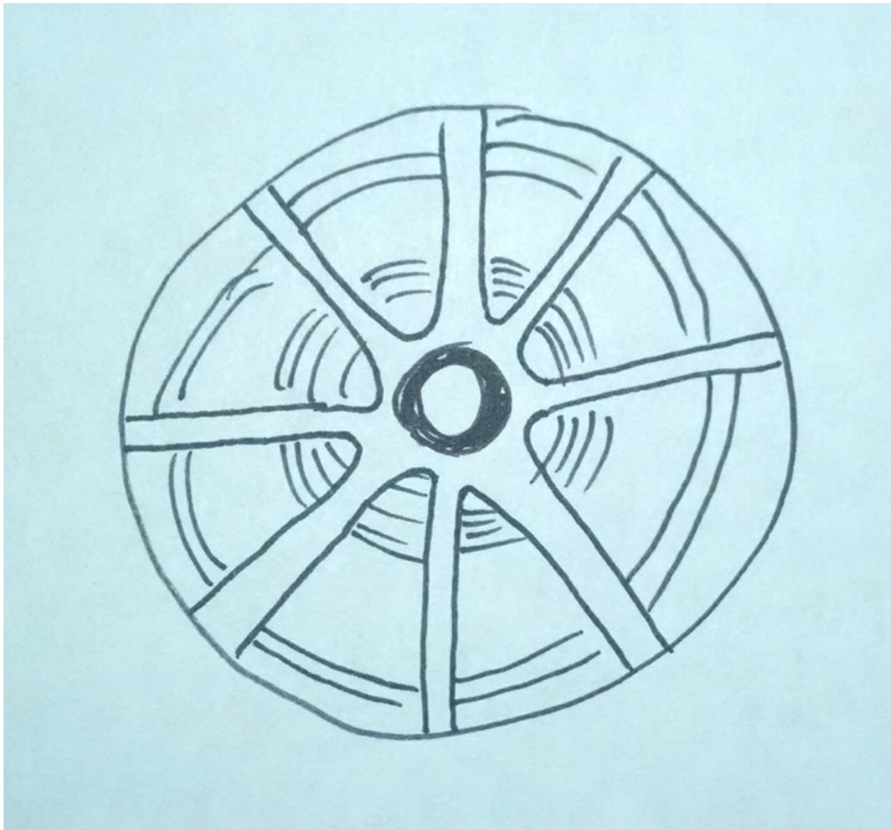

Figure 9: Impeller

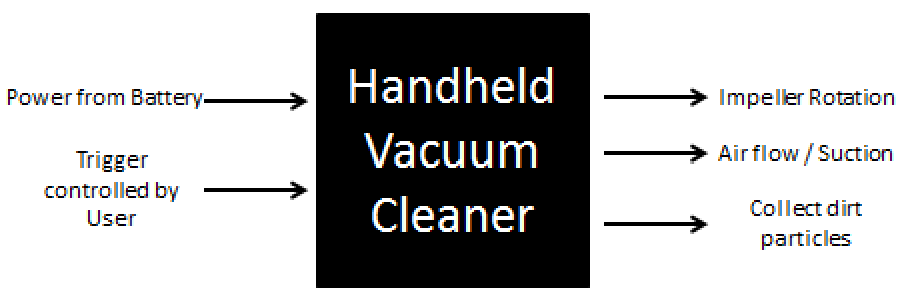

Figure 10: Black Box Diagram

Table 3: Post-It-Note Concept Generation

Concept Generation						
Collection System	**Attachments**	**Handle Design**	**Battery**	**Type of Vacuum**	**Usability**	**Filtration**
*Clear dust-collecting cup to see when it is at capacity	Narrow nozzle feature for corners and other hard to reach places	*Trigger mounted on handle of vacuum	Voltage and current sensor to determine remaining charge	*Impeller and HEPA filter combo which allows contents to be dumped in a connected bag	*Organization of internal wiring in housing	*Dual filter zone separating fan from contents (debris is collected in middle zone between filters)
*Detachable dirt container	Brush attachment for different surfaces	Handle for carrying the vacuum	Battery indicator	Bagless	*Counterweight (needed if the vacuum is front heavy)	*Multi-stage filitration
		Power switch on the handle		Cyclonic vacuum		
**These are the concepts that received votes*						

Table 4: Impeller Decision Matrix

Criteria	Design 1	Design 2	Design 3
Ease of Production	0	0	0
Predicted Cost	0	0	-1
Maintenance	0	-1	0
Durability	0	0	0
Effectiveness	1	0	0
Total	1	-1	-1

Table 5: Collection System Decision Matrix

Collection System

	Design 1	Design 2	Design 3
Criteria			
Ease of production	0	0	0
Cost	1	1	1
Maintenance	0	0	-1
Capacity	-1	-1	1
Weight	0	0	0
Totals	**0**	**0**	**1**

Table 6: Filtration System Decision Matrix

Filtration System			
	Design 1	**Design 2**	**Design 3**
Criteria			
Ease of Production	-1	0	0
Predicted Cost	-1	0	1
Maintenance	-1	0	1
Ease of Flow	-1	1	0
Longevity	0	0	0
Total	-4	1	2

Table 7: AHP Method

Criteria	Assembly	Cost	Weight	Aesthetics	Fan	Filter	Collection	***Total***	***Weighted***
Ease of Assembly		3.00	4.00	5.00	0.25	0.50	0.50	13.25	0.176236
Cost	0.33		3.00	5.00	0.25	0.33	1.00	9.92	0.1319
Weight	0.25	0.33		2.00	0.25	0.50	0.50	3.83	0.050986
Aesthetics	0.20	0.20	0.50		0.20	0.25	0.25	1.60	0.021281
Fan	4.00	4.00	4.00	5.00		3.00	4.00	24.00	0.31922
Filter	2.00	3.00	2.00	4.00	0.33		1.00	12.33	0.164043
Collection	2.00	1.00	2.00	4.00	0.25	1.00		10.25	0.136333
							Σ	75.18	1

Table 8: Overall Configuration

Criteria	Weight	Design 1 Rating	Design 1 Weighted Score	Design 2 Rating	Design 2 Weighted Score	Design 3 Rating	Design 3 Weighted Score
Ease of Assembly	0.176	4	0.705	3	0.529	2	0.352
Cost	0.132	3	0.396	3	0.396	2	0.264
Weight	0.051	3	0.153	3	0.153	3	0.153
Aesthetics	0.021	3	0.064	3	0.064	5	0.106
Fan	0.319	4	1.277	3	0.958	3	0.958
Filter	0.164	2	0.328	4	0.656	5	0.820
Collection	0.136	3	0.409	3	0.409	4	0.545
	Score	3.331		3.164		3.199	
	Rank	**1**		3		2	

