CCAT-P WALL CLIMBING ROBOT TESTING TEAM

M.ENG. PROJECT REPORT

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Contents

1 Abstract

CCAT-p is a 6 meter diameter telescope being built in the Atacoma Desert in Chile. CCAT-p likely stands for Cerro Chajnantor Atacoma Telescope- Prime. While many universities are involved in the construction, Cornell University, and particularly Cornell's Astronomy Department, is one of the leaders on the program. The CCAT-p Wall Climbing Robot is a sub-project for the telescope intending to measure the curvature of the telescope's mirrors semi-regularly to ensure proper alignment is maintained. This report is for MAE 6900 for an Master of Engineering (M.Eng.) Research project report by and for Becca Lublin. I worked on the Testing Team, with Hansheng Zhang and Lydia (Yuetong) Liu, and went with the robot and Bob Qian to Braunschweig, Germany for testing.

2 Introduction

The CCAT-p Wall Climbing Robot aims to aid in the completion of a test on the curvature of the mirrors on the CCAT-p ground telescope being built in Chile, to be operational starting in 2021. Cornell University is the main US sponsor for the telescope, working in conjunction with Etalon Gmbh in Braunschweig, Germany and a Canadian university. Cornell is designing the science while Etalon is working on the optics and Canada the telescope itself. Etalon uses a laser system to measure the curvature by reflecting off a puck that is moved about to different points within a field. The lasers measure relative position. Typically, the puck is held at the end of a long stick by a human person and moved about manually, but the CCAT-p telescope has a diameter of 6m and thus would be too large to do this effectively. The solution is our robot.

The project was started last Fall 2018, and is ongoing through this semester (Fall 2019), to be completed by Summer 2020. In order to move the project forward, the team planned to have a working deliverable to send to test functionality with Etalon's laser tracking system in Germany in mid-November 2019.

3 Testing Overview

The testing team's job was to take the requirements of the robot, specifying where needed, and creating tests to confirm requirements were met. There were 27 requirements the robot needed to be able to meet, but certain tests took precedence over others. The key tests that needed to be completed before the robot left for Germany were an eddy current sensor test, pressure test, and fan test. I also tacked on Humidity test.

3.1 Top Level Requirements

At the beginning of the semester, we, the Robot Testing Team, went through the Top Level Requirements, given by the CCAT-p project to the Robot team, and a list of potential Functional Requirements made last academic year by the overall team.

CCAT-p Wall Climbing Robot Requirements

1. CCAT-p Environmental Requirements
   (a) Operating air temperature: -21°C to +9°C
   (b) Survival air temperature: -30°C to +25°C
   (c) Air pressure: 50 to 53 kPa
   (d) Relative humidity: 0 to 90 %
   (e) The observatory provides single phase 230 V, 50 HZ AC power. Observatory plug receptacles are CEE 7/3.
2. Measurement Program
   (a) Retro-reflector must be placed at a minimum of 5 points per panel (over Z adjusters, with a goal of 9 points (additional 4 points between outer adjusters)
      i. Primary mirror: 87 panels, approximately 30 incline
      ii. Secondary mirror: 78 panels, approximately 20 overhang
      iii. Each panel face is approximately 675 x 675 mm
   (b) Placement repeatability is 1 cm absolute
   (c) Retro-reflector z-axis offset from mirror surface measurement or repeatability is 0.5 micrometers RMS
   If z-axis offset is being established via measurement, z-offset measurements must be synchronized with Etalon measurements to within 1 ms, not accounting network latency. (NB: Etalon/Project should weigh in on synchronization)
   (d) Total mirror measurement time should not exceed 1 hour per mirror.
   (e) The robot must navigate in a pre-planned path across each mirror surface, stopping for each measurement.
   (f) At each measurement position the robot control system must broadcast a start single measurement request to the Etalon multiline server
   (g) The Retro-reflector must be unobscured to the laser measurement system (60 degree of clearance around)
   (h) The robot cannot inject greater than 1 micrometer RMS of un-filterable vibration into the mirror surface during measurements.
   (i) Measure multiple elevation angles in one night without human interaction.
3. Safety and Operability
   (a) The robot cannot become detached from the mirror surface, or if detachment occurs cannot impact any mirror or observatory surface or equipment
   (b) The robot must be capable of completing a full measurement cycle of one mirror without interruption (i.e., the robot must be continuously operable for the duration of one mirror measurement cycle)

