

# Master of Engineering Project Report

## CCAT-p Wall-Climbing Robot

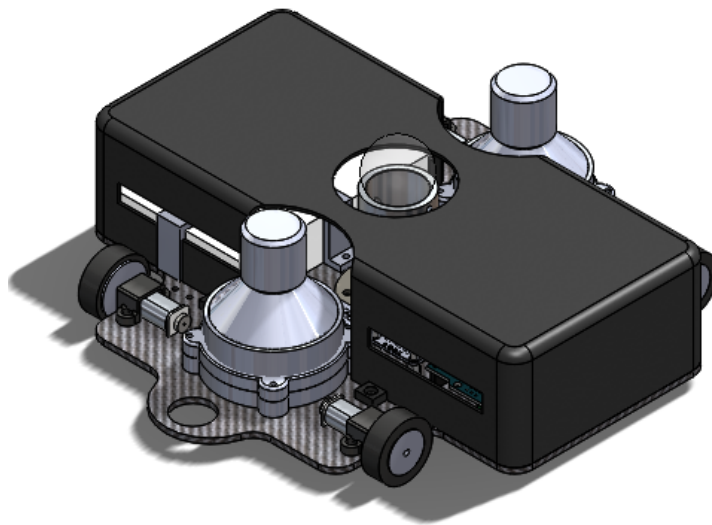
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# 1 Acronyms

- BOM - Bill of Materials (list)
- CCAT-p - Cerro Chajnantor Atacama Telescope - prime
- EDF - Electronic Ducted Fan
- ESC - Electronic Speed Controller
- IC - Integrated Circuit
- IMU - Inertial Measurement Unit
- RPL - Rapid Prototyping Lab
- SLA - Stereolithography
- 3S - 3 Cell Battery

# 2 Abstract

This report encompasses all the design and manufacturing work done to improve the functionality of the CCAT-p metrology robot in order to meet top-level requirements. Over the course of the year many subsystems including the robot cover, fans, fan mounts, electronics, electronic mounts, and chassis were tested, analyzed, redesigned, and re-manufactured for use on the second prototype. This iteration of the robot will be manufactured and tested by future team members. For those subsystem redesigns we were not able to manufacture in the Spring semester, we have outlined the important design features and our recommendations on how they should be made. Our findings also indicate that there are a few outstanding issues that need to still be addressed by future team members.

### 3 Introduction

The CCAT-p robot is a collaborative project working in tandem with the Space Sciences department to design and manufacture a metrology robot capable of climbing walls. This robot will eventually be used to perform metrology and verify the shape of the mirrors of the CCAT-prime observatory which is currently under construction in Chile. There are three top-level requirements of the robot that must be met in order to achieve this. First, the robot must be able to traverse the mirror surfaces without damaging or displacing them. Second, it shall be capable of providing accurate metrology data with a precision to  $\pm 2$  microns. Finally, the robot must be capable of traversing the entire mirror surface in a single run. These top-level requirements were broken down into subsystem requirements each with their own set of functional requirements. Of these functional requirements, one of the most difficult to implement has been the wall-climbing functionality of the robot.

Creating a design that meets all these requirements necessitates many different skills across the broader engineering field including robot control techniques, circuit design, and estimation methods. The mechanical engineering specific aspects of the project that we employed included mechatronics, design principles, 3D printing, structural analysis, and testing. Over the past two semesters we have used all these different methods to develop the robot to its current state. The prototype in use at the start of the Fall 2019 semester had some of the primary functions detailed in our system requirements list. It was able to drive around on a set of four wheels mounted to a carbon fiber chassis and there were two small fans mounted to the design to enable the wall climbing function. The tire and wheel combination had been chosen since it would not leave scratches or scuffs on the mirror surface when moving around. However, the fans mounted at the time provided only a fraction of the thrust required for the robot to traverse a vertical surface and none of the metrology sensors were mounted to the chassis. Over the past year we have worked to improve upon this design. The main goals we started with were to make the wall-climbing aspect of the design fully functional, incorporate the sensors needed for metrology onto the chassis, improve upon existing components, and redesign the chassis for a more optimal subsystem layout. At the current date of May, 2020, we have achieved the majority of these goals and laid out plans for the ones we were not able to finish. This report will detail our approach to creating project requirements, implementing designs into the prototype and improving upon them iteratively as well as how we tested our designs. For the goals we were not able to accomplish, this report will lay out what we were able to accomplish and the road-map for synthesizing them into the next iteration of the robot.

## 4 Methodology and Design Details

### 4.1 Design Requirements

The CCAT-p observatory gave a list of requirements that drove the design of the robot. The requirements that were applicable to the mechanical design of the robot are:

- The robot must be able to operate at an air temperature of  $-21^{\circ}\text{C}$  to  $9^{\circ}\text{C}$
- The robot must be able to operate at 50 - 53 kPa ( $\approx 0.5\text{atm}$ )
- The robot must not be more than 1 kg of mass
- The robot must not induce more than 2 microns of error in the measurement system  
The robot must not detach from the mirror surface at any time
- The mirror surface can be oriented from an angle of  $0^{\circ}$  to  $110^{\circ}$  ( $20^{\circ}$  overhang)
- The power draw of the robot must not exceed 1kW

### 4.2 Methodology

When we first began work on the robot our first goal was to identify each robot subsystem and link them to the top-level and functional requirements. We then tested and evaluated each of these subsystems at its current state to see if these requirements were met. Using a Pugh matrix, we ranked subsystems in order of priority to fix, update, or even completely redesign. Once a particular subsystem was chosen, we used an iterative approach to design to develop full functionality. At the end of each iteration we re-tested and analyzed the results. This can most clearly be seen with our fan design.

## 5 Component Design and Testing

### 5.1 Fan Design

Before we had joined the project it had already been determined that the best way to keep the robot attached to the mirror surface was through the use of fans. This would create a low pressure region between the mirror surface and the robot's chassis, adhering the robot to the mirror.

#### 5.1.1 Fan Design Requirements

The requirements that drove the design and selection of the fans were that the robot must not detach from the mirror surface at any time, meaning it must be able to stick to the mirror while at a variety of angles ranging from  $0^{\circ}$  to  $110^{\circ}$ . This requirement gets even more difficult given that the robot will be operating at 0.5 atm since the fans will generate half as much suction force due to the low pressure at the high altitude of the Andean mountains. Additionally, the fans could not be very heavy due to the strict mass budget of 1 kg. Finally,

the power draw of the fans had to be taken into account as the power draw of the entire robot was not to exceed 1kW.

Another aspect of the fans that needed to be taken into consideration was the height of the fans. The height needed to be less than the center-line of the puck which was taking measurements with Etalon’s laser measurement system. If there was anything higher than the puck, it could obstruct the measurement system.

### 5.1.2 Fan Comparison

Significant research had to be performed to find a fan that would meet all of the above requirements. Data from different fan options found online was entered into a spreadsheet so that they could be easily compared.

Fan Name	Length (mm)	Thrust (N)	Mass (g)	Diameter (mm)
JETFAN 80	66	29.4	120	80
Powerfun EDF	69	16.0884	178	70
Changesun	N/A	19.2276	190	64
Schubeler	N/A	16.677	147	70
VASAFAN	N/A	9.81	73	50
Changesun + Fan	67	N/A	143	64
Powerfun EDF	66	7.55	75	50
Powerfun EDF	66	11.58	150	64

Figure 1: Fan Comparison showing dimensions, mass, and available thrust.

There were fans available that ranged from diameters of 50 mm to 80 mm, masses from 75 g to 190 g, and all of their heights were about the same. Each fan had a rated thrust and that ranged from 7.55N to 29.4N. However, since these fans were intended for RC airplanes and drones, the correlation to suction force was not known, thus this was not necessarily a good rating for the fans. Based on the comparison we ordered 2 fans: the Powerfun EDF with a 50mm diameter, and the Powerfun EDF with a 64mm diameter. This would give us two fans to test, one that was very light and small, but not a lot of thrust force and a fan that was medium sized and had a thrust rating in the middle of the range.