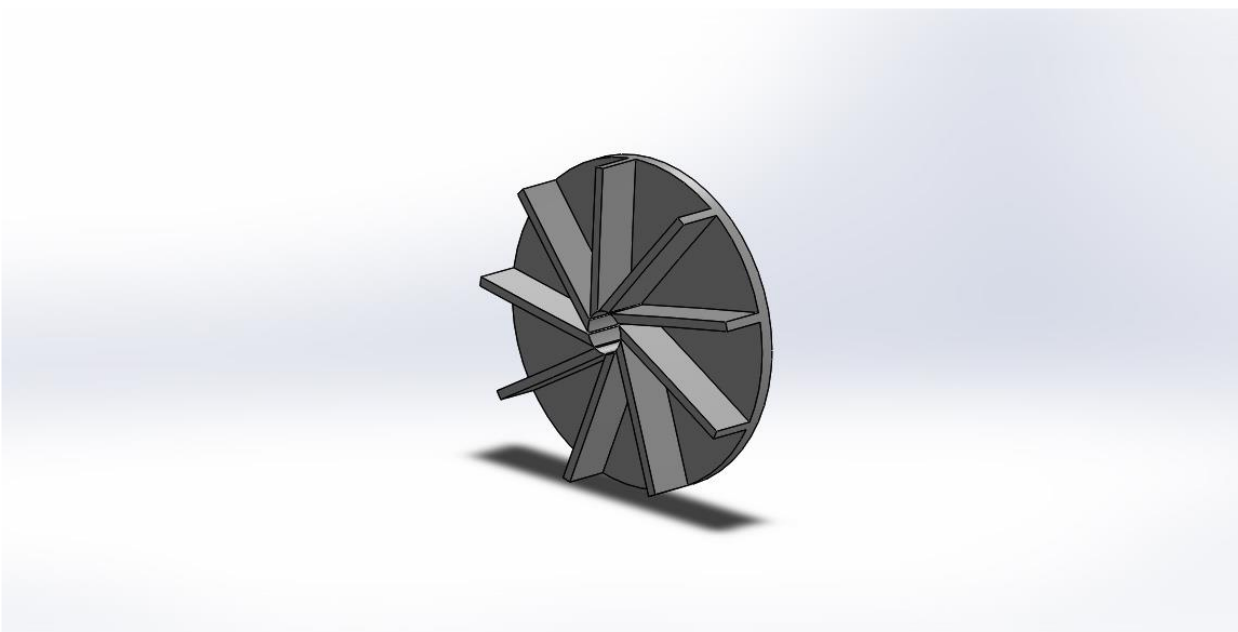

Figure 11: Centrifugal Fan

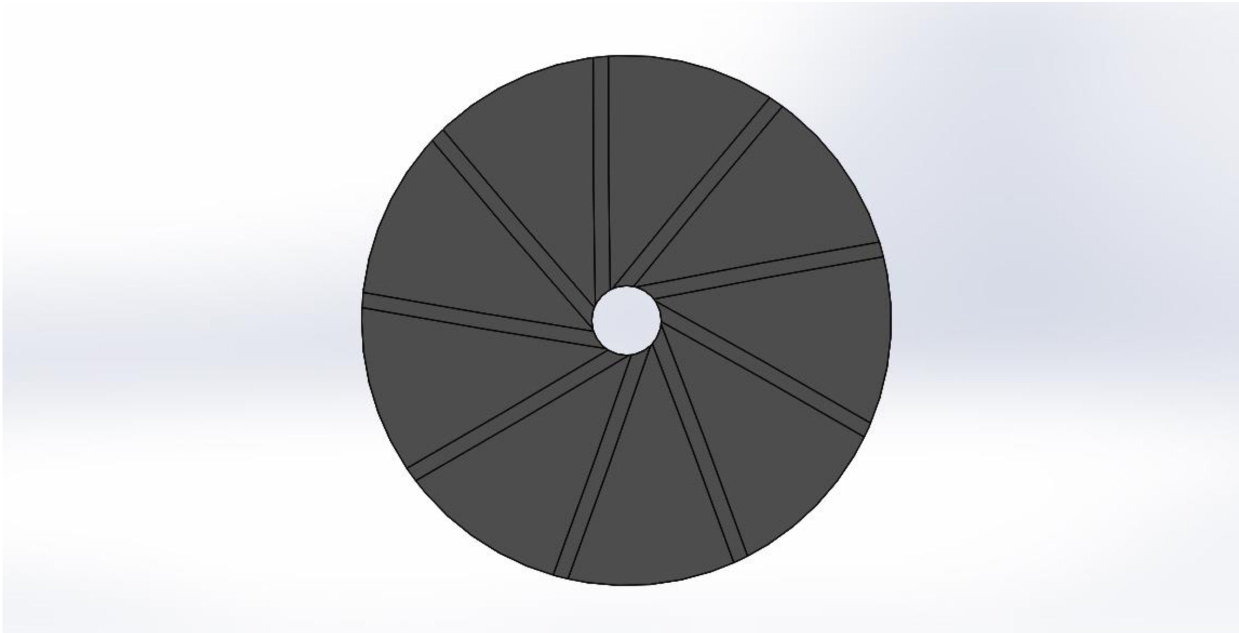

Figure 12: Centrifugal Fan Front View

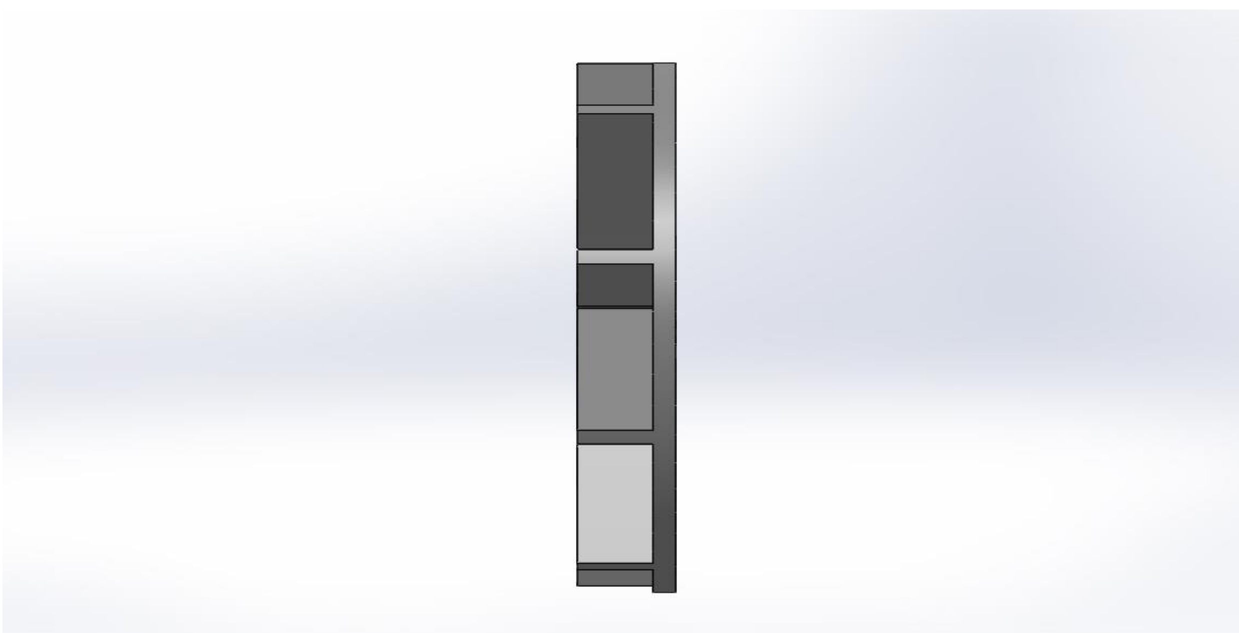

Figure 13: Centrifugal Fan Side View

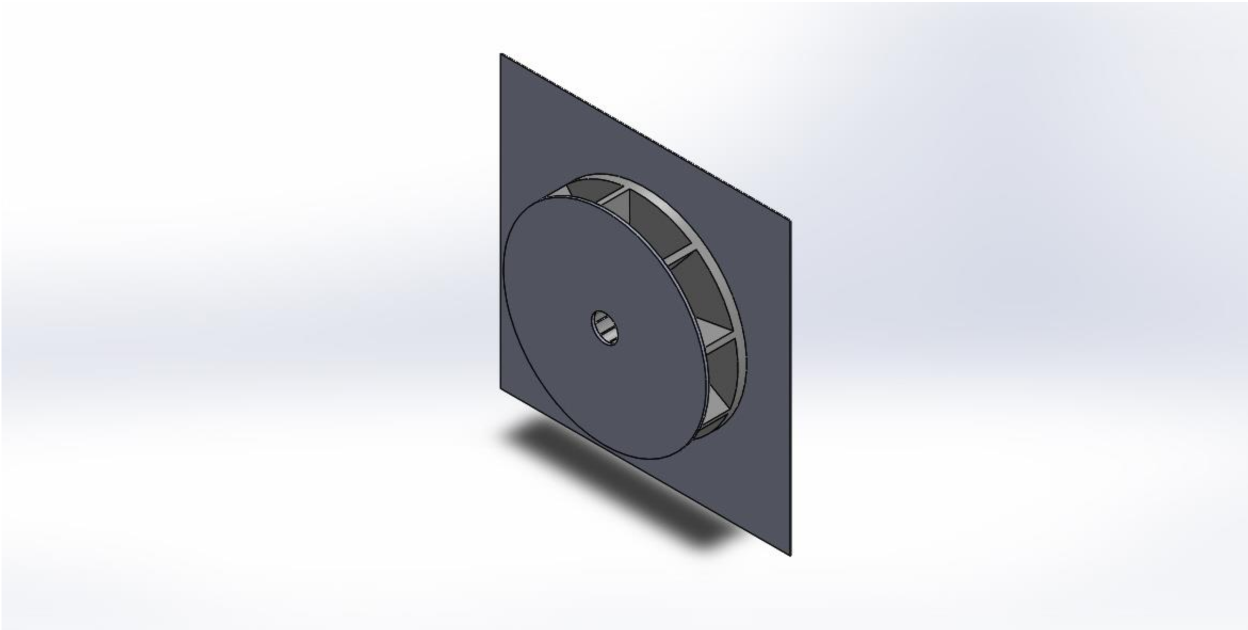

Figure 14: Assembled Fan and Fan Housing

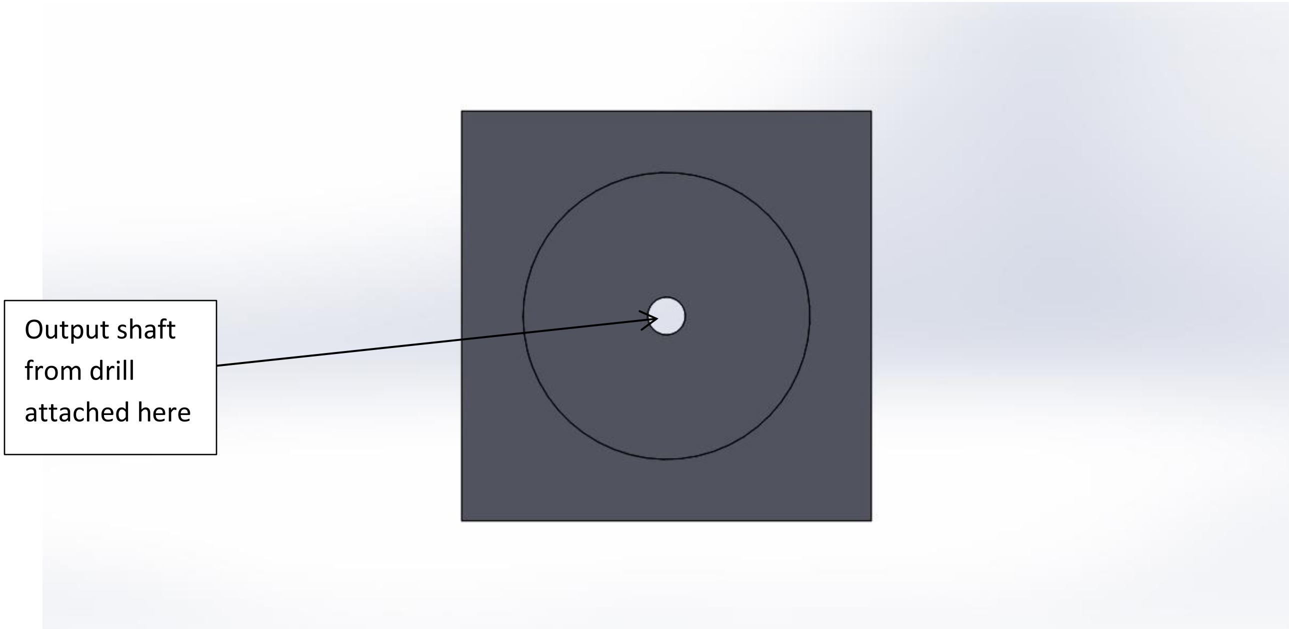

Figure 15: Assembled Fan and Fan Housing Front View

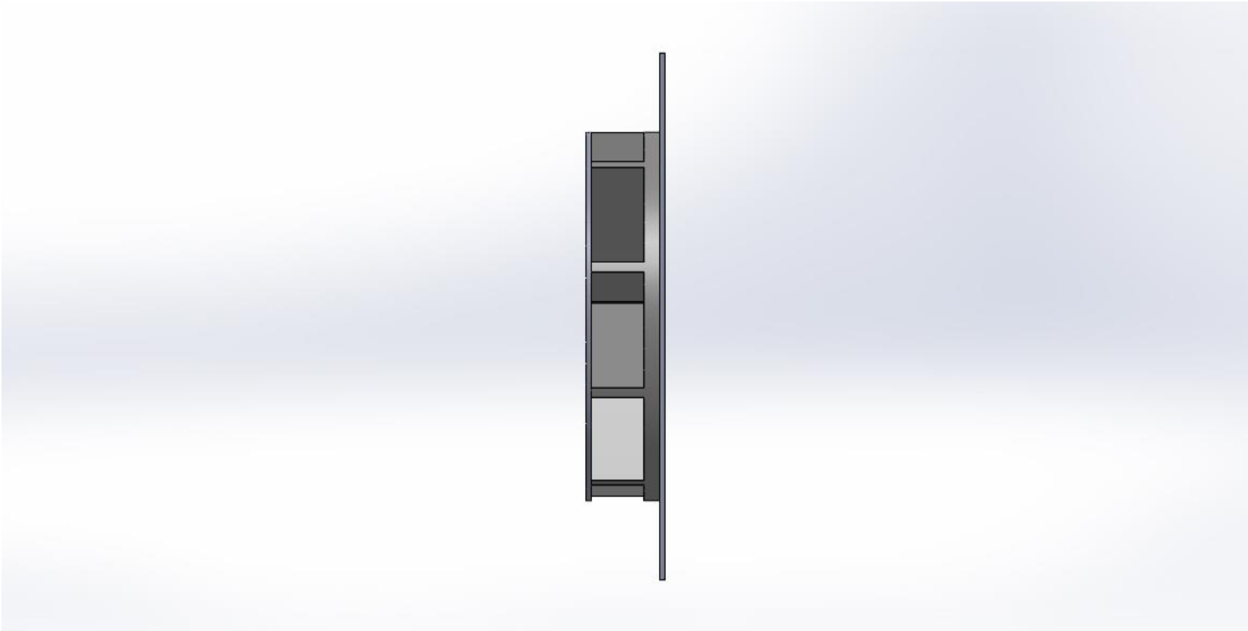

Figure 16: Assembled Fan and Fan Housing Side View

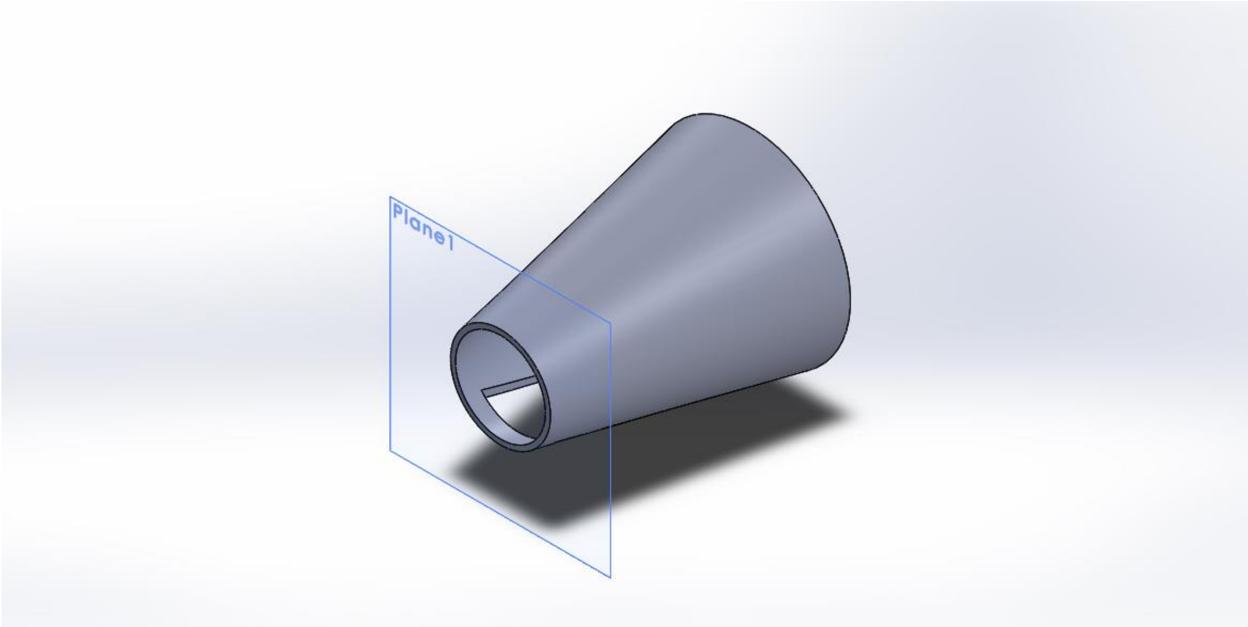

Figure 17: Housing

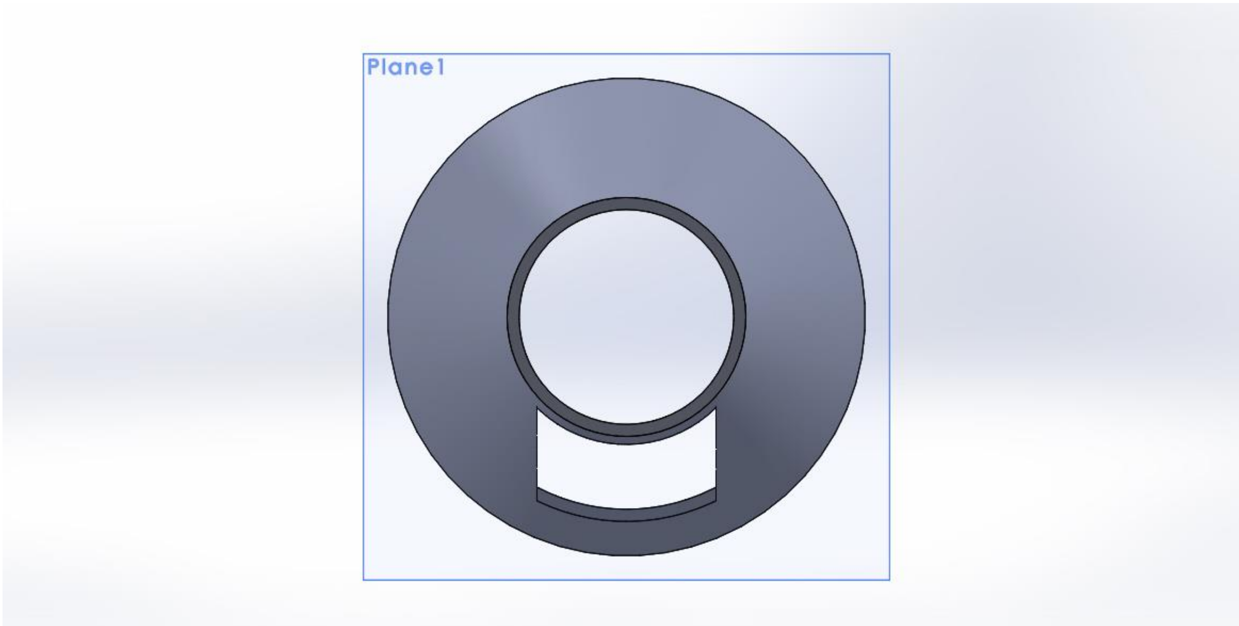

Figure 18: Housing Front View

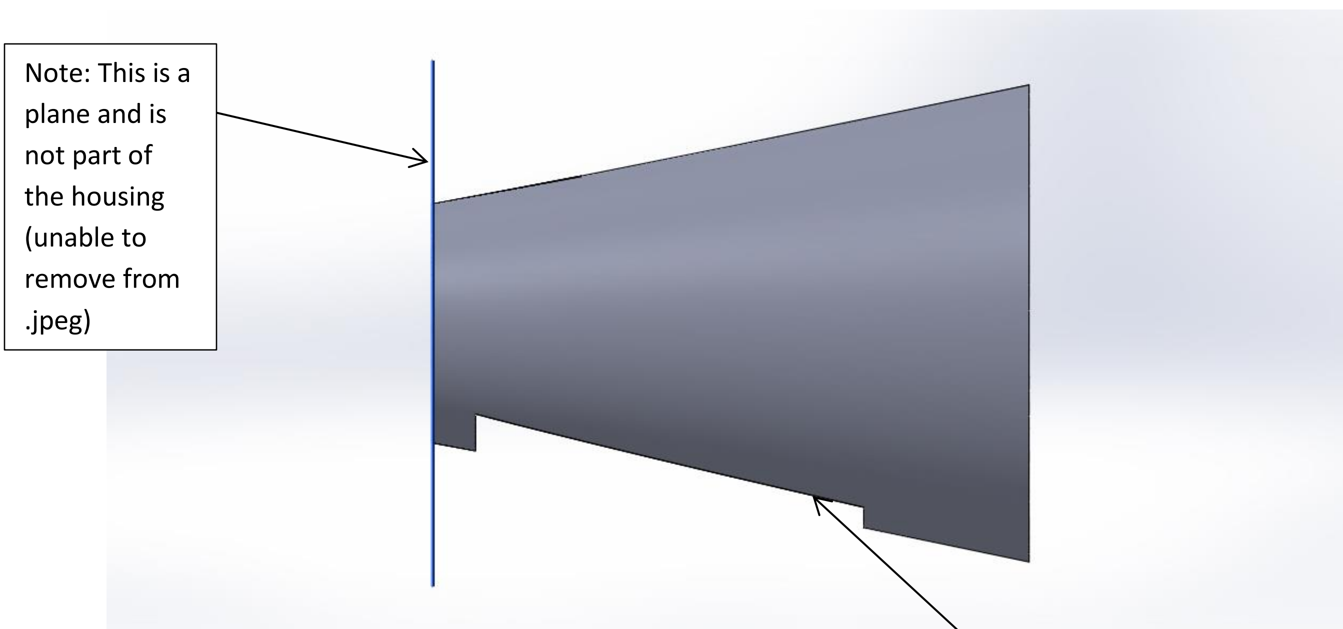

Figure 19: Housing Side View

Figure 20: Housing Back View

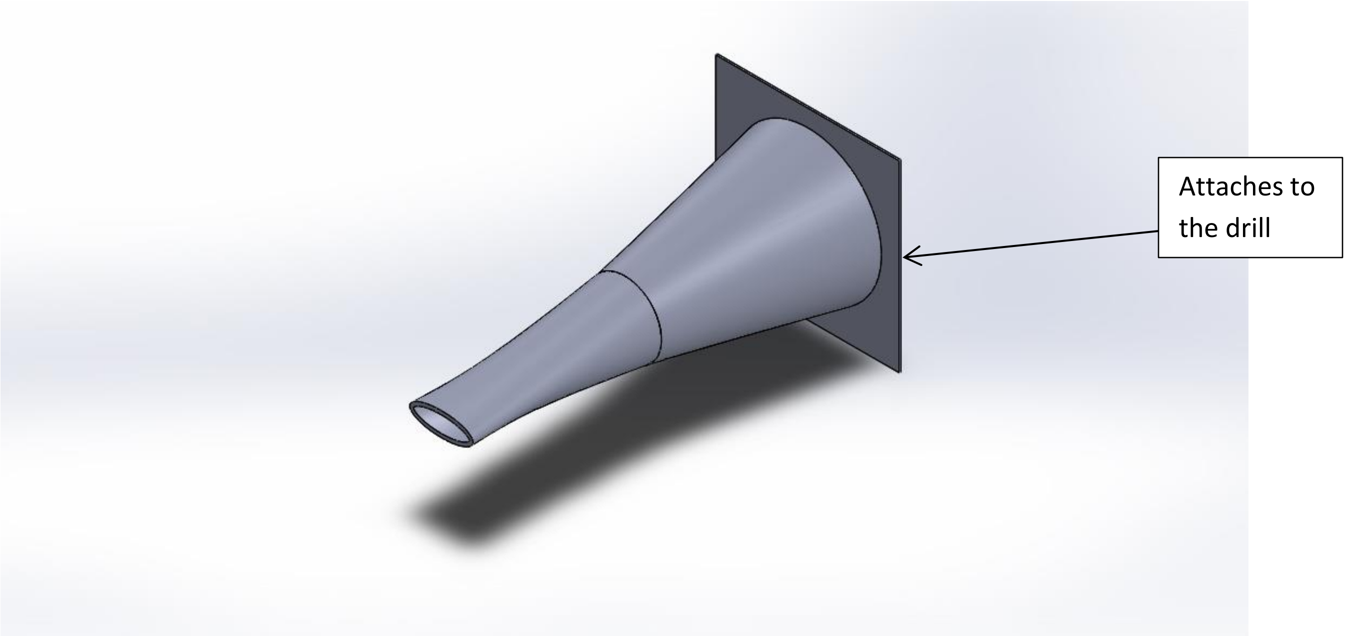

Figure 21: Final Assembly

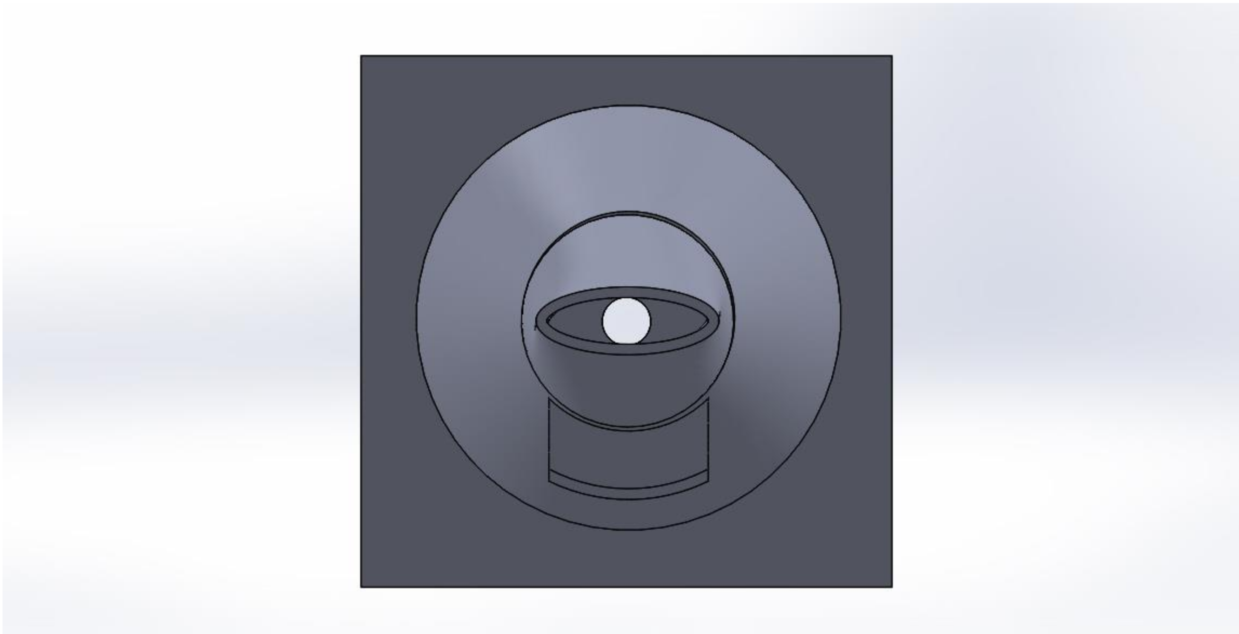

Figure 22: Final Assembly Front View

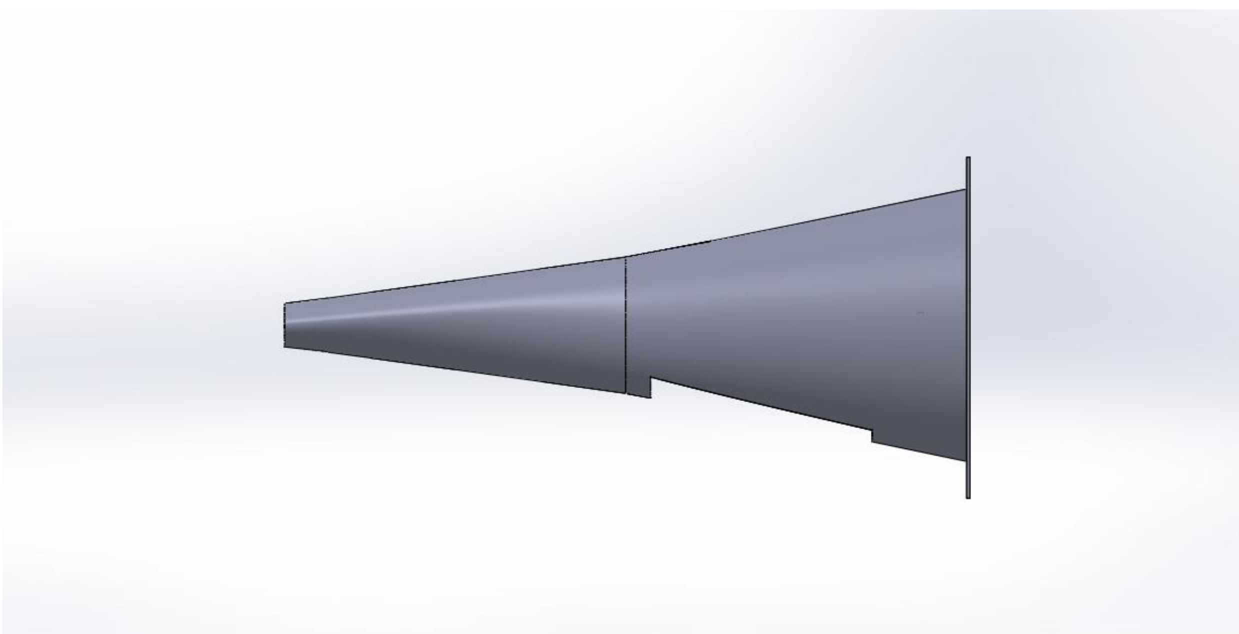

Figure 23: Final Assembly Side View

Figure 24: Final Assembly Top View

Figure 25: Final Assembly Bottom View

Table 9: Calculation Results

η_f	Air Velocity (ft/min)			Flow Rate (Q) ft^3/min (correspond to respective air velocity)			Flow Rate (Q) m^3/s			Inlet Diameter (ft)
1	4000	5000	6000	5.454153912	6.817692391	8.181230869	0.002574074	0.003217592	0.003861111	0.041666667
	4000	5000	6000	21.81661565	27.27076956	32.72492347	0.010296296	0.01287037	0.015444444	0.083333333