   (c) The robot cannot drive off of the edge of the mirror
   (d) In the event of any operational anomaly, the robot must be capable of placing itself in a safe mode
      i. Safe mode is defined as the robot meeting all safety requirements in a full power-off state
      ii. An operational anomaly is defined as a violation or potential imminent (within 1 s) violation of any safety or operability requirement
   (e) The robot must be capable of traversing the mirror surfaces, including any surface gaps or defects
   (f) The robot cannot be capable of scratching, scuffing or in any other way damaging or affecting the performance of any mirror surface.
   (g) The robot must be capable of carrying out the measurement program (Sec. 2) in the full range of environmental conditions (Sec. 1)
   (h) The robot must survive and be capable of placing itself into a safe mode in the event of total loss of observatory power
   (i) The robot must reply to Observatory Control System alarms/alerts (interface must be provided by project)
   (j) The robot must operate safely in the event of an earthquake, up to acceleration of 1 g.
   (k) The robot has a series of voltage dividers to prevent damage when it is tethered.

4. Requests
   (a) The project has requested that at least one design carried forward include a physical tether between the robot and the observatory structure
      i. The tether system may not interfere with the measurement program in any way
      ii. The tether must be used to satisfy safety requirements and can be used to satisfy the existence of the safe mode
   (b) The total robot mass must be treated as an evaluative factor in selecting the design (mass should be minimized)
   (c) Robot shall be able to ‘orient’ itself (with turning) on corner of panel within TBD seconds
   (d) Robot shall be able to ‘orient’ itself (without turning) on corner of panel within TBD seconds
   (e) Robot shall be able to rotate 90 degrees with < TBD error.

3.2 Functional Requirements

As we went through the list, we highlighted requirements that had changed or were now defunct. Then, we checked that all Top Level Requirements had at least one Functional

Requirement that could be traced to it. We gave each Functional Requirement a Requirement ID and identified a potential qualification and acceptance test type, e.g. Etalon Test, Demonstration on Test Panels, Wheel Drive Test, if the robot met each requirement. Our final list consisted of 37 requirement IDs, as follows.

1. The suction force of the fan must exceed the weight of the robot under 50kPa air pressure conditions
    - Top Level Requirements: 1, 3.7
    - Change during Semester: No change
    - Test Type: Pressure Chamber Test
2. The electronic control systems will not be damaged by temperatures between -30°C and +25°C
    - Top Level Requirements: 1, 3.7
    - Change during Semester: Added
    - Test Type: Thermal Test
3. The electronic control systems will not be damaged by a 90% relative humidity environment
    - Top Level Requirements: 1, 3.7
    - Change during Semester: No change
    - Test Type: Humidity Test/Specification Sheets
4. The robot will have a series of voltage dividers/regulators to prevent damage to the microcontroller and other electronics.
    - Top Level Requirements: 1
    - Change during Semester: No change
    - Test Type: High Voltage Test
5. Distance between center of puck and edge of robot must be less than the distance between edge of mirror and measurement points
    - Top Level Requirements: 2.1
    - Change during Semester: No change
    - Test Type: Demonstration on Test Panels
6. The point locations to be measured on each panel must be standardized
    - Top Level Requirements: 2.1
    - Change during Semester: No change

- Test Type: Demonstration on Test Panels

7. The robot will be told which of the two mirrors it is measuring and in which orientation
   - Top Level Requirements: 2.1
   - Change during Semester: No change
   - Test Type: GUI Demonstration
8. The robot must be able to determine the puck's position on a panel to 1 cm accuracy
   - Top Level Requirements: 2.2
   - Change during Semester: No change
   - Test Type: Demonstration on Test Panels
9. The robot must be able to determine when it crosses onto each new panel
   - Top Level Requirements: 2.2
   - Change during Semester: No change
   - Test Type: Demonstration on Test Panels
10. If the puck is actuated, there must be feedback control on the actuators to ensure the .5RMS requirement is satisfied
    - Top Level Requirements: 2.3
    - Change during Semester: No change
    - Test Type: Etalon Test
11. Actuation of puck must place eddy current sensor off mirror surface between 0.35mm and 2mm
    - Top Level Requirements: 2.3
    - Change during Semester: No change
    - Test Type: Demonstration on Test Panels
12. The robot must have a speed of 150 mm/s
    - Top Level Requirements: 2.4
    - Change during Semester: No change
    - Test Type: Data from IMU
13. Deleted: The robot must have sufficient battery life (1 hour) to complete its task without needing to be charge. Requirement no longer applicable due to confirmation of tethering.
14. The robot will have a pre-planned path

- Top Level Requirements: 2.5
- Change during Semester: No change
- Test Type: Demonstration on Test Panels