### 5.1.3 Fan Testing

As mentioned earlier, although a thrust rating was given for each fan, it was not known how this rating translated to a suction force on the robot. It was calculated that the max suction force that the fans needed to create was 15N at 0.5atm. It was planned to use two fans mounted on the chassis, so a single fan needed to create 7.5N of force to be able to use that fan. However, since the fan testing would be performed at 1atm, a single fan needed to create 15 N of force to be a viable fan option.

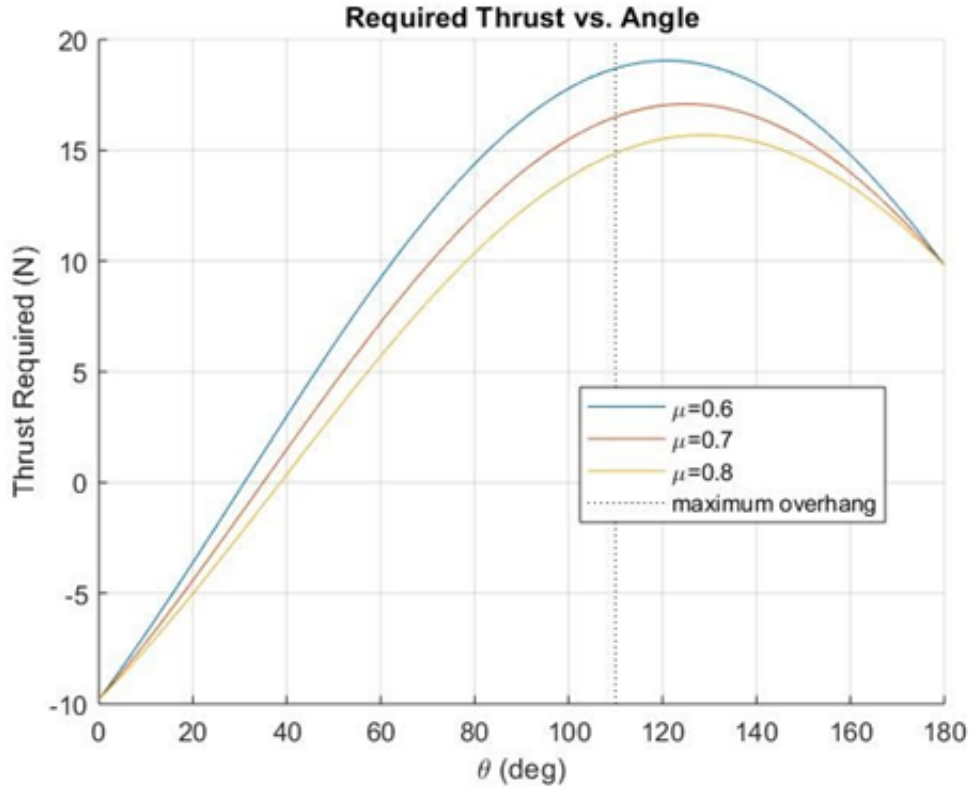


Figure 2: The required force vs. the inclination angle of the mirrors with different coefficient of friction values for the tires. The coefficient of the existing tires is 0.8 or higher.

A test stand was built to determine how much suction force a single fan could create. This test stand, as shown in Figure 4, consisted of a wooden structure with a pulley mounted on it. This pulley had a cable running over it, with one end attached to the simulated robot which was a 20 cm x 20 cm sheet of acrylic to function as the chassis, with the fan mounted on it, and the other end was tied to a digital force gauge.

The fan was then powered by a 3S battery and controlled by an electronic speed controller, an Arduino UNO, and a potentiometer to act as a throttle. As you turn the potentiometer, the speed of the fan changes. Then to measure the max force created by the fan, the fan is run at full throttle, and the tester pulls on the digital force gauge until the chassis separates from the test stand.

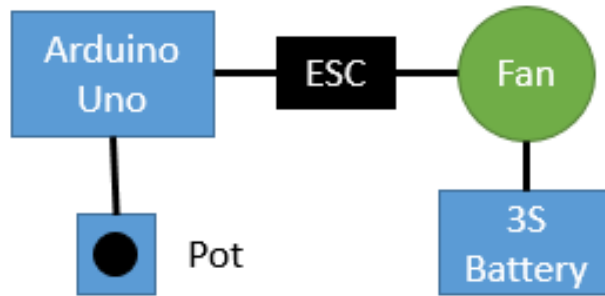


Figure 3: Electronic Schematic for Fan Testing

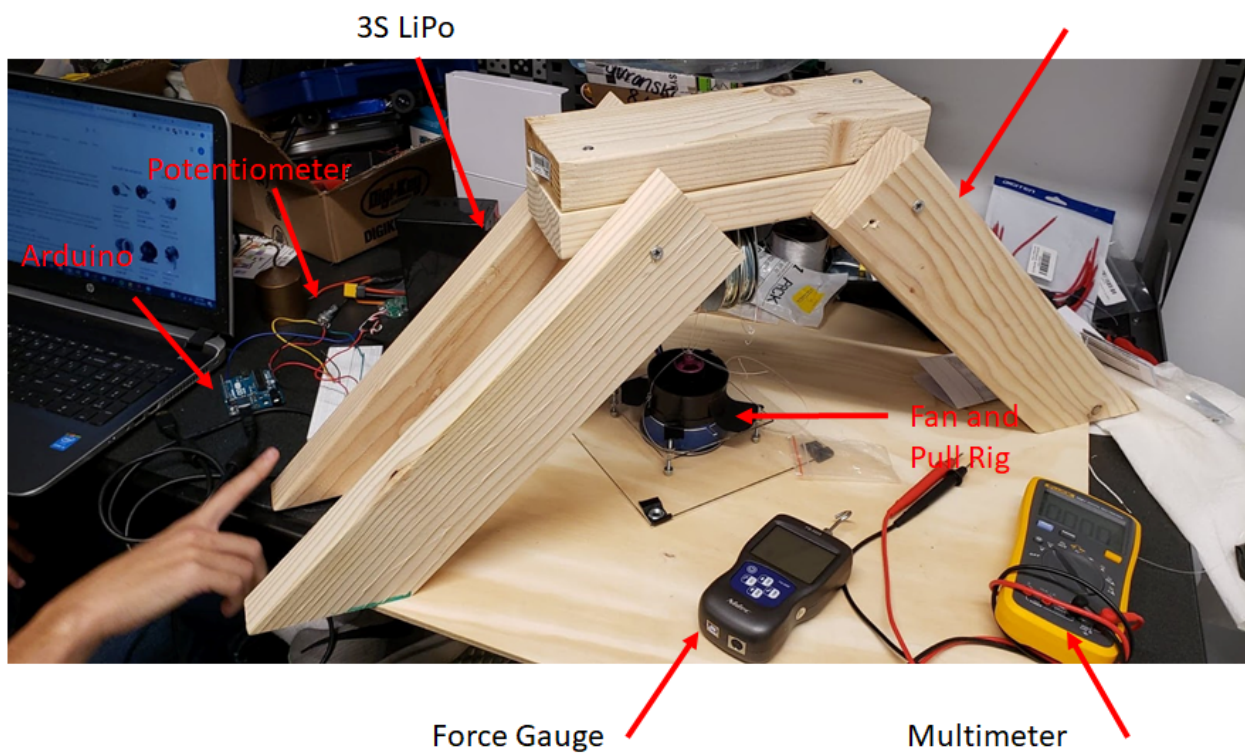


Figure 4: Fan Test Stand

The first test that was conducted was with the 50mm fan. First it was mounted into the acrylic base, then the cable was attached to the base and run over the pulley. Next, the fan was turned to full throttle and the tester pulled on the force gauge until the acrylic separated from the test stand, and the max force was recorded. This test was repeated seven times as shown in the table below.



Test Number	Max Force (N)	Weight (N)	Net Force (N)
1	17.03	0.73575	16.29425
2	15.64	0.73575	14.90425
3	17.29	0.73575	16.55425
4	16.85	0.73575	16.11425
5	14.6	0.73575	13.86425
6	11.63	0.73575	10.9425
7	10.05	0.73575	9.31425

Figure 5: Suction Force Test for the 50 mm 11 blade Powerfun EDF

The test was only run seven times because after the fourth run, the battery started to drain. This is because when running at max throttle there is a power draw of 500 W. However, the average net force from the first four runs was 15.97N. This meets our requirement of 15N per fan to be able to stay secured to the mirror surface at all times.