	4000	5000	6000	49.08738521	61.35923152	73.63107782	0.023166666	0.028958332	0.034749999	0.125
0.9	4000	5000	6000	5.454153912	6.817692391	8.181230869	0.002574074	0.003217592	0.003861111	0.041666667
	4000	5000	6000	21.81661565	27.27076956	32.72492347	0.010296296	0.01287037	0.015444444	0.083333333
	4000	5000	6000	49.08738521	61.35923152	73.63107782	0.023166666	0.028958332	0.034749999	0.125
0.8	4000	5000	6000	5.454153912	6.817692391	8.181230869	0.002574074	0.003217592	0.003861111	0.041666667
	4000	5000	6000	21.81661565	27.27076956	32.72492347	0.010296296	0.01287037	0.015444444	0.083333333
	4000	5000	6000	49.08738521	61.35923152	73.63107782	0.023166666	0.028958332	0.034749999	0.125
0.7	4000	5000	6000	5.454153912	6.817692391	8.181230869	0.002574074	0.003217592	0.003861111	0.041666667
	4000	5000	6000	21.81661565	27.27076956	32.72492347	0.010296296	0.01287037	0.015444444	0.083333333
	4000	5000	6000	49.08738521	61.35923152	73.63107782	0.023166666	0.028958332	0.034749999	0.125

(Cont'd)

Drill Power (watts)	Fan Static Pressure (in of water)			Fan Static Pressure (Pa)			ω (rad/s)-corresponds to drill power	Head Loss (m)			Pump Specific Speed, N_f		
31.324	48.93160044	39.14528	32.62107	12192.48	9753.986	8128.322	2581.132524	1031.513	825.2103	687.6753	0.129826	0.171593	0.215515