15. The micro-controller will have a procedure for troubleshooting communications
    - Top Level Requirements: 2.6
    - Change during Semester: No change
    - Test Type: Etalon/Here Test
16. The robot must be able to communicate with the Etalon multiline server (WiFi), or at minimum its router.
    - Top Level Requirements: 2.6
    - Change during Semester: Added router to requirement
    - Test Type: Etalon Test
17. Reflector holder and tether must allow 180 degrees of clearance around the reflector
    - Top Level Requirements: 2.7
    - Change during Semester: Change from 60/120 degrees to 180 degrees
    - Test Type: Static Measurements
18. The robot cannot vibrate surface more than 1 micrometer RMS of un-filterable vibration
    - Top Level Requirements: 2.8
    - Change during Semester: Added
    - Test Type: Vibration Test
19. The robot will be able to measure multiple elevation angles without human interaction within a period of 12 hours.
    - Top Level Requirements: 2.9
    - Change during Semester: Added
    - Test Type: Demonstration on Test Panels
20. The robot wheels will have sufficient grip with surface with no slippage in vertical configuration under -30°C and 90% relative humidity
    - Top Level Requirements: 3.1
    - Change during Semester: No change
    - Test Type: Wheel Drive Test under Worst Case Conditions

21. The robot will be able to sense if it starts to detach from the mirror surface
    - Top Level Requirements: 3.1
    - Change during Semester: No change
    - Test Type: Demonstration on Test Panels
22. The robot will have a method of minimizing damage to itself if it falls from the vertical mirror
    - Top Level Requirements: 3.1
    - Change during Semester: No change
    - Test Type: Fall Damage Mitigation Test

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23. The robot will be able to sense if there is not another mirror panel past a panel edge it was intending to drive over
    - Top Level Requirements: 3.3
    - Change during Semester: No change
    - Test Type: Demonstration on Test Panels
24. For each failure mode, there will be a corresponding troubleshooting or safe mode procedure
    - Top Level Requirements: 3.4, 3.8
    - Change during Semester: No change
    - Test Type: Demonstration on Test Panels
25. The robot will return to the base of each mirror in the event of an anomaly or failure
    - Top Level Requirements: 3.4, 3.8
    - Change during Semester: No change
    - Test Type: Demonstration on Test Panels
26. The robot will know the fastest route to the base of the mirror as part of its pre-planned trajectory
    - Top Level Requirements: 3.4
    - Change during Semester: No change
    - Test Type: Demonstration on Test Panels
27. The robot must be able to traverse mirror surfaces, including surface gaps or defects

- Top Level Requirements: 3.5
- Change during Semester: Added
- Test Type: Surface Test

28. The robot must not damage surface of mirror
    - Top Level Requirements: 3.6
    - Change during Semester: Added
    - Test Type: Surface Test
29. The robot must survive complete loss of observatory power
    - Top Level Requirements: 3.8
    - Change during Semester: Added
    - Status: Battery Testing
30. The robot must detect loss of observatory power
    - Top Level Requirements: 3.8
    - Change during Semester: Added
    - Test Type: Signal Test
31. The robot must respond to Observatory Alarms/alerts
    - Top Level Requirements: 3.9
    - Change during Semester: Added
    - Test Type: Etalon Test
32. The robot must operate safely during an earthquake with accelerations up to 1g
    - Top Level Requirements: 3.10
    - Change during Semester: Added
    - Test Type: Shake Table Test
33. Tether must retract faster than the robot's pendulum swing in case of robot detachment
    - Top Level Requirements: 4.1
    - Change during Semester: No change
    - Test Type: Etalon Test
34. Tether must be approximately parallel (allowed to be non-parallel up to 30°to mirror) to the mirror surface to eliminate potential interference with laser measurements
    - Top Level Requirements: 4.1

- Change during Semester: No change
- Test Type: Etalon Test

35. Robot shall be able to orient itself on corner of panel with turning within TBD seconds
    - Top Level Requirements: 4.3
    - Change during Semester: Added
    - Test Type: Demonstration on Test Panels
36. Robot shall be able to orient itself on corner of panel without turning within TBD seconds
    - Top Level Requirements: 4.3
    - Change during Semester: Added
    - Test Type: Demonstration on Test Panels
37. Robot shall be able to rotate 90 degrees with <TBD% error
    - Top Level Requirements: 4.3
    - Change during Semester: Added
    - Test Type: Demonstration on Test Panels

Next, we grouped the requirements by test type started writing testing instructions for 5 tests, each of us taking 1-2 tests.

- High Voltage Test
- Surface Test
- Power Loss Test
- Thermal Test
- Vibration Test

We finished writing 10 test instruction drafts by the end of September.