Based on this data, this is the fan that was selected to update the current prototype to provide wall climbing capability. In order to test if this fan would work at 0.5atm, the robot was mounted with two of these fans, and placed in a rotatable pressure chamber in the Cornell Space Sciences Building. The pressure chamber was decreased to 0.5atm, then the fans were turned on, and the chamber was rotated from 0° to 90°. The robot stayed attached to the mounting plate in the pressure chamber at 0.5atm at 90°, proving that the fan that was tested in the lab would work under the physical conditions when running at the CCAT-p observatory.

#### 5.1.4 Fan Mount Design

There have been two total fan mount designs. The initial proposal used two pieces that clamped around the fan hub and were bolted together before the entire assembled mount holding the fan was screwed down to the chassis. This design was lightweight, with a mass of only 12.5 grams. However, there were a few issues. The current carbon fiber chassis has mounting holes that are not evenly spaced, so adjusting the tolerances on these fan mounts to fit into the holes on the chassis proved difficult. Furthermore, these mounts were made on a Prusa Mk3 material extrusion printer and thus the tolerances did not meet expectations. Extra adhesive in the form of hot glue was needed to complete the seal between the fan hub and ring section of the mount. In terms of manufacturing, this design also made heavy use of fillets and bevels in order to improve strength characteristics from the material extrusion process.

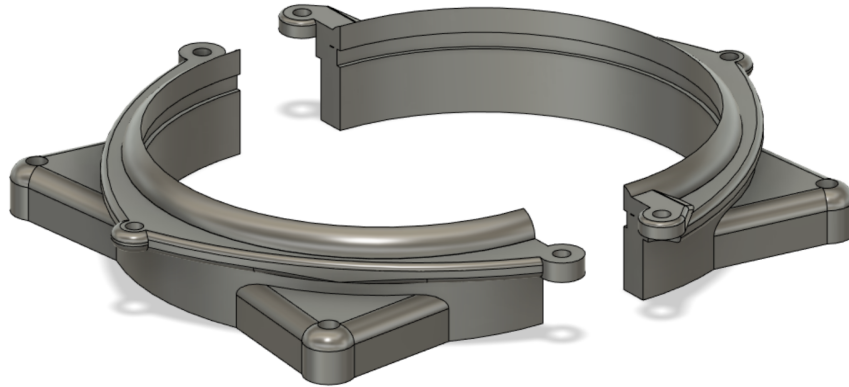


Figure 6: The initial fan mount design. The parts would slot together, one on top of the other, around the fan and then be screwed together holding the fan in place. The entire assembly was then screwed down onto the chassis.

The new fan mount design will address many of the issues found in the first iteration. A more simple step assembly using fewer overall screws will be used. The new fan mounts take the appearance of two rings that slot on top of one another around the fan and are then screwed down onto the chassis (see figures 7 and 8). The design will still be 3D printed and current mass estimates place it as weighing approximately the same as the previous design.

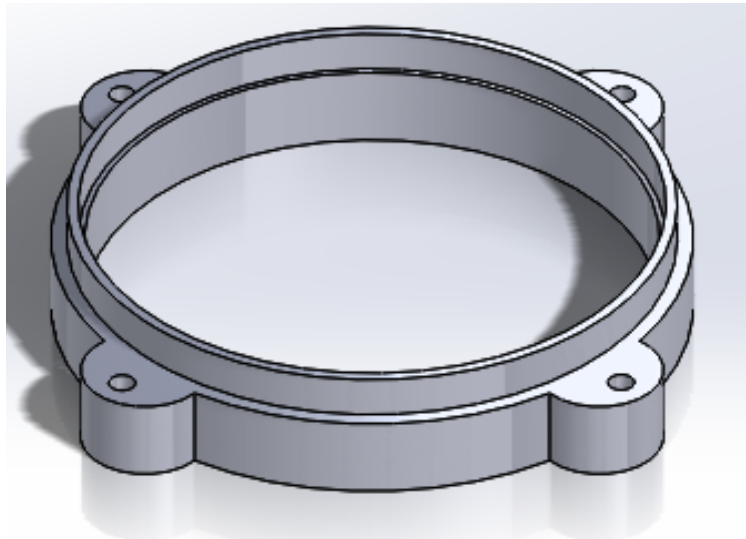


Figure 7: A view of the redesigned fan mount bottom half. The thin-walled protrusion on top slots into the upper half for easy alignment. This design may have to be amended though if tolerances cannot be met.

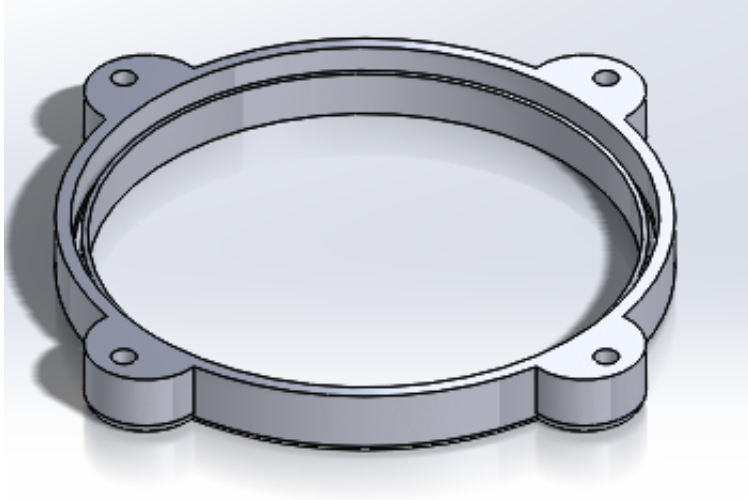


Figure 8: A bottom view of the upper fan mount section.

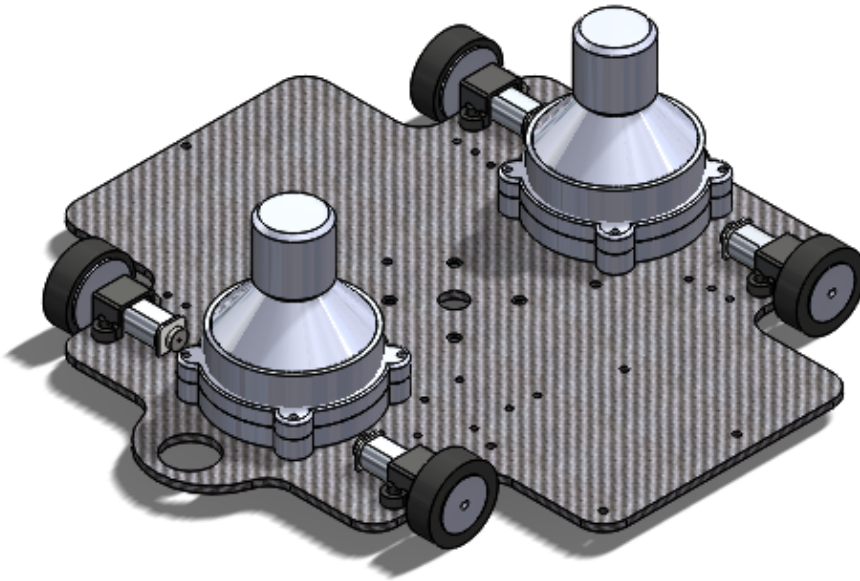


Figure 9: The redesigned chassis (see section 5.4) with the new fan mounts and fan hubs mounted.

## 5.2 Electronics Mounting

When the project began, there were no mounting provisions for the electronics. Everything was secured to the chassis with either tape or an adhesive. Mounting provisions for the eddy current conditioner, the Raspberry Pi + Motor Shield, the IMU, the Teensy, and the ESCs will be discussed.