85.86	33.53073693	26.82459	22.35382	8354.988	6683.99	5569.992	1975.182133	706.8518	565.4814	471.2345	0.263815	0.348688	0.437939
123.84	21.49466295	17.19573	14.32978	5355.911	4284.729	3570.607	1397.380412	453.1228	362.4982	302.0818	0.39078	0.516499	0.648704
31.324	44.0384404	35.23075	29.35896	10973.23	8778.587	7315.49	2581.132524	928.3616	742.6893	618.9077	0.140501	0.185703	0.233236
85.86	30.17766323	8.485361	1.988263	7519.489	2114.331	495.4234	1975.182133	636.1666	178.8774	41.91399	0.285507	0.826673	2.688883
123.84	19.34519665	15.47616	12.8968	4820.32	3856.256	3213.547	1397.380412	407.8105	326.2484	271.8737	0.422912	0.558969	0.702044
31.324	39.14528035	31.31622	26.09685	9753.986	7803.189	6502.657	2581.132524	825.2103	660.1683	550.1402	0.153478	0.202854	0.254776
85.86	26.82458954	21.45967	17.88306	6683.99	5347.192	4455.994	1975.182133	565.4814	452.3851	376.9876	0.311876	0.412211	0.517721
123.84	17.19573036	13.75658	11.46382	4284.729	3427.783	2856.486	1397.380412	362.4982	289.9986	241.6655	0.461971	0.610594	0.766883
31.324	34.25212031	29.96317	21.84272	8534.738	7466.042	5442.637	2581.132524	722.059	631.6448	460.46	0.169644	0.209686	0.291152
85.86	23.47151585	18.77721	15.64768	5848.491	4678.793	3898.994	1975.182133	494.7962	395.837	329.8642	0.344727	0.455631	0.572255
123.84	15.04626406	12.03701	10.03084	3749.138	2999.31	2499.425	1397.380412	317.1859	253.7488	211.4573	0.510633	0.674911	0.847662