1. Humidity Test
2. Shake Table Test
3. Surface Test
4. High Voltage Test
5. Survive Power Loss Test
6. Thermal Test

7. Vibration Test
8. Wheel Drive Test (one of the tests I worked on)
9. Accuracy Test
10. Cross onto a new Panel Test

Following the completion of the first drafts of these tests, we started looking into where we could find the equipment needed for each test. First, we investigated if we could do the test with the equipment available in the robot lab, with hand tools. Then, we identified any large chambers or machinery we might need, and researched if it was available in the Cornell University Mechanical and Aerospace Engineering (MAE) Labs. If the equipment was not in the MAE Labs, we researched if it was available elsewhere on campus. Four tests needed equipment elsewhere on campus, and we notated what machine, what school and department on campus, and who the contact was for that lab.

- Pressure Chamber Test
  - Machine: High Pressure Validation Center
  - Equipment Contact: Thomas Nikola, TN46
  - Department: AS: Astronomy
  - Testing Team Contact: Hansheng
  - Website: https://foodscience.cals.cornell.edu/about-us/facilities/geneva-facilities/hpp-validation-lab/
- Thermal Test
  - Machine: TA Instruments Q400EM Thermo-mechanical Analysis
  - Equipment Contact: Philip Carubia, PMC228
  - Department: Engineering: Material Science
  - Testing Team Contact: Hansheng or Lydia
  - Website: https://www.ccmr.cornell.edu/instruments/ta-instruments-q400em-thermomechanical-analysis-tma/
- Humidity Test
  - Machine: Cornell AES Growth Chamber Prototypes
  - Equipment Contact: Nick Van Eck, NJV1
  - Department: CALS: Food Science
  - Testing Team Contact: Becca
  - Website: https://cuaes.cals.cornell.edu/greenhouses/sustainable-growth-chambers/

- Surface Test
  - Machine: Micro Hardness Tester
  - Equipment Contact: Philip Carubia PMC228
  - Department: Engineering: Material Science
  - Testing Team Contact: Hansheng or Lydia
  - Website: https://www.ccmr.cornell.edu/instruments/micro-hardness-tester/

Lydia and Hansheng organized the Pressure Test by emailing first Stephen Parshley and Terry Herter for the best contact who directed them to Thomas Nikola. In order to use the chamber, the robot needed to be battery powered for the duration of the test, connected to the wifi router, and stand on a base plate. They measured dimensions for the base plate and completed the High Voltage Test on the transformer to get an average transformed voltage result at 12.18V. Hansheng located a thin plate of scrap metal, and I took it to the machine shop and cut it to dimension.

4 Test Plans

4.1 Pressure Test

The first step for the pressure test was organization and writing a drafted plan. Hansheng wrote the initial test plan, see below. Under 0.5 atmosphere, the fan will provide enough suction force.

Test Requirement ID	1
Top Level Requirement	3.7
Test Classification	Pressure heightChamber Test
Author	Hansheng Zhang
Version	1
Number of people for testing	2
Location	Space Sciences Building, Ithaca

Objective The ultimate goal is that the fan will provide enough suction force when the surrounding air is at 50kPa air pressure (0.5 atmosphere, 350 torr).
Scope The operating environment is 50 to 53 kPa air pressure. In this environment, the robot will be able to attach on the surface panel, which means that the fan could provide enough suction force.
Safety Equipment
Safety glasses

Insulating gloves
Testing Location Space Sciences Building Room 210
Required Materials Robot (connected by WIFI and powered by battery), PC, Router, Stop Watch
Testing Environment 0.5 atmosphere, temperature TBD since nitrogen will be added into the testing facility

4.1.1 First Draft Testing Procedure

This is the written test procedure available in the CCAT-p robot test folder, written by Hansheng Zhang.

1. Set the pressure of the pressure chamber to 50 kPa and make the condition stable.
2. Before placing the robot, run through range of motion for plate and pressure change steps below.
3. Start the robot and fans.
4. Rotate the testing plane 30 degrees, respect to the horizontal plane.
5. Observe through the window on the cover and determine whether the robot is attached to the testing plane in a stable way.
6. If the robot attaches to the plane stably, try to move the robot forward or backward for a couple centimeters.
7. Keep running the test for 5-10 minutes.
8. Record running time.
9. Repeat procedure 3 - 7 by setting the angle between the testing plane and horizontal plane to 60 degrees, 90 degrees, 145 degrees and 180 degrees.
10. If the robot passes all of the above tests, try to rotate the testing plane up and down. Record the status of the robot. Does it still attach to the testing plane in a stable way? Is the robot able to move a little bit?

In order to use the pressure chamber available in the Astronomy Department

4.1.2 First Round/Second Draft Testing Procedure

This testing procedure differed from the first draft in that the robot was not ready for certain parts of the test procedure and certain functions. This is my (Becca Lublin) observation of the steps followed on the first trial, which took place on October 23rd.