### 5.2.1 Eddy Current Conditioner Mounting

The eddy current conditioner is a large electronic component of the eddy current measurement system that is on-board the robot. It is essentially a large box that needs to be mounted on the robot chassis. The challenge with this, is that there are no mounting holes on the conditioner, meaning a bracket needs to be designed to restrict its motion in all directions, so it does not move while the robot is driving or climbing walls.

To accomplish this, a cross-shaped bracket with two mounting holes was designed as shown in figure 10. These mounting holes would line up with two holes in the chassis so it could be bolted down.

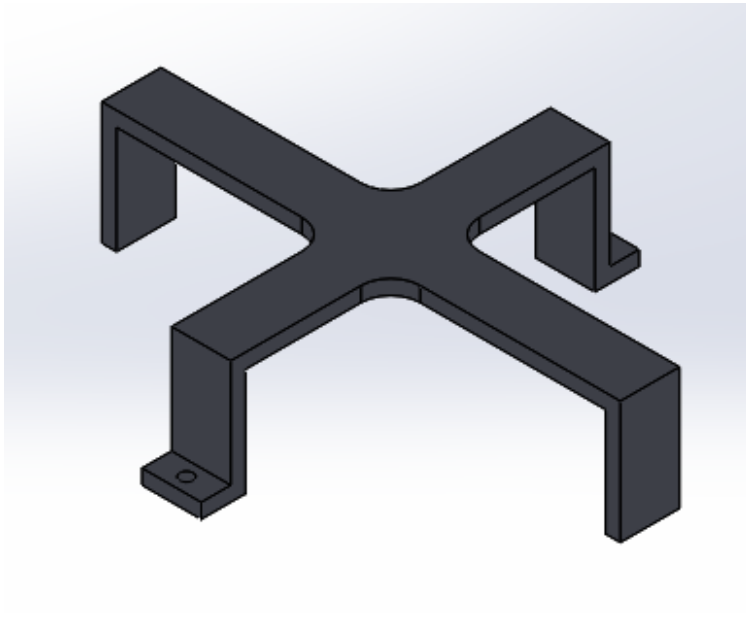


Figure 10: Eddy Current Conditioner Bracket

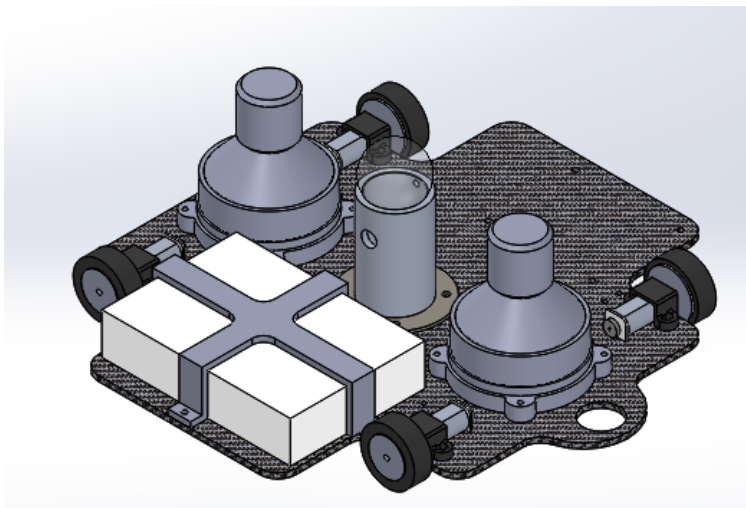


Figure 11: Mounting of Eddy Current Bracket to Chassis.

### 5.2.2 Raspberry Pi Mounting

The Raspberry Pi needed to be mounted to the chassis of the robot as well. This was simple as the Raspberry Pi already has four mounting holes in a 58mm x 49mm rectangular pattern. This pattern was copied onto the chassis and M2.5 nuts were used as standoffs to raise the Pi from direct contact with the chassis.

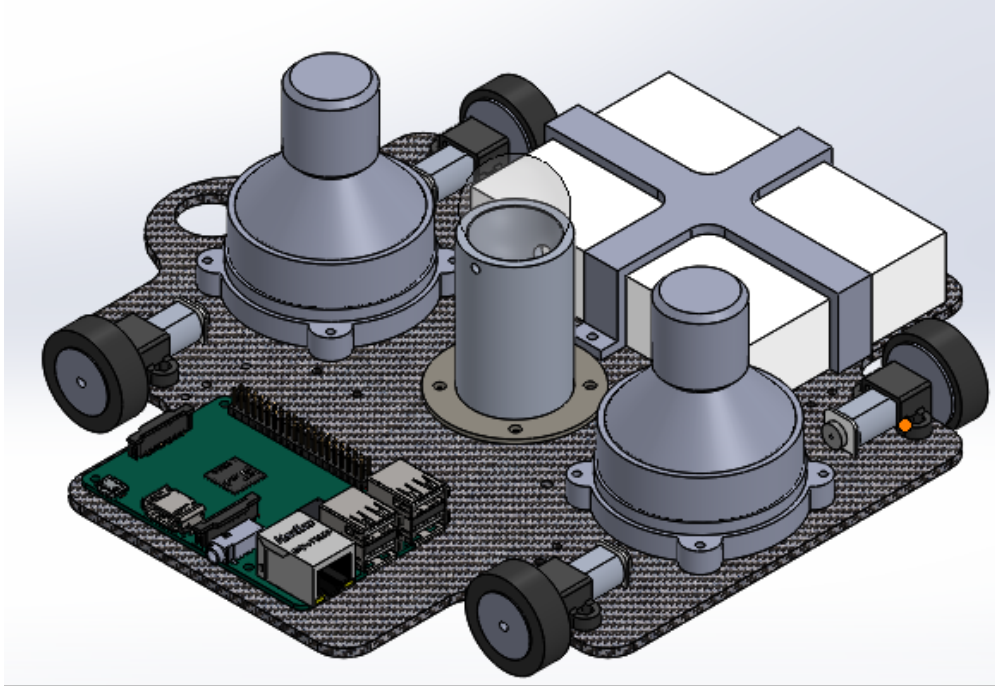


Figure 12: Raspberry Pi mounting on robot (opposite the Eddy current sensor in white).

### 5.2.3 IMU Mounting

The inertial measurement unit being used is the Adafruit BNO055. The IMU mounting was simple as it had a 0.85" x 0.60" rectangular four-hole pattern. This pattern was copied onto the chassis and M2.5 hexagonal spacers with a height of 15mm were used to mount the IMU.

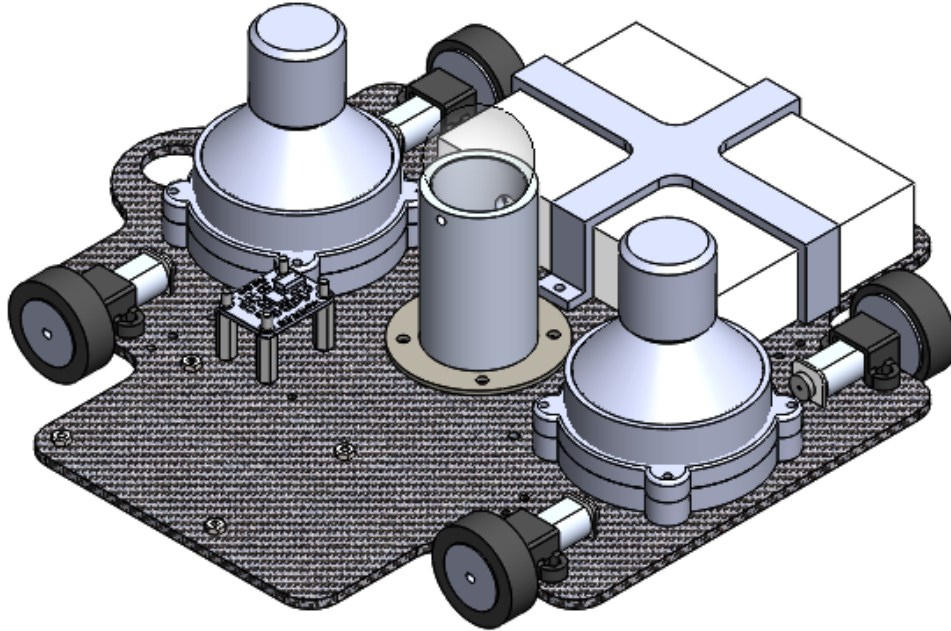


Figure 13: IMU mounting on robot.