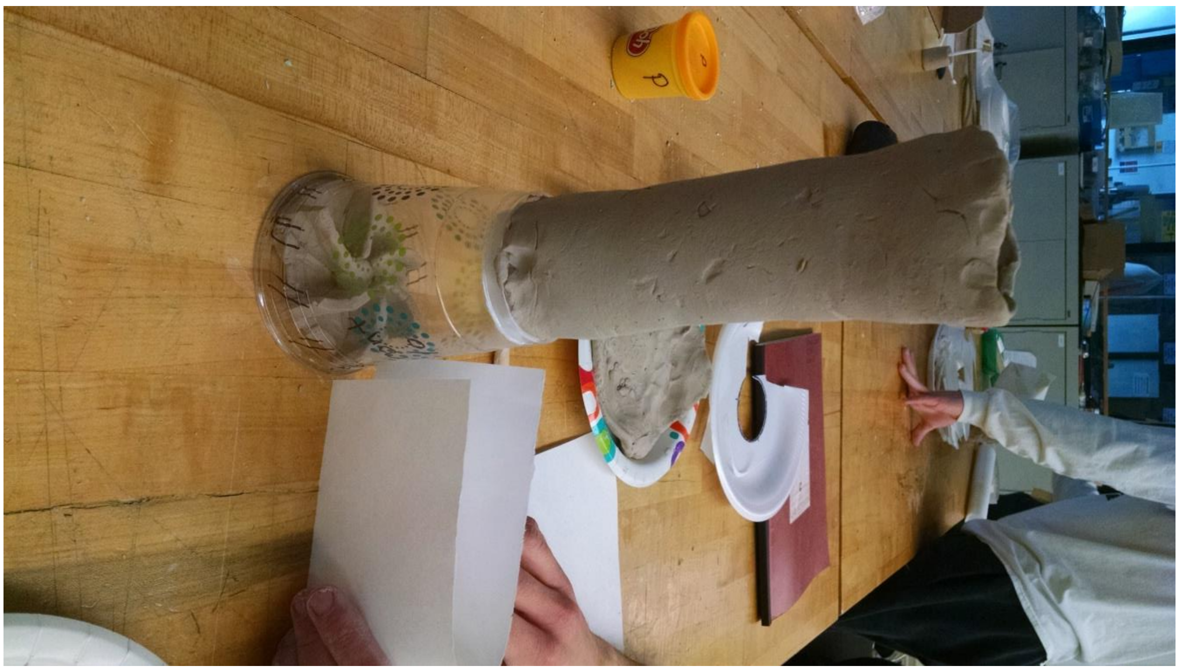

Figure 26: Preliminary Prototype

Figure 27: Housing and Nozzle Top View

Figure 28: Housing and Nozzle Side View

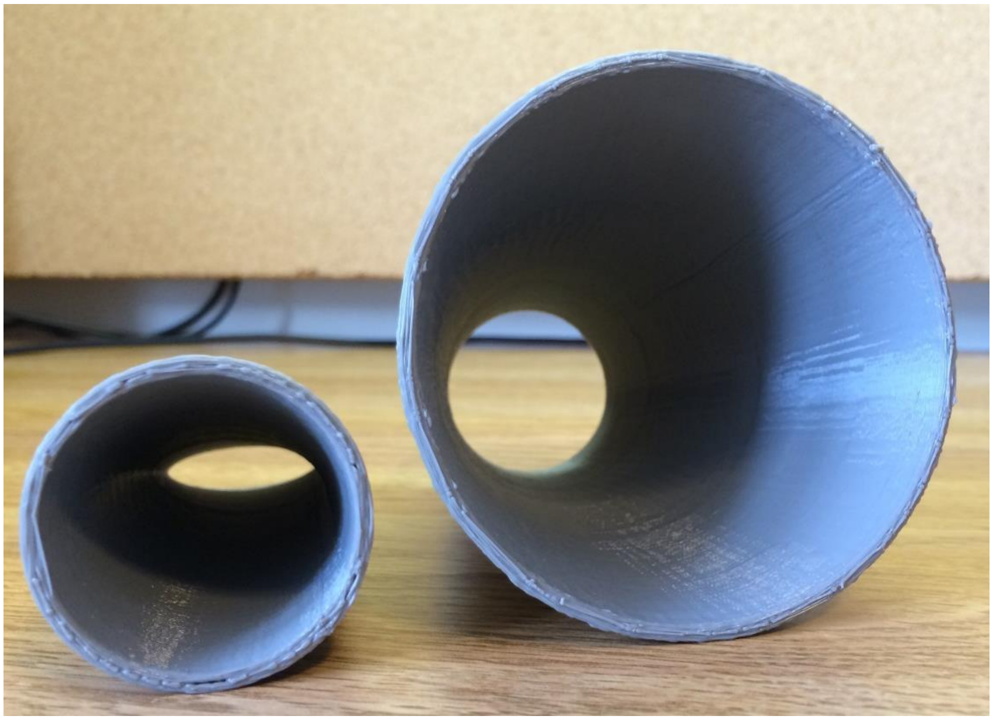

Figure 29: Housing and Nozzle Back View

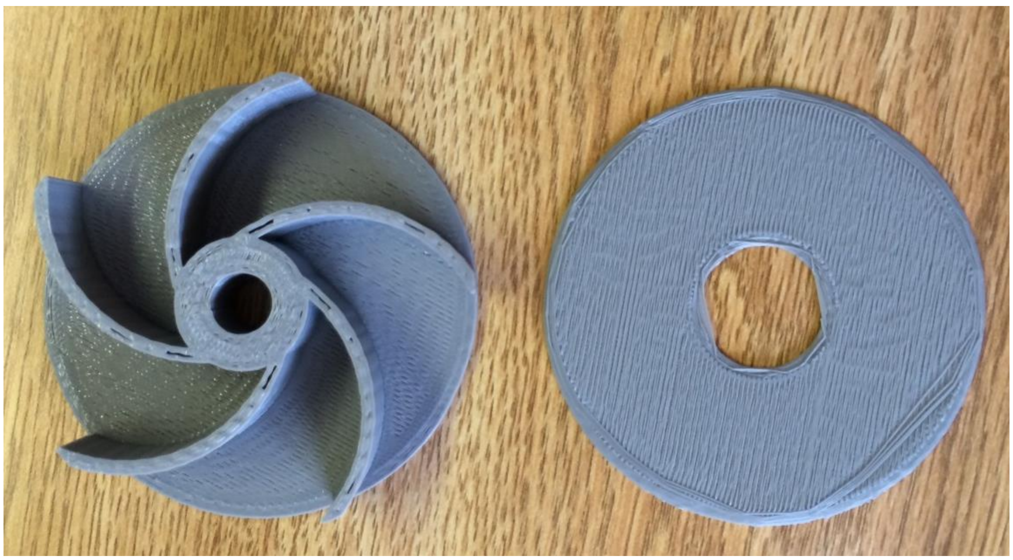

Figure 30: Impeller and Front Plate

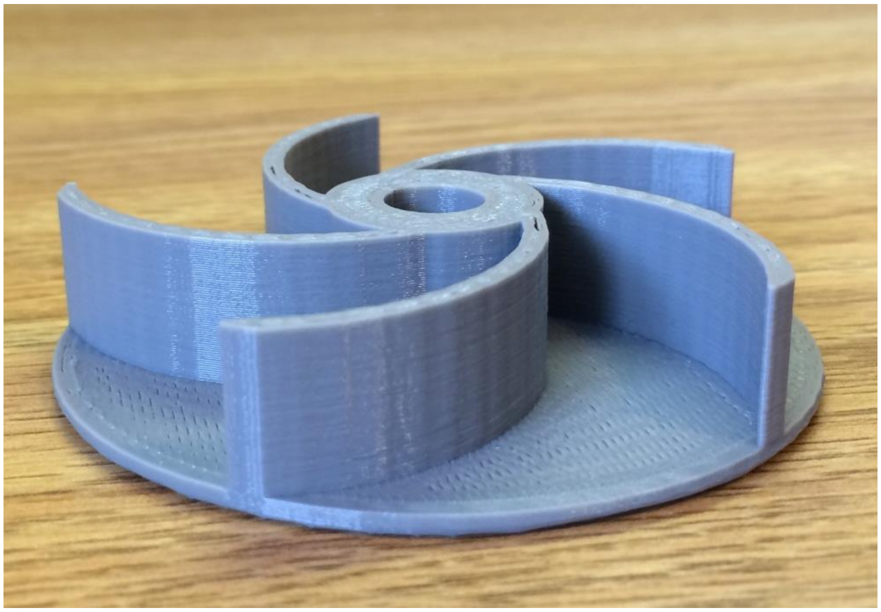

Figure 31: Side View of Impeller

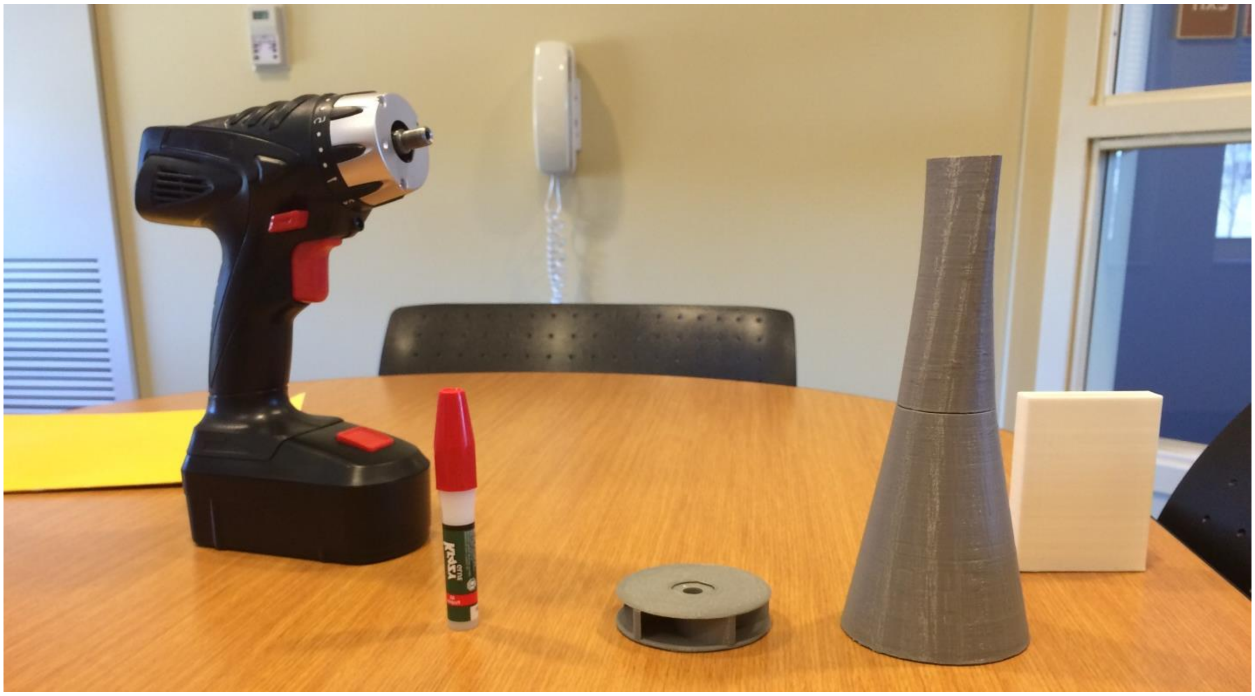

Figure 32: Assembled Parts

Figure 33: Assembled Nozzle and Housing Side View

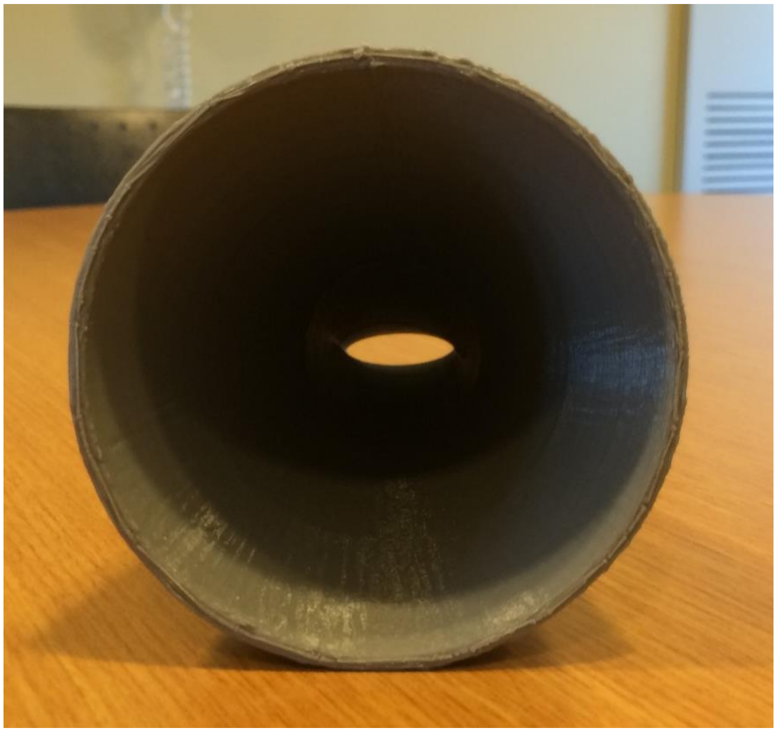

Figure 34: Assembled Nozzle and Housing Back View

Figure 35: Assembled Nozzle and Housing Side View

Figure 36: Assembled Nozzle and Housing Front View

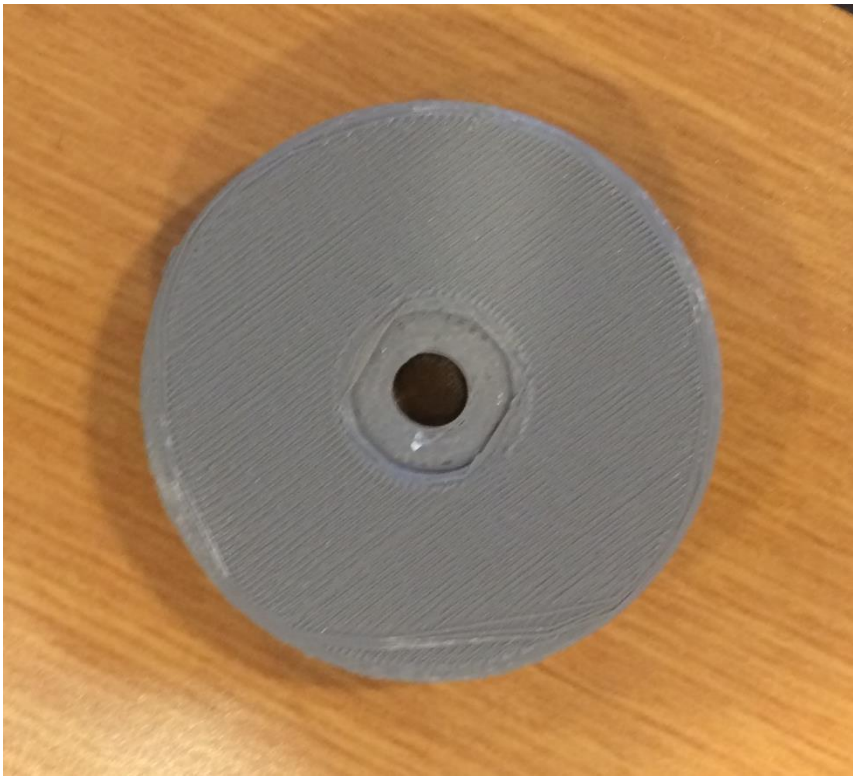

Figure 37: Assembled Impeller and Front Plate Top View

Figure 38: Assembled Impeller and Front Plate Side View

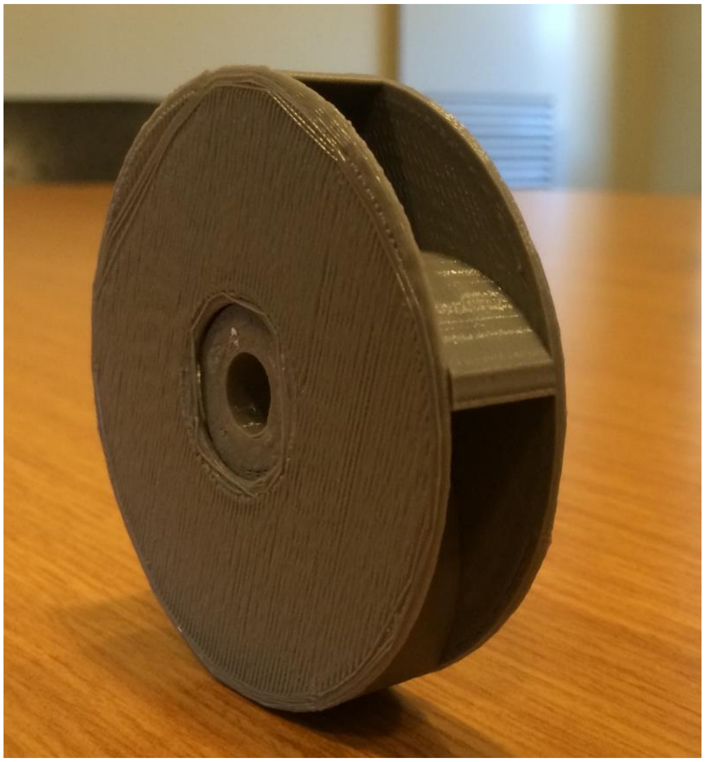

Figure 39: Assembled Impeller and Front Plate

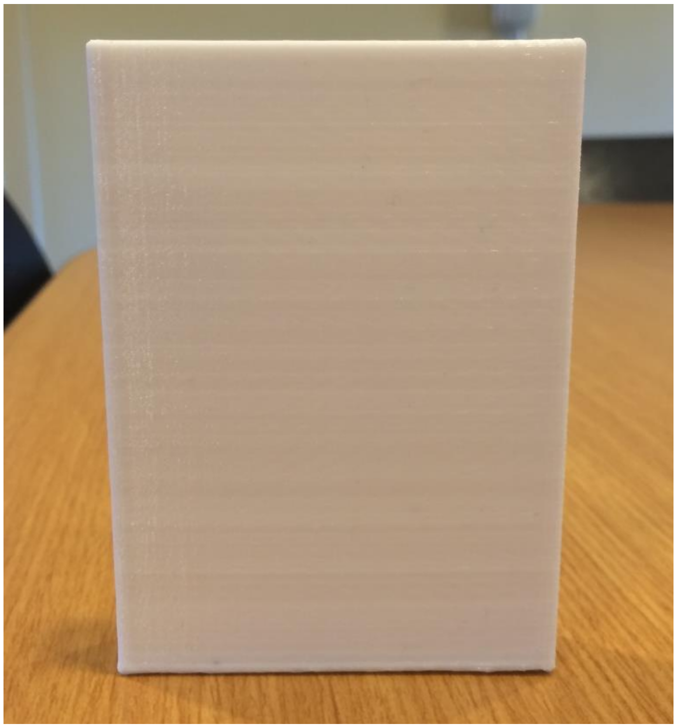

Figure 40: Collection Bin Side View

Figure 41: Collection Bin Top View

Table 10: DFE Goals

Life Cycle Stage	DFE Goals
Materials	• No raw material usage • Any polymers used must be 100% recyclable • The polymers will be non-toxic to protect the consumer and the environment • Use renewable resources
Production	• Reduce the use of process materials • Injection molding will be the main process used in manufacturing components of the vacuum

Table 11: DFE Consideration Questions

Life Cycle Stage	Questions
Materials	• What types of recyclable materials will be used? • If unavoidable, what types of non-recyclable materials will be used? • How much, and what types of additives will be used? • What is the environmental profile of the materials?
Production	• How many types of production processes will be used? • What types of production processes will be used? • How much waste, if any, will be generated? • Can production waste be separated for recycling? • How high will energy consumption be?