1. Set up the testing equipment
2. Place Base Plate
3. Attach Base Plate with three screws to table (Note: The footprint was a little off due to measurements being imprecise and the holes had to be expanded slightly so that the screws would attach to the underlying table.)
4. Set up WIFI connection (Note: The network was not working and we had to go grab a monitor from the lab. This problem was fixed with the router being movable.)
5. Open the GUI
6. Attach robot to battery pack
7. Connect TCP
8. Turn robot on
9. Turn robot off
10. Place robot on base plate
11. Tape sensors to table with aluminum tape
12. Cover table with chamber cover using 12 large bolthead screws from below
13. Seal chamber with Nitrogen gas
14. Connect chamber to vacuum pump and barometer
15. Turn pump on
16. Pump air out until barometer reads 350 torr.

17. Adjust the pressure until it settles around 350 torr (Note: Stopping the pump does not guarantee pressure will stay at the point)
18. Turn robot on
19. Drive robot forward 5 cm and back 10 cm, to check electronic functionality.
20. Turn fans on
21. Turn fans off
22. Turn robot off
23. Disconnect TCP
24. Reverse pump. Bring pressure back up to room pressure.
25. Disconnect pump and barometer
26. Open pressure chamber
27. Remove robot and equipment
28. Clean Up

The results for this round of testing were that the robot could move and the electronics worked beneath 0.5 atmosphere.The robot was not ready for rotational testing at this point.

4.1.3 Second Round/Third Draft Test Instructions

By the time we did the second round pressure test, the new fans had been mounted, the GUI had been edited, and the Eddy Current Sensor was broken and in the process of being repaired or replaced via the Controls Team. The second round test was somewhere between the original test instructions and the first round test instructions. The robot was connected to the base plate by three tethers for safety reasons and the intent was to rotate the plate at 0.5 atmosphere until the robot began to slip, at which point we would lower the angle slowly back down to zero. The pressure chamber rotated on the outside connecting to a rotator disk with holes along the rim. Each hole was a distance

of 10°from the previous hole, which allowed for a smooth transition between angles. Unlike the first round of testing, the goal was not for the robot to be able to move, but to successfully hold on with the fans going.
We started the test at 10°, as that is the angle at which we needed while sealing the table. After turning the fans on, we slowly rotated the disk from 10°to 80°while filming the robot to check where it slipped. The fans died somewhere between 40°and 70°, as the fans drained the battery within a few minutes. We determined that we needed a stronger battery for a longer life inside the test fixture.
Our contact in the Astronomy Department recommended an Absorbed Glass Matte (AGM) Battery. The battery is completely sealed, preventing toxification of fixture due to pressure. It has a high power density. Per the available space in the pressure chamber next to the robot, the holder needed to have dimensions of 7"x6"x4".

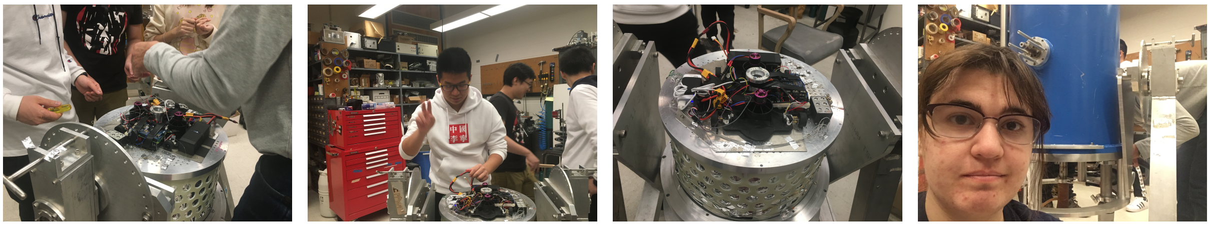

Figure 1: Pressure Test Set Up

4.2 Humidity Test

I spent most of November working on organizing the Humidity Test and preparing for the Etalon Tests, which are the next section. I identified the plant growth chambers as the best compared to a humidity chamber. There are over 125 plant growth chambers at Cornell organized by the College of Agriculture and Life Science. As Nick told me, less than half have the capability of removing humidity for a tight set point. they ranged in age between 10 and 20 years old, have a humidity range of 30-85% RH (Relative Humidity). Some of those are 30-70% while others are 50-85%, with a tolerance of about 5% RH. He also mentioned some small, reach-in chambers designed to run at 100% humidity that are in the Plant Pathology Department, and gave the contact person Shan Jin's information, sj723@cornell.edu.

During a meeting in early-November, Stephen Parshley pointed out that relative humidity in the chamber would be different in Ithaca than in the environmental conditions mentioned. The environmental requirements state that the robot needs to survive between 0% and 90% *Relative* Humidity, not *Absolute* Humidity.