### 5.2.4 Teensy Mounting

The Teensy is another electronic component that needs to be mounted to the chassis. This was slightly difficult as it had no mounting holes, and there needed to be access to a USB port on one side of the Teensy. To accomplish this a U-shaped bracket with two mounting holes was designed that would prevent motion in one direction, and double sided tape or adhesive would be placed on the bottom side of the Teensy in contact with the bracket, preventing it from moving in the other two directions. The hole pattern would then be copied to the chassis and bolted with M2.5 bolts.



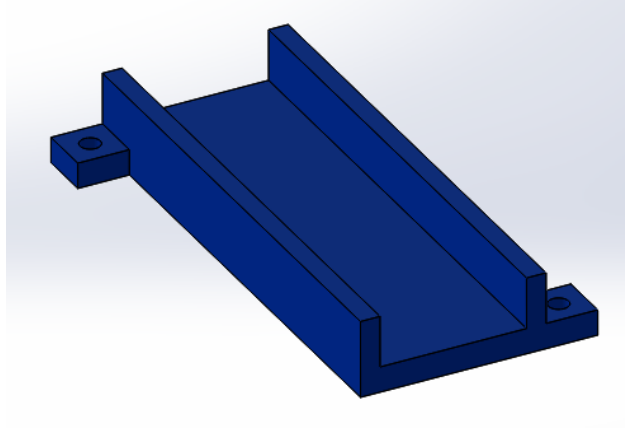


Figure 14: The bracket design for holding the Teensy in place. Note the sharp corners; if this design were to be 3D printed bevels would likely be added along those vertices.

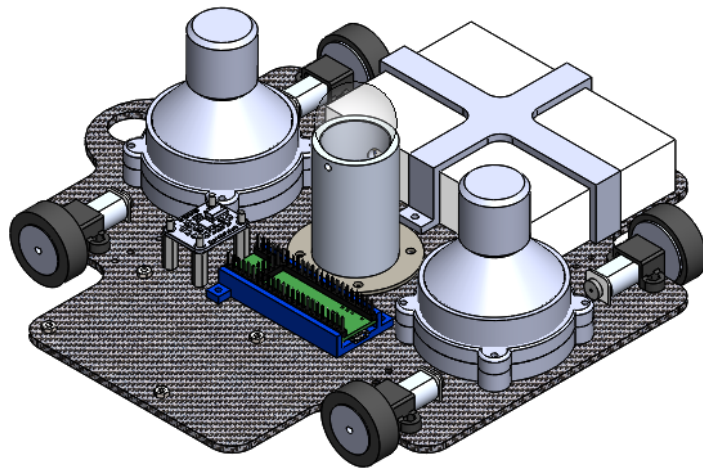


Figure 15: Teensy and bracket mounting location on robot.

### 5.2.5 ESC Mounting

The electronic speed controllers (ESCs) are support electronics that connect to the fans. They were not modeled, but look like Figure 16. The ESC is approximately 1" x 1.5" x .125" with three wires sticking out on both sides. There will be two of them on the robot.



Figure 16: Image of ESCs that go with Powerfun Fans.

The ESCs can be secured to the robot using cable ties, tape or an adhesive. There are many possible attachment points, such as part of the robot cover as well as other mounting brackets which could be adjusted to provide mounting points for the ESCs. Designing exact mounting provisions for the ESCs was not completed this semester.

### 5.2.6 Manufacture of Brackets and Mounting Provisions

Detailed analysis of the manufacturing of the brackets was not conducted. However, it is expected that they will be 3D printed to keep them simple to produce and lightweight. All of the brackets that will be bolted to the chassis will be done with M2.5 nuts and bolts. In addition to all of the electronics, a small breadboard will be secured to the chassis with double sided tape or adhesive at the request of the controls team.

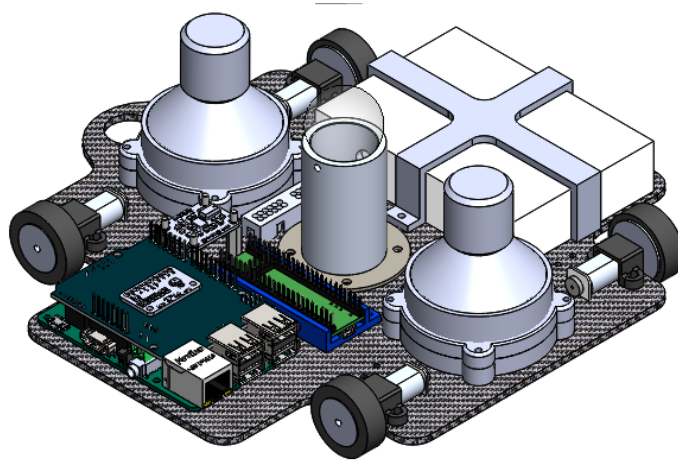


Figure 17: Model of the robot with all electronics mounted.



## 5.3 Robot Cover Design

The robot cover is meant to provide protection to the robot with a requirement for an IP67 rating. Another important aspect of the design is that it only needs to protect vulnerable components on the chassis at this IP67 rating. This means that the cover does not have to fully enclose the fan hubs or the wheel mounts, only mission critical electronics and sensors. The design of the cover must also be such that it is not taller than the puck tower (center) or either of the fan hubs.

### 5.3.1 Initial Cover Design

The initial design for the cover was relatively simple. The main body was designed to cover only the essential components while leaving room for the puck tower, fan hubs, and a hole for the power tether and additional wiring. Mounting the cover to the chassis was also simplified as we anticipated needing to be able to remove and reattach it multiple times in order to switch out or repair other robot components. In order to do this we designed two inset lips on the underside of the robot. This can be seen in figure 18. An adhesive such as double-sided duct tape or hot glue would be used to bond the cover to the chassis. Given that both of these adhesives are water soluble and not particularly strong to begin with, removing the cover would be straightforward.

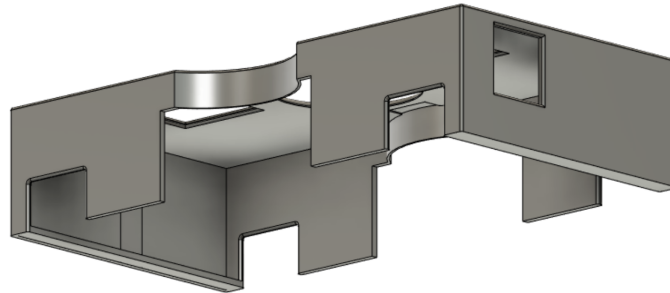


Figure 18: The inset lips for mounting the cover to the chassis. The square hole above the lip on the right side of the cover was made to provide access to the Raspberry Pi and Arduino boards.

The entire cover was designed for 3D printing at the Upson Rapid Prototyping Lab (RPL). This can be seen in the cover through a few different aspects. The most prominent of these are the beveled edges seen all over the cover. This was not done purely for aesthetic reasons but more so because when 3D printing rounded corners are almost stronger in terms of max shear and yield strength than straight edges. This cover design also made use of variable thickness. Given that the robot has a strict top-level mass constraint requirement, designing the cover to be as lightweight as possible while still being functional was an important aspect of the design approach. Since the cover is non-load bearing, most surfaces were made to be as thin as possible (limited mainly by the minimum feature size of the printers in the RPL).

The only areas that were made slightly thicker were the two lips and the areas immediately surrounding them as we did not wish for the cover to deform or crack when being removed from the chassis.

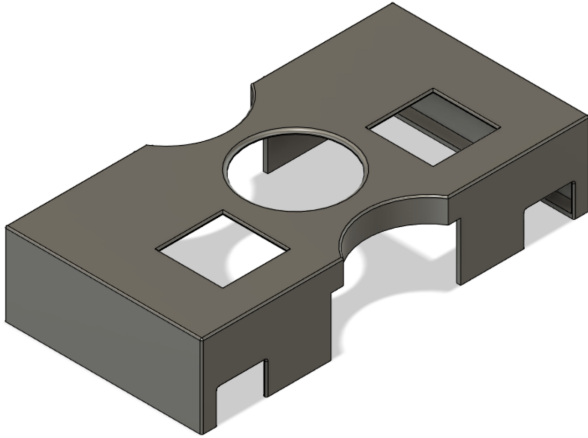


Figure 19: The initial robot cover design. Note the beveled edges.