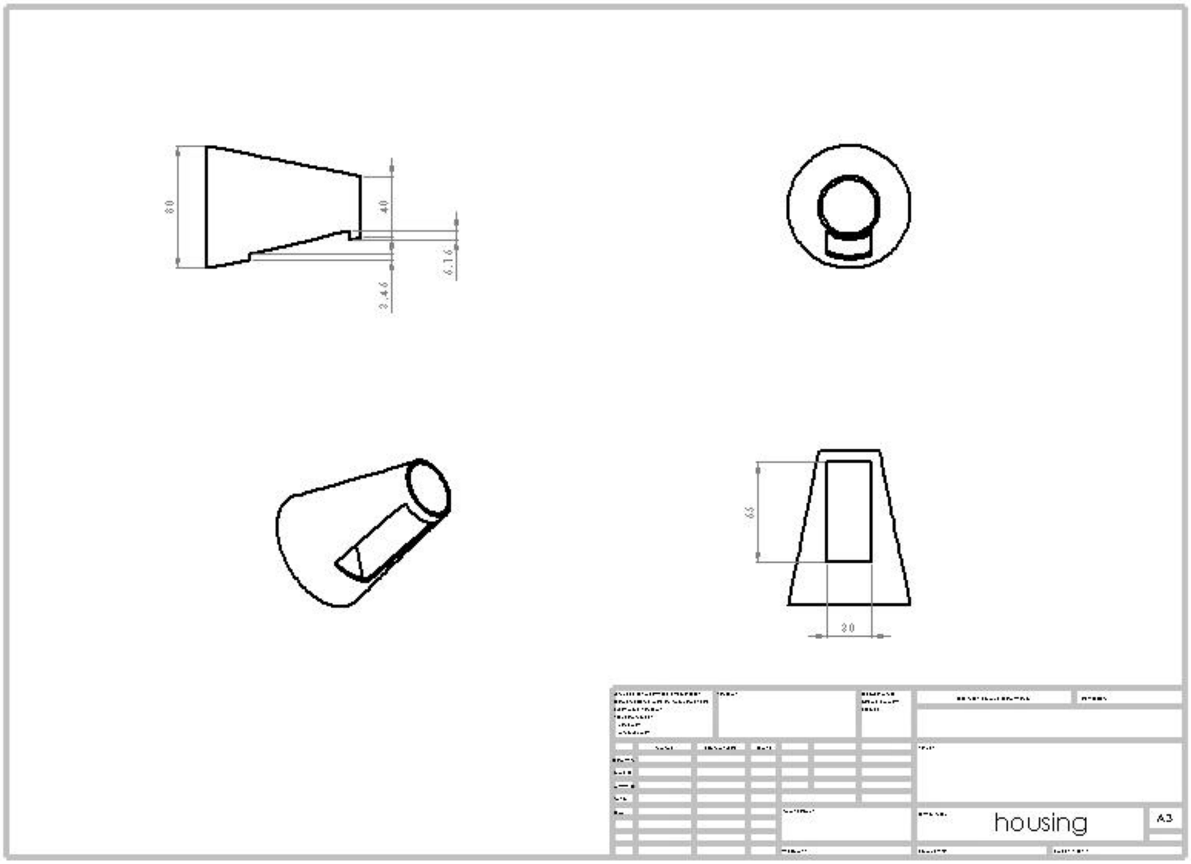

Figure 42: Housing Drawing

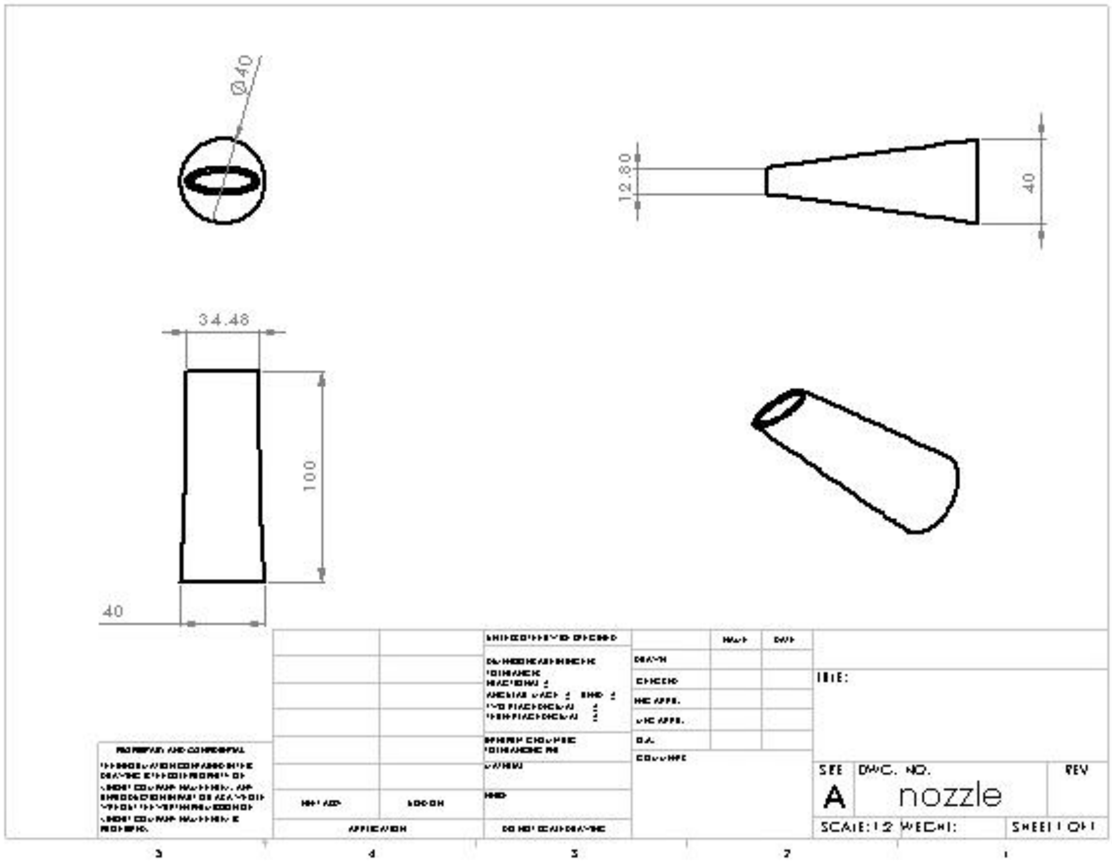

Figure 43: Nozzle Drawing

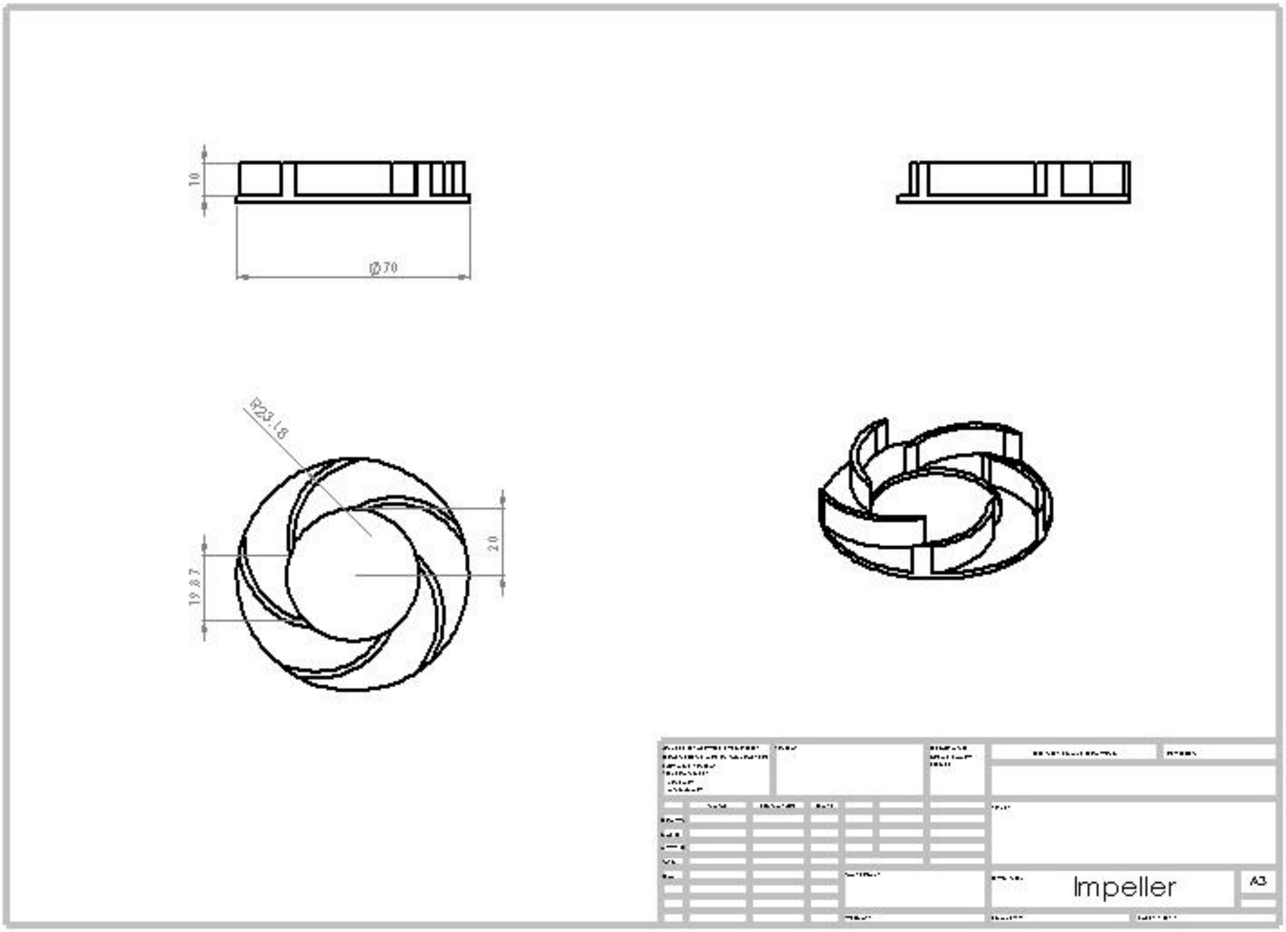

Figure 44: Impeller Drawing

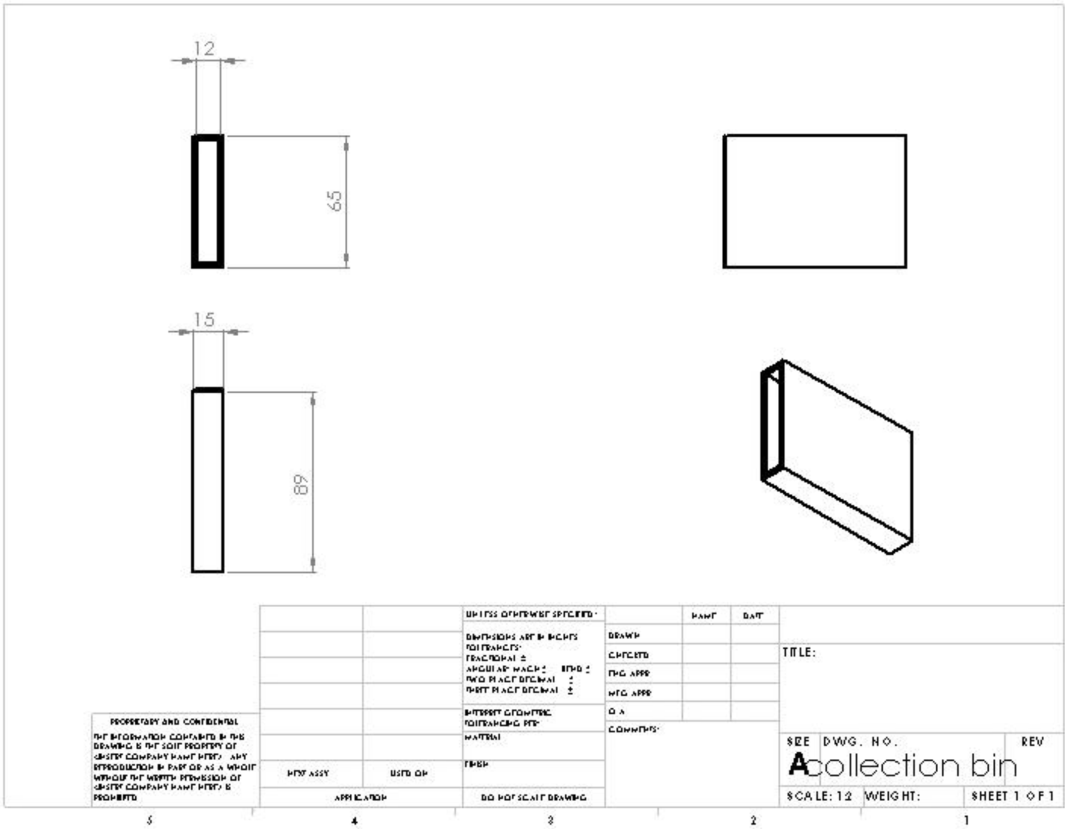

Figure 45: Collection Bin

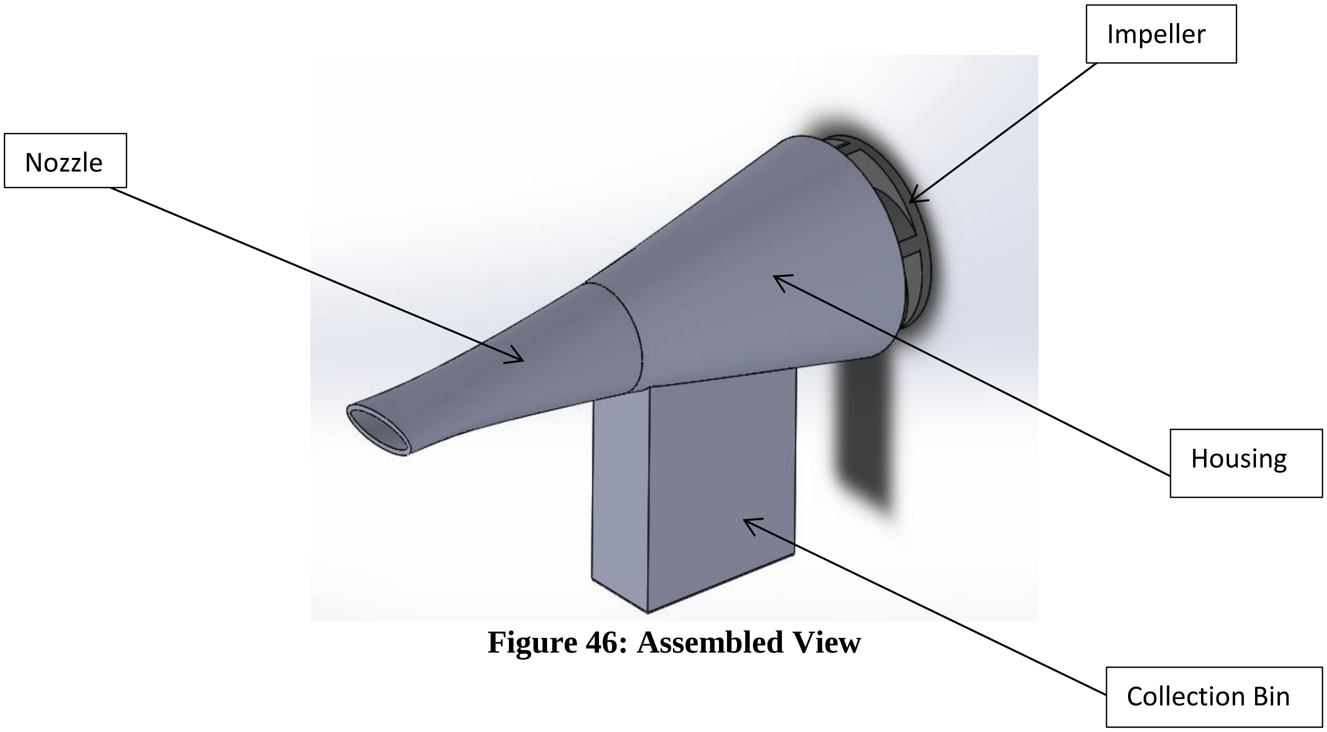

Figure 46: Assembled View

Note: Figure 46's components will be attached to the drill

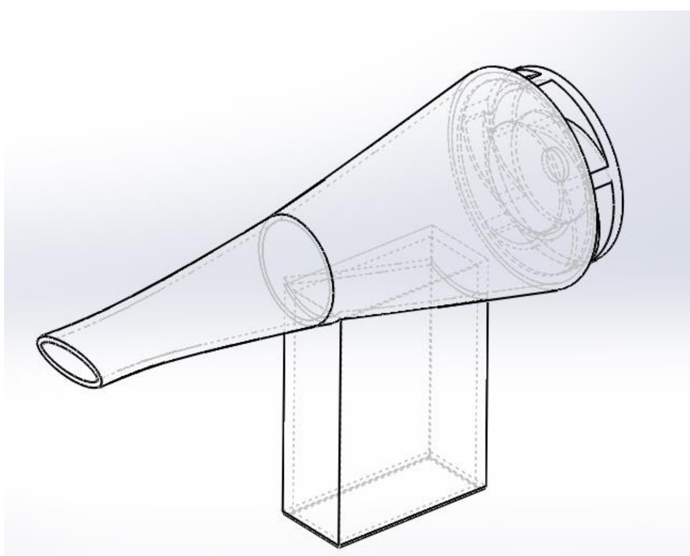

Figure 47: Assembled View with Hidden Features

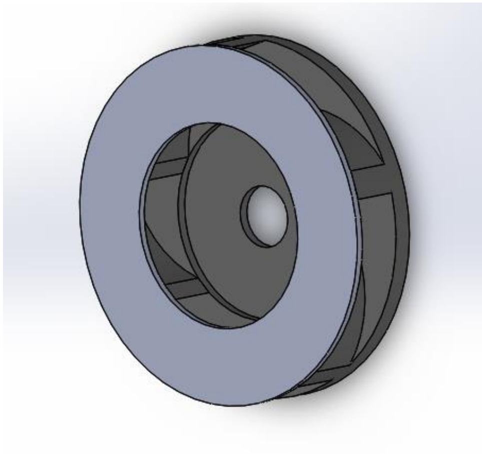

Figure 48: Impeller Close Up View

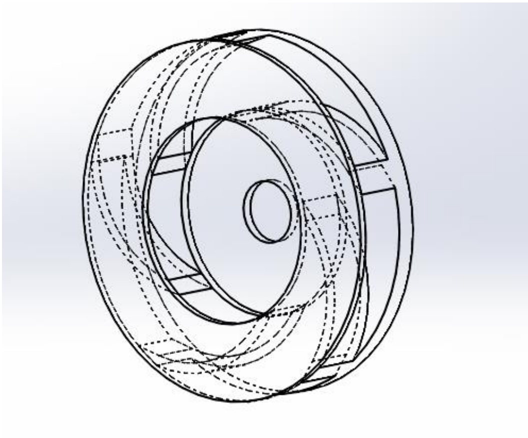

Figure 49: Impeller Close Up View 2