Building on that, I researched the environmental conditions of Ithaca, NY, and Cornell University specifically. On the Cornell website, I found that Ithaca, NY has an average pressure of 98.2 kPa. We know from the environmental requirements that the air pressure in Chile will be between 50 to 53 kPa, and the temperature will be between -21°C and 9°C. Relative Humidity is defined as

$$RH = \frac{m_{vap}}{m_{vap,max}} \tag{4.1}$$

where m_{vap} is the mass of vapor and $m_{vap,max}$ is the maximum possible mass of vapor. Using the ideal gas law,

$$\begin{aligned} PV &= mRT \\ m &= \frac{PV}{RT} \end{aligned} \tag{4.2}$$

where P is pressure, V is volume, R is the gas constant, and T is the temperature. I assumed constant gas constant, temperature, and volume between the two settings and so was able to cancel those out such that I was left with $m = P$. Using ratios of the desired relative humidities, I was able to derive the equivalent relative humidity for the 90% relative humidity requirement to test in Ithaca as about 50% relative humidity. Due to the chamber constraints, I altered the test to measure between 30% RH and 50% RH.

After some back and forth, I arranged a meeting with Nick and Marc Daly to see the Emerson Lab chamber in Bradfield Hall G-35. The growth chamber, number 18, had an available temperature range of 5-30°C, which would allow us to test the thermal environment on the warmer end while testing the humidity. The humidity was able to rise quickly, but took hours to drop, increasing the lead time necessary between tests.

Figure 2: User Interface for Humidity Test

The first part of the test was programming in the test coding to the machine. It has to be done manually and saved as a file. The program reads in 24 hour time and needs to begin at 0:01 and end at 23:59. If you want it to work right away, you need to check what time the clock is seeing and enter times based on that. As mentioned, the humidity rising is fast, but lowering is slow. I designed the test to raise the humidity at 10% per hour, and planned to drive the robot back and forth inside the chamber once every half hour.

There were some issues with scheduling with the rest of the Testing Team and the Controls Team. I first wanted to complete the test with some extra circuit boards to ensure functionality before risking the robot at 50% RH. After a couple weeks of pestering, I went into the lab and took one of each board, careful to take the ones that were not in sealed packages, i.e. neither new nor unused. When I went to complete the test, I found the chamber humidity had risen to nearly 85% RH. I reprogrammed the humidity to drop down to the start conditions for the test, but it was dropping at a rate of about 3-4% per hour. I decided to come back the next day, and found that the chamber was much closer to the starting humidity, but not quite there yet. I tried to go back a couple other times that week, but soon turned my focus to the Etalon Tests as those were more important in the short term. Any repeat testing of the chamber will likely need to be completed over multiple days, so as to give the chamber time to decrease in humidity to the starting point.

5 Etalon Tests: Braunschweig, Germany

5.1 Travel Preparation

The initial deadline to get the robot ready to ship off to Etalon in Braunschweig, Germany was the end of November if shipping, but second week of November if carrying. There was always the plan to have a couple people from the team go with the robot to perform the tests. There was a board review meeting on October 30, 2019 and we wanted to have a physical robot to show and demonstrate by that point. As there was a redesign this semester to meet the changed requirements for visibility (Req. ID 17) and for more powerful fans to increase the suction force, there was some uncertainty in September about whether the older version with the old fans would be sent or the newer version with the new fans would be sent. The new fans were added in mid-October, and so the newer version was slotted to head to Germany. Around the same time, the team decided to send two people to Germany with the robot, one testing team member(me; Becca Lublin) and one mechanical team member (Bob Qian). I started work on the Etalon Test Plan. I grouped the tests into categories, and then identified which ones the robot was ready to test in. These requirements were the following.

- Software
  - (15) Troubleshooting Communications
  - (16) WIFI Connection
  - (31) Emergency Response
- Tether

- Tether retraction
- Angle

- Feedback Control
  - (10) 0.5 micron RMS
- Vibration
  - (18) 1 micrometer RMS vibrations
- Demonstration on Test Panels: 12 tests: 5-6,8-9,11,14,19,21,23,24,25,26

Right away, we can eliminate the tether requirements, as the tether has not been designed yet. The robot actuation is not yet ready, so that one is out. We have Test Panels in the Cornell lab, so we can do those in Ithaca. This brings it down to only the Software and Vibration Requirements. After speaking with the team, I added that the robot uses its own network via a router for the wifi connection and Etalon is not the Observatory, so we can't test emergency responses and so can eliminate those as well. We can still troubleshoot the communications, but that is something we do as we go and can be done with the Cornell lab. So that brought us down to just the Vibration Requirements. It wasn't until later that I was able to fully identify what we were trying to do in addition to the Vibration Testing, namely the Repeatibility and Functional Tests. The Vibration Testing, which was originally one of my test plans, was altered to use Etalon testing rather than a shake table, once the team identified what vibrations would matter most.