### 5.3.2 Updated Cover Design

Upon testing the initial cover design we concluded that more vertical clearance would be needed to account for all the wiring and other electronics. The cutouts on top of the cover were also removed in order to better protect the electronics. Previously, they were there to provide quick access to the robot internals. The design was also made thinner overall to further reduce mass and the bevels were increased in radius to further strengthen the corners. Another significant change made in the updated design is the mounting design. The updated cover has brackets towards the center of the cover that will be bolted directly to the chassis. This goes in line with the redesigned chassis for the next iteration of the robot prototype.

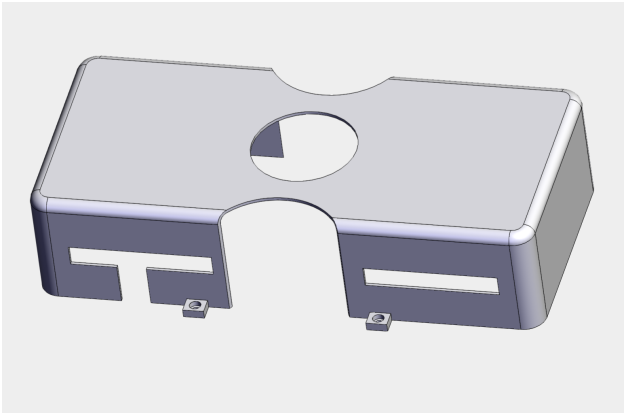


Figure 20: A graphic of the updated robot cover design. Note the brackets protruding towards the center of the design.

### 5.3.3 Cover Manufacturing

The initial cover design was made at the RPL using the Stratasys Objet 30. Currently, the plan for future cover iterations is to continue using this printer. This stereolithography (SLA) machine was chosen for a few reasons. The primary reason is the minimum feature size (i.e. “resolution”) of this printer. The Objet has a 28 micron layer resolution that allows it to meet tight tolerances and thus accurately reproduce the design. While the VeroBlue material used by the Objet is proprietary, it has very favorable qualities for this design. The two most outstanding are its low polymerized density of 1.19 g/cm<sup>3</sup> and strong tensile and flexural strength at 60MPa and 70MPa respectively. This low density combined with high strength allows us to create thinner designs that cut down on mass without sacrificing any needed strength. While its water absorption factor is higher than some other high strength polymers such as PEEK or PFTE, topping out at 2.2%, this is not a primary concern as the robot’s operating environment will be at high altitudes in the Atacama desert, one of the most arid locations in the world.

### 5.3.4 Cover Mounting

The most recent design of the cover makes use of brackets that will be directly bolted to the chassis for mounting. This was chosen in order to create a more permanent fixture that we can test upon manufacturing the next robot prototype iteration. In terms of strength, bolted brackets are a stronger solution than removable adhesive. However, they also add more weight. Even though the current cover design is the thinnest yet, it is possible that the mass of the bolts needed for fixing the cover to the chassis could offset these gains made and another solution for cover mounting may be needed. Testing should be done to confirm this.

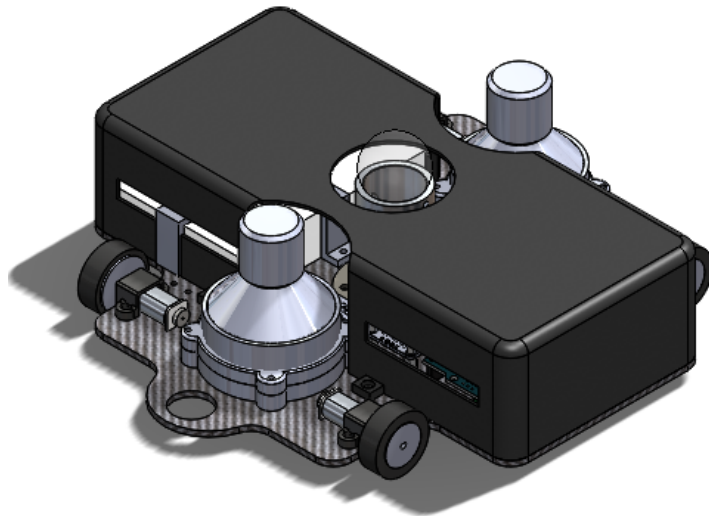


Figure 21: A graphic of the updated robot cover design mounted on the fully assembled second prototype. Note the height of the cover above the fan mounts. This is to allow room for all the wiring

### 5.3.5 Future Cover Design Changes

Once the new cover and chassis are manufactured testing of the cover will commence. The results of these tests will heavily influence any further design iterations of the cover. One aspect of the design that will likely change is the inset cuts for the fan hubs. The current fans are still too tall and do not allow the viewing requirements for the puck tower to be met. Either new hubs or hub and motor combinations will likely be needed. Future iterations of the cover design will have to account for this. Another major consideration is compatibility with the robot tether system that is currently being designed. As this aspect of the project is still in its early stages, we can only note that the design of the cover will have to change in order to account for this.

## 5.4 Chassis Design

When this project was taken over, an initial chassis had already been designed. However, it was designed for different fans, and there were no mounting holes for the electronics. It was made out of 2mm thick carbon fiber. This semester, improvements were made to the chassis to account for mounting the electronics and new fans and also to reduce the vibrations induced by the fans. Additionally, the original chassis was not machined well. Dimensions were different from the drawing causing difficulty when trying to secure parts to the chassis. As mentioned in the previous sections, brackets for the fans and electronics were designed with holes in them to bolt to the chassis. The hole pattern for these brackets was transferred to the chassis where they would be mounted. All of the new holes are suited for M2.5 bolts.

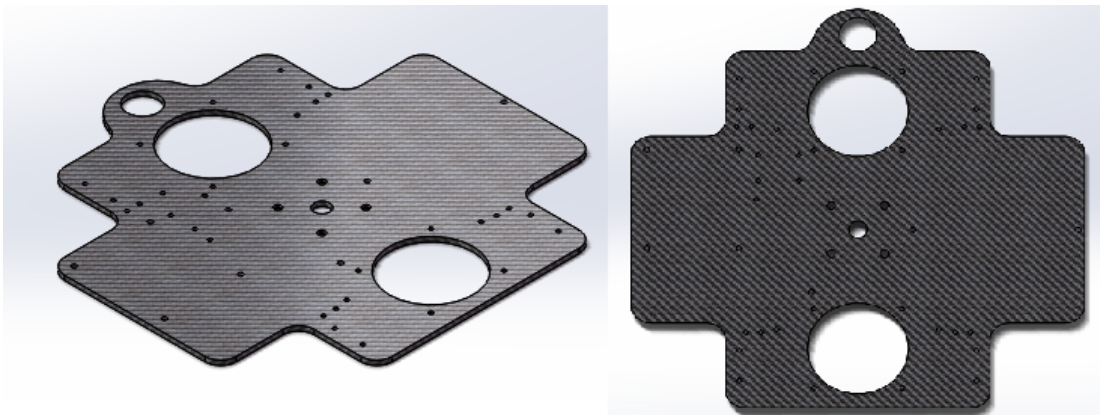


Figure 22: Updated robot chassis with holes for mounting fans and electronics.

When the robot was tested in Germany with the previous chassis design, the measurements saw a lot of noise due to vibrations induced by the fans. One idea to reduce these vibrations was to increase the thickness of the chassis. Previously the mass of the chassis was 106 g at a thickness of 2 mm. However, based on our mass budget we could not increase the thickness of the chassis without finding mass savings somewhere as the robot mass was already 989 g. However, the new robot cover design decreased its mass from 157g to 99g saving 58g. This mass savings then allowed the chassis thickness to increase by 50% from 2mm to 3mm

increasing the chassis mass to 159g, and making the total robot mass 984g. This increase in thickness should dampen the noise added to the measurements significantly. However, no actual testing could be done as this chassis has not been manufactured yet.