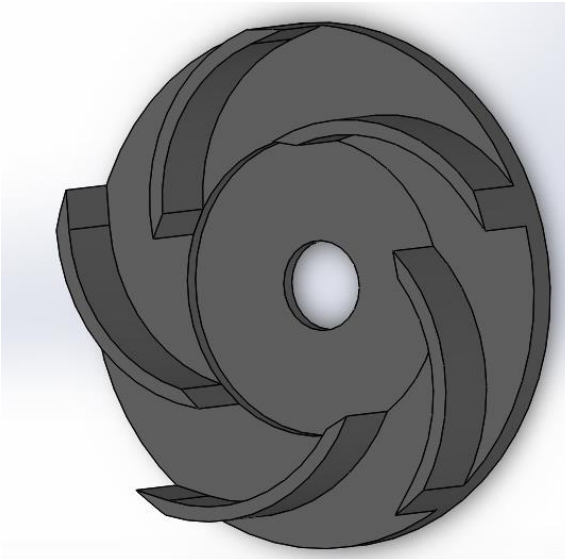

Figure 50: Impeller without Front Plate

Table 12: Bill of Materials

Component	Purchased Materials	Processing	Assembly	Total Unit Variable Cost	Tooling and Other NRE	Total Unit Fixed Cost	Total Cost
Housing	15.88	0.552	0.8	17.232	0.233	0.233	17.465
Collection Bin							
Nozzle	0.243	0.137		0.38	0.141	0.141	0.521
Impeller	0.084	0.072	0.75	0.906	0.091	0.091	0.997
Drill	20		7.5	27.5			27.5
Filter	0.012		1.2	1.212			1.212
Fasteners			1.5	1.5			1.5
Bolts	0.4			0.4			0.4
Washers	0.25			0.25			0.25
Nuts	0.25			0.25			0.25
Total Cost (Per Unit)							**$50.095**
Total Cost (Per 100000)							**$5009500**