While working on the test plan, I arranged time to talk to both the Controls Team and Mechanical Team to get a better understanding of the robot subsystems. Eddie walked Bob and I through the GUI in mid-November, and we made sure that it would work on both our laptops, and that we could redownload a new version if needed from the drive in a reasonable amount of time. Bob gave me a brief overview of the functions and where the Mechanical Team was at, a little more in depth than the weekly meetings did. We had one packing list, split into sections consisting of Robot, Paperwork, Clothes, Travel Things, and Homework. We planned to bring the minimum amount of luggage, so that we could carry everything on and not worry about losing parts of the robot in lost baggage on the way. Through some research,

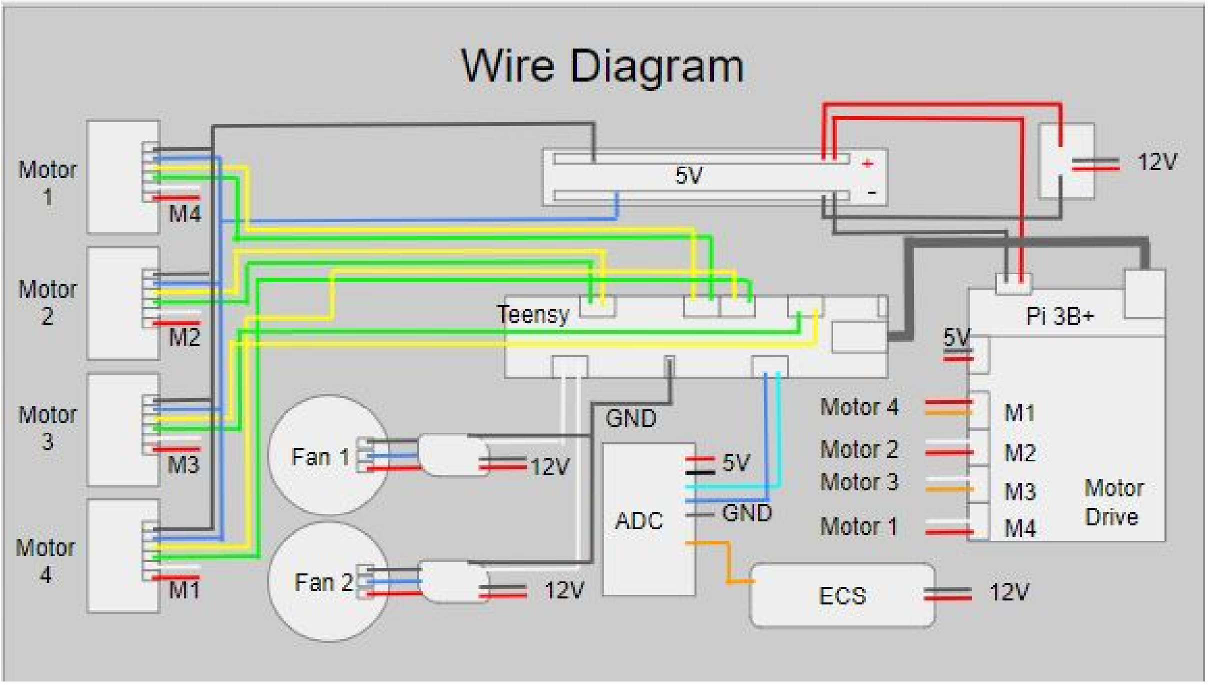

Figure 3: Wire Diagram

we found an aluminum case with foam layers, that we cut to the shape of the robot using an exacto knife. For the remaining space, we cut slots for extra parts such as an extra fan, extra Pi and Arduino boards, and connectors. Only including what is directly related to the robot, the needed inventory to bring to Germany and back to Ithaca was as follows, included here for reference for the next trip to Etalon. Also included is what we needed that we didn't have.