#### **5.4.1 Chassis Manufacturing**

The old carbon fiber chassis was made at Cornell. However, it had many tolerancing inaccuracies. So it is recommended that in the future, the chassis manufacturing is outsourced to a carbon fiber machining company that can achieve the needed tolerances.

### **5.5 Bill of Materials List**

In addition to designing the robot, a bill of materials (BOM) was generated so that the next people to work on this project could see everything they would need to buy to make a fully functional robot. This BOM has the part description, the quantity required, the unit mass of each part, and the total mass of all the parts added together. This gives an accurate mass calculation for the robot so that the mass does not go above the 1 kg mass budget. The only material not on the BOM is the mass of the wiring on the robot, but that should not be a significant addition to the mass as the part placement of the electronics was optimized to reduce all of the wire lengths.

## 6 Conclusions and Recommendations

Over the past two semesters we have made significant progress in updating previously integrated subsystems on the robot as well as designing entirely new ones. At this current stage the first iteration of the robot prototype has reached maturity and is able to be tested with full fan, wall-climbing, eddy-current, and pathing functionality. The project is ready to move forward with a second prototype incorporating the new subsystem designs, the most salient of those being the chassis redesign. There are still a few outstanding issues that must not be disregarded however. The selected fans still do not allow the robot to meet the puck tower viewing requirement and must be altered or exchanged to meet this. Furthermore, many of the redesigned systems such as the electronics mounting, new fan mounts, and robot cover were not able to be manufactured this semester and must be tested thoroughly before and after mounting them to the new prototype before any final design considerations are made. Another aspect of the project that will likely be affected by these redesigns is the mass budget. With a strict top-level constraint of 1kg staying in place, the new robot prototype must meet this requirement and it is likely that this will require future team members to alter these updated designs to allow for that. Another consideration comes from the test results of the 1st prototype. While performing test runs in Germany, we noticed that the fans created significant oscillations and vibrational noise in the Eddy current sensor measurements. This must be addressed. While we did not have the means to do so in the Spring 2020 semester, the new fan mounts and hubs will need to be remodeled to incorporate vibration dampening. As mentioned previously, we also believe that a thicker chassis will also diminish the adverse effects of this noise but this must also be tested for confirmation.

This past Spring semester another branch off of the mechanical design team was started, the robot tether team. This team is working with us and the rest of the mechanical team to design a tether and harness system that can provide power to the robot and protect it in case of some system failure that would lead to it falling off the mirror surface. As mentioned briefly in the cover design section, this facet of the project is still very early on its development. Much of the work done so far has been identifying failure modes, identifying safety factors, and analyzing expected forces. There are no mechanical models for the tether or a system layout for how it will interface with the robot and robot cover. So while we cannot make any concrete design recommendations on how to best incorporate the tether system onto the robot we strongly recommend that any future design changes or iterations make incorporating the tether system a top consideration when doing so.

We also recommend making a few changes to the electronics layout. The current design uses standard pin-out breadboards for wiring and the wires themselves are clad as well. In order to reduce overall mass, we advise that the second prototype switch these out for IC breadboards and non-clad (but still the same gauge) wires. Significant progress was made in the wiring layout of the design and thus the need for an adjustable pin-out will not apply for the second robot prototype. An important consideration to keep in mind here is that IC breadboards do require soldering and while solder can be removed, it is a difficult process.

In summary, significant progress was made this last year on the CCAT-p wall climbing robot. When we began the project all that we had was a robot with driving capability, there was no wall climbing ability, and everything was attached to the chassis using tape or adhesives. Now, the physical robot is equipped with powerful fans that allow the robot to

stay attached to the mirror surface at all angles under the working conditions of the CCAT-p observatory. Although not implemented onto the physical robot yet, there is now a concrete electronics layout, and mounting provisions for each of the major electronics components such as the eddy current sensor, the Raspberry Pi, and the IMU. Additionally, improved fan mounts and robot cover have been designed. All of the work that was done this year should be able to be picked up by the next students to work on this project, and the new design can be easily implemented to make a successful wall climbing robot for the CCAT-p observatory.

## 7 Appendix

This section will contain additional graphics for the subsystem and robot assembly. We anticipate that some of these photos may be useful for future members of the mechanical design team.

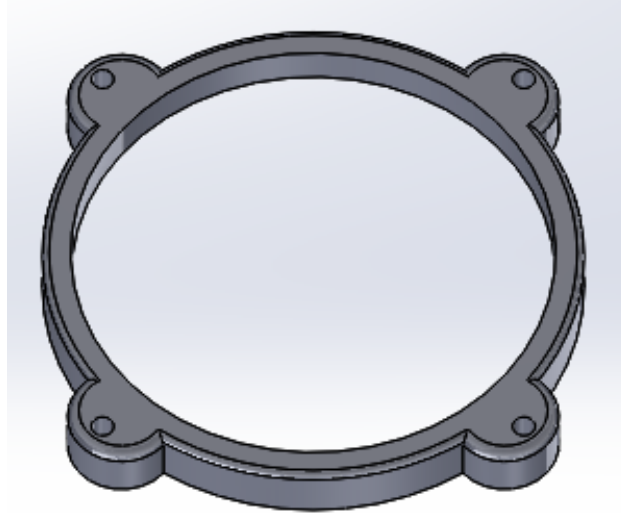


Figure 23: A top view of the redesigned fan mount

Name	QTY	Link	Unit Price	Unit Mass	Total Price	Mass (kg)
T6:1 Micro Metal Gearmotor HP 6V with Extended Motor Shaft	4	<a href="https://www.pololu.com/product/2215">https://www.pololu.com/product/2215</a>	\$16.95	0.0095	\$67.80	0.038
Magnetic Encoder Pair Kit for Micro Metal Gearmotors, 12 CPR, 2.7-18V (HPCB compatible)	4	<a href="https://www.pololu.com/product/3061">https://www.pololu.com/product/3061</a>	\$8.95	0.001	\$35.80	0.004
Eddy current sensor and conditioner	1	Lion Precision		0.123	0	0.123
Powerfun EDF 50mm 11 Blades Ducted Fan with RC Brushless Motor 4900KV	2	<a href="https://www.amazon.com/Ducted-Brushless-Airplane-49/">https://www.amazon.com/Ducted-Brushless-Airplane-49/</a>	\$28.27	0.075	\$56.54	0.15
Electronic Speed Controller	2			0.045	0	0.09
Zerodur Puck Tower	1			0.0355	0	0.0355
Puck Tower Plate (Zerodur?)	1			0.0097	0	0.0097
RPI 3B	1	<a href="https://www.adafruit.com/product/3055?sr=raspberrypi">https://www.adafruit.com/product/3055?sr=raspberrypi</a>		0.0412	0	0.0412
Adafruit 9-DOF IMU - BNO 055	1	<a href="https://www.adafruit.com/product/2472">https://www.adafruit.com/product/2472</a>	34.95	0.003	34.95	0.003
Line Sensor Breakout - QRE1113 (Analog)	8	<a href="https://www.sparkfun.com/products/9454">https://www.sparkfun.com/products/9454</a>	2.95	0.0005	23.6	0.004
Adafruit Motor/Stepper/Servo Shield for Arduino	1	<a href="https://www.adafruit.com/product/1438">https://www.adafruit.com/product/1438</a>		0.021	0	0.021
Wheels (Hubs + Tires)	4			0.00866	0	0.03464
Teency	1			0.008	0	0.008
Carbon Fiber Chassis	1			0.159	0	0.159
Fan Mounts	2			0.026	0	0.052
18 bit I2C ADC + PGA	1			0.002	0	0.002
Wheel mounts	4			0.01	0	0.04
Robot Cover	1			0.099	0	0.099
AC-DC Onboard Converter	1			0.039	0	0.039
Cabling				0	0	0
M2.5 Bolts	20			0.0006		0.012
M2.5 Hexagonal Standoffs	4			0.0006		0.0024
M2.5 Hex Nuts	28			0.0006		0.0168
				<b>0.71606</b>	<b>\$218.69</b>	<b>0.98424</b>