Table 13: NPV

	Year 1				**Year 2**			
($ values in thousands)	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Development cost	-750	-750	-750					
Ramp-up cost			-500	-500				
Marketing/support cost				-150	-150	-150	-150	-150
Production cost					-1253	-1253	-1253	-1253
Production volume					25,000	25,000	25,000	25,000
Unit production cost					0.0501	0.0501	0.0501	0.0501
Sales revenue					2,505	2,505	2,505	2,505
Sales volume					25,000	25,000	25,000	25,000
Unit price					0.1002	0.1002	0.1002	0.1002
Period Cash Flow	-750	-750	-1250	-650	1103	1103	1103	1103
PV Year 1, r=10%	-750	-732	-1190	-604	999	974	951	927

(cont'd)

Year 3				**Year 4**			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
-150	-150	-150	-150	-150	-150	-150	-150
-1253	-1253	-1253	-1253	-1253	-1253	-1253	-1253
25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
0.0501	0.0501	0.0501	0.0501	0.0501	0.0501	0.0501	0.0501
2,505	2,505	2,505	2,505	2,505	2,505	2,505	2,505
25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
0.1002	0.1002	0.1002	0.1002	0.1002	0.1002	0.1002	0.1002
1103	1103	1103	1103	1103	1103	1103	1103
905	883	861	840	820	800	780	761

Project NPV	**7,227**

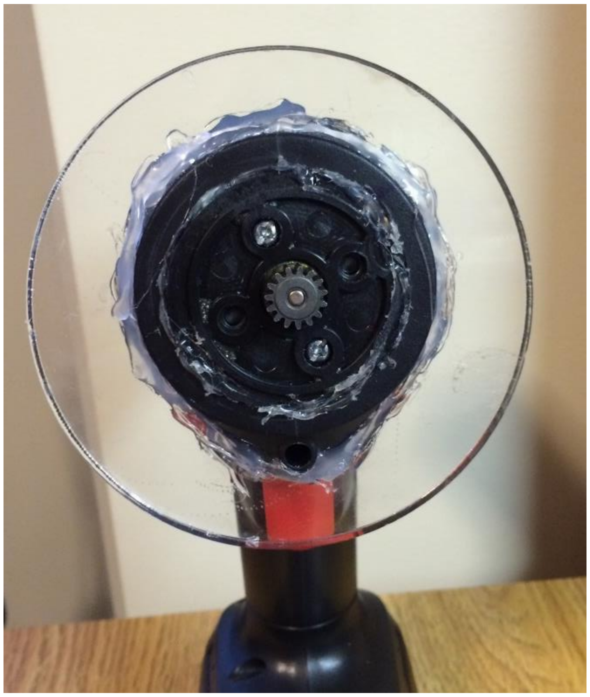

Figure 51: Drill with Acrylic Plate Front View

Figure 52: Drill with Acrylic Plate Side View

Figure 53: Housing, Nozzle, and Collection Bin Side View

Figure 54: Housing, Nozzle, and Collection Bin Front View

Figure 55: Filter

Figure 56: Collection Bin

Figure 57: Collection Bin Opening

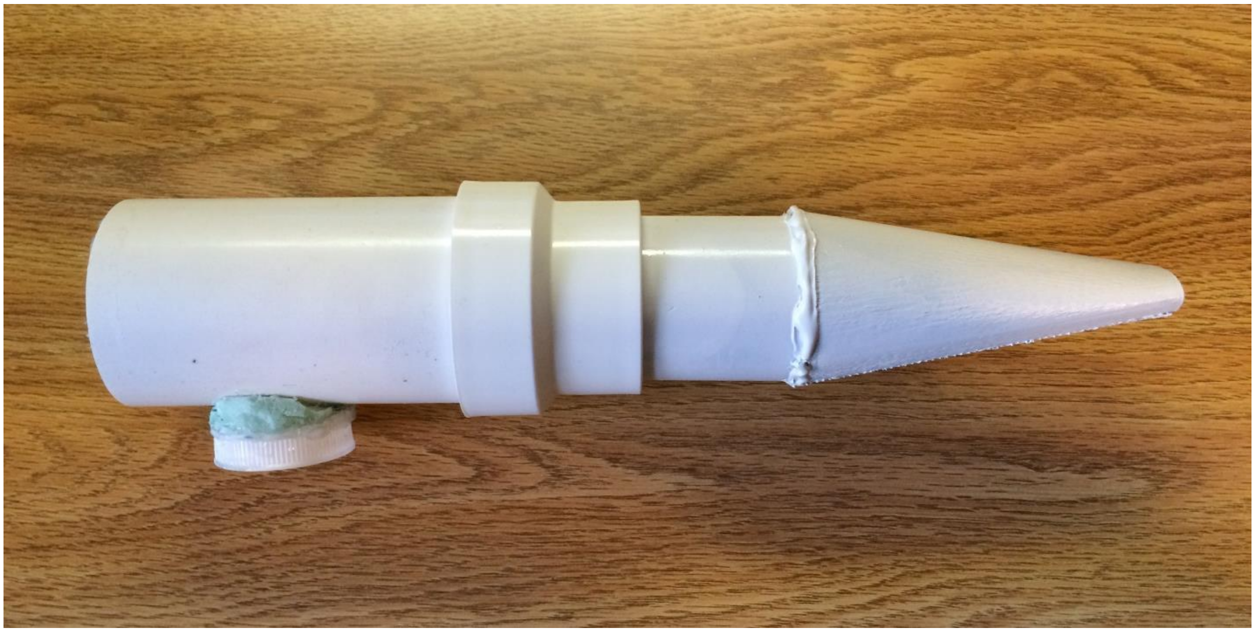

Figure 58: Nozzle and Housing Side View

Figure 59: Nozzle and Housing Back View

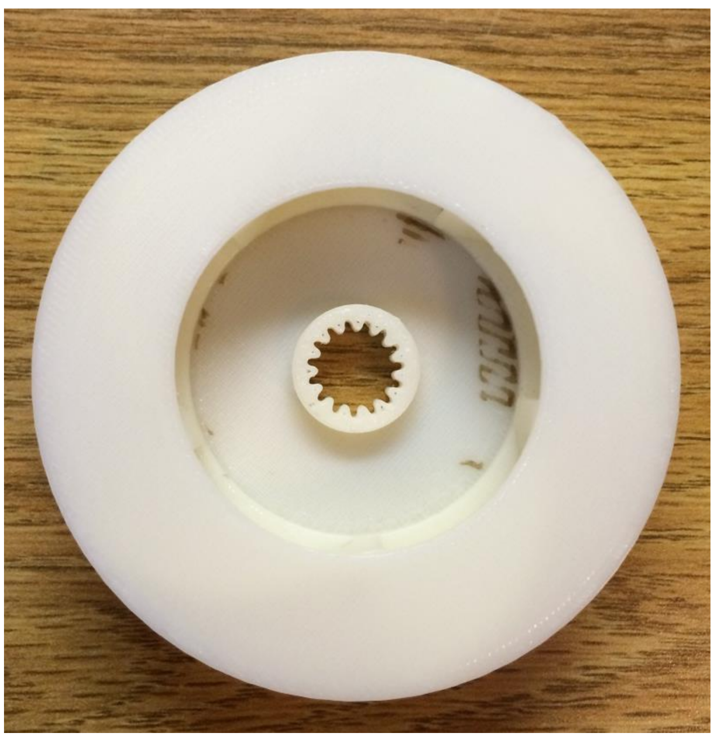

Figure 60: Impeller Front View

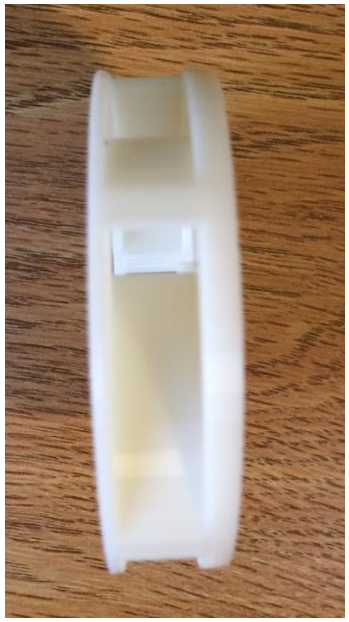

Figure 61: Impeller Side View

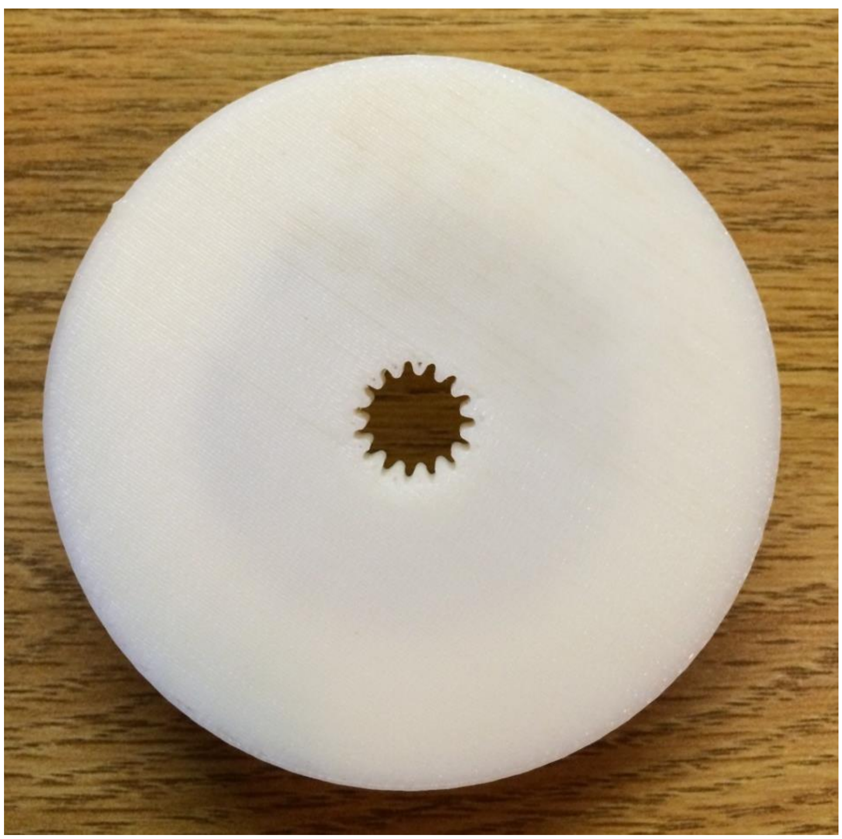

Figure 62: Impeller Back View

Figure 63: Exhaust Holes and Impeller

Figure 64: Impeller in Housing

Figure 65: Final Assembled Prototype

Figure 66: Final Prototype Testing