Figure 24: The current BOM list



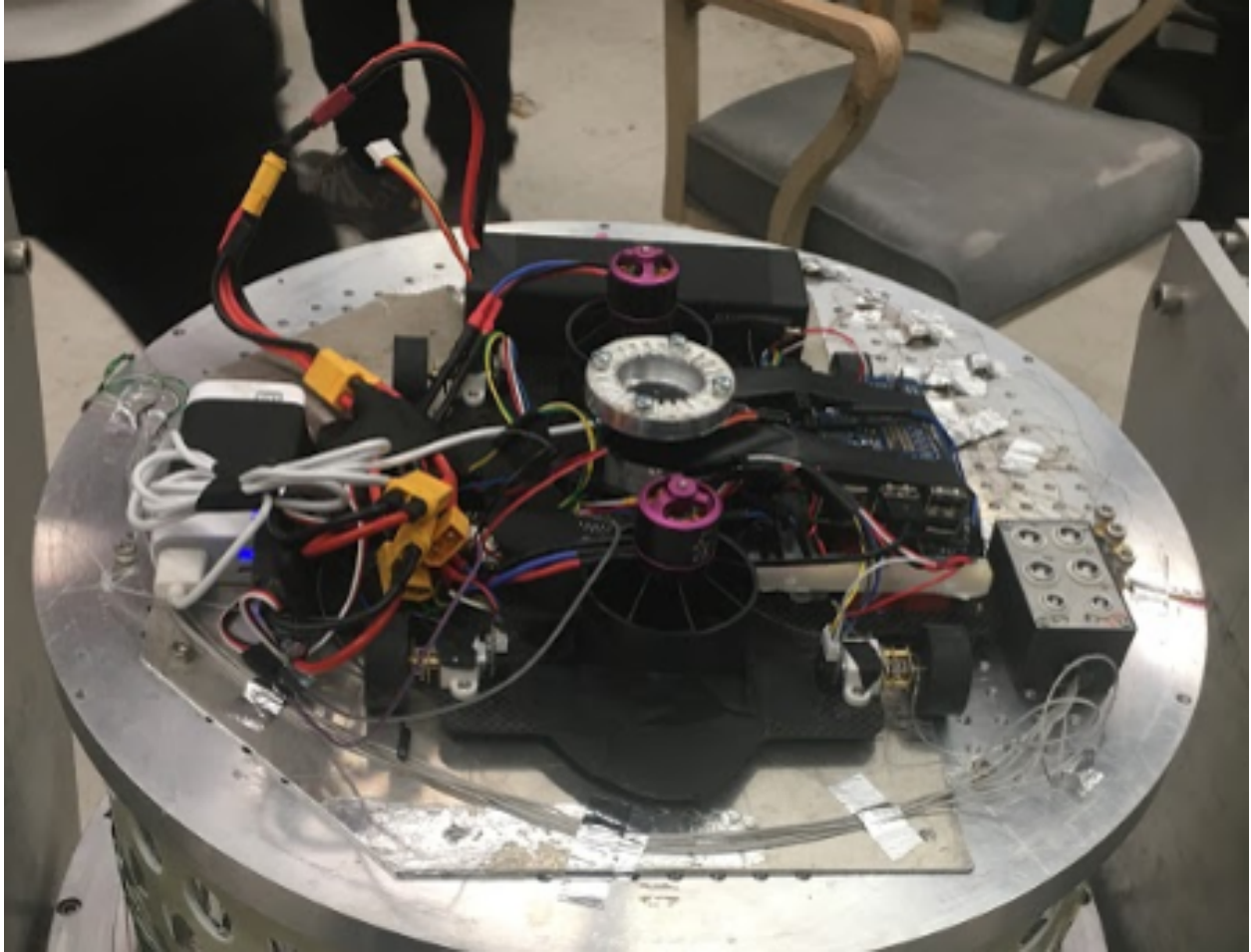


Figure 25: The first robot prototype after pressure chamber testing. Note the two fan hubs (capped in purple) and the center puck tower. Here the puck tower was modeled in aluminum rather than the final Zero-Dur material that will be used for manufacture.

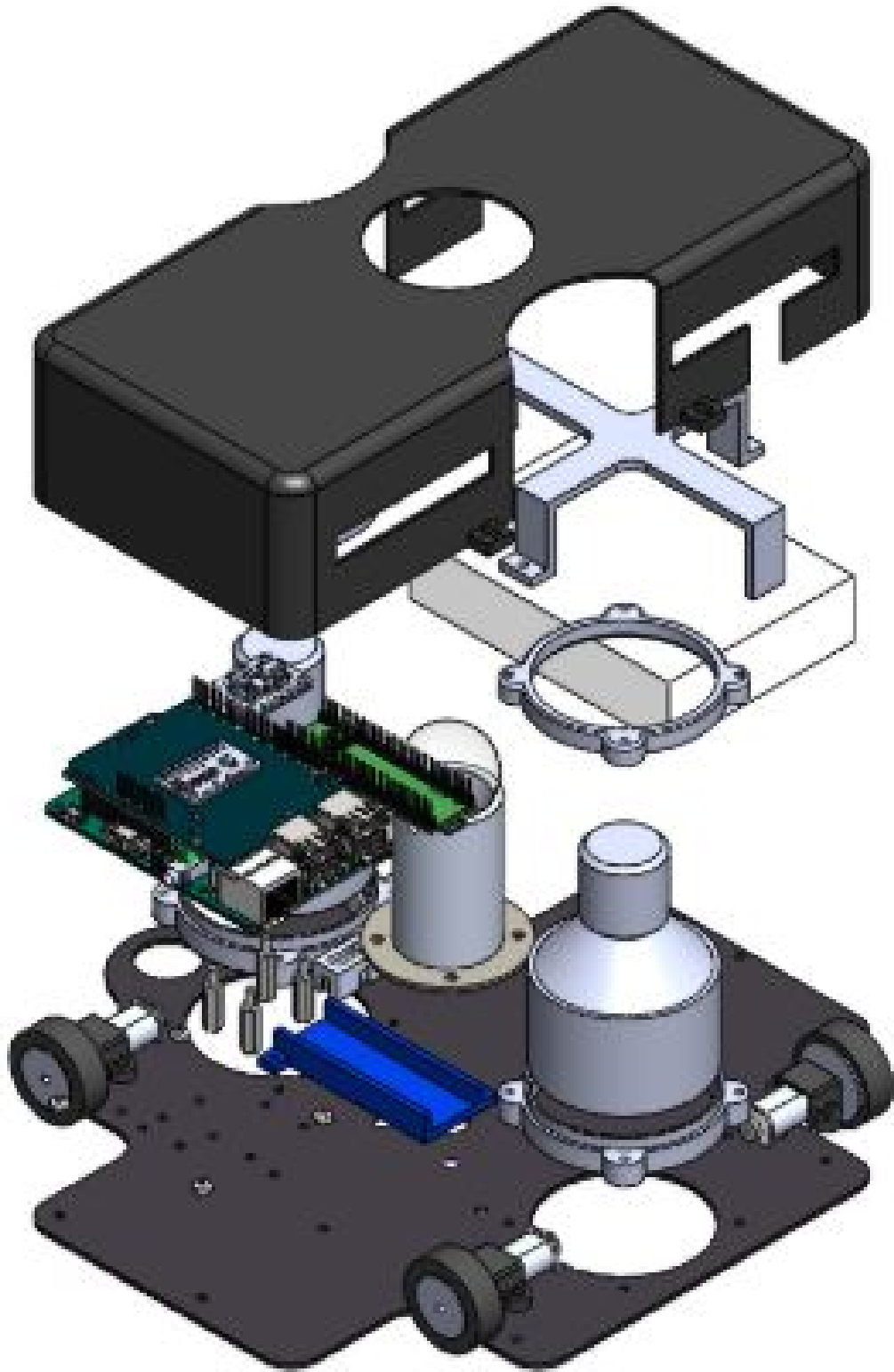


Figure 26: An exploded view of the assembly for the second robot prototype in its state as of the writing of this paper.