- Robot
  - Entire robot
  - 1 Spare Fan
  - 2 Spare Sets of Fan mounting brackets
  - 1 Spare Arduino Board
  - 1 Spare Raspberry-Pi Board
  - Transformer+cables
  - Extra Wires
  - Extra Connectors

Pin Layout.JPG

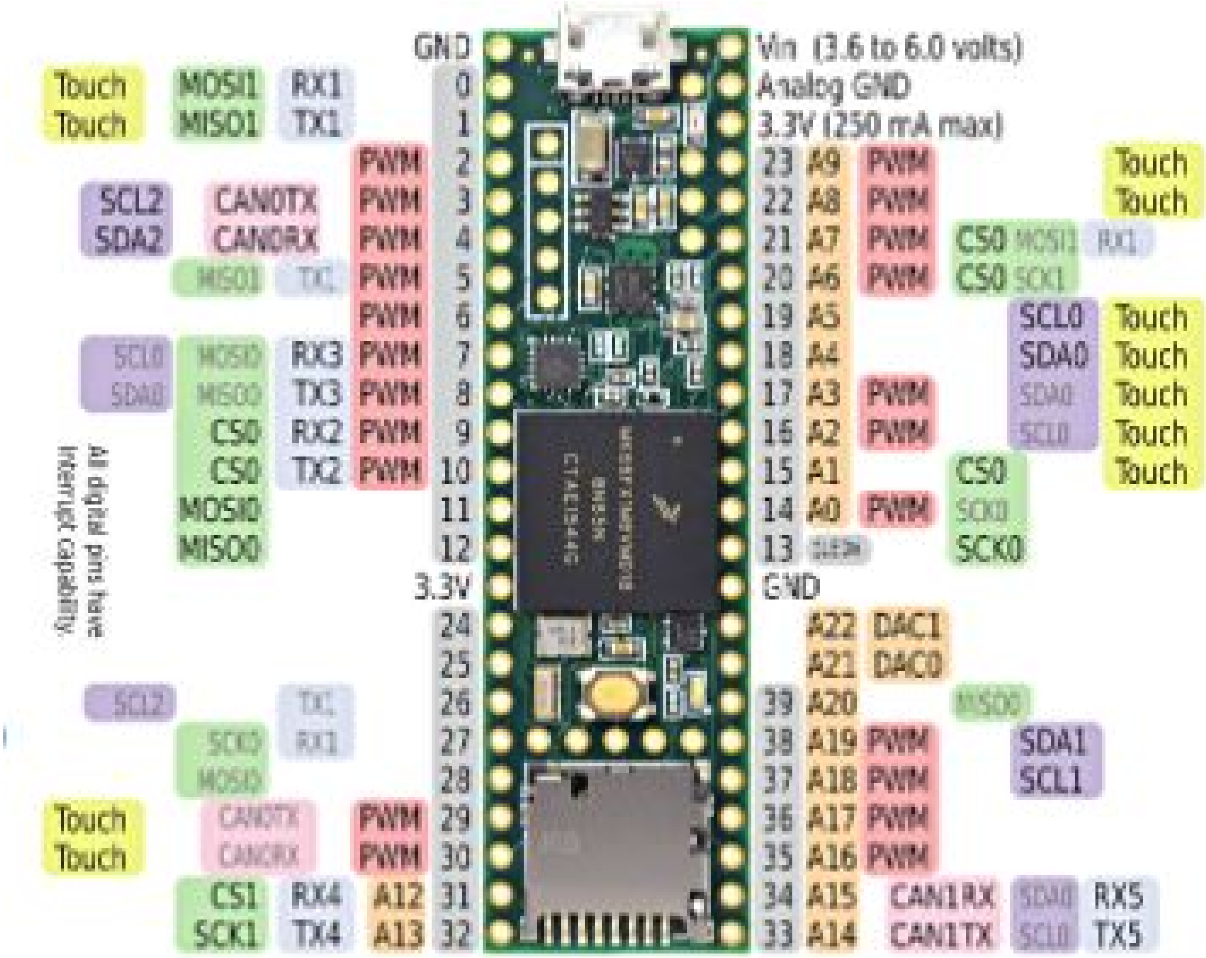

Figure 4: Teensy Board Pin Layout

  - Plug Adaptors (2)
  - HDMI to USB cable
  - Router
  - Ear Plugs, for hearing protection.
- Paperwork
  - Pin Diagram
  - Inventory
  - Wiring Diagram
  - Etalon Test Instructions/Data Street
  - Carry-on Flight Restrictions (FAA and EU)
  - Letter from Terry; translated into French and Dutch for layovers.
- Things We Needed but Didn't Bring
  - Battery and Battery Charger (Note: FAA guidelines say that our batteries are okay, but its pushing the bounds.)
  - Transformer for 230V to 12V
  - Cable Ties
  - Extra wheel and motor
  - Eddy Current Sensor Specification Sheet
  - More Hearing Protection (ear plugs work)

We had originally intended to bring a cover for the robot that would cover up the wiring, but we had some issues fitting it with the wire bend radii and so left it behind.

5.2 Test Day 1: 4 December 2019

Etalon Gmbh is a small company in Braunschweig Germany consisting of about 30 employees. The Managing Director is Heinrich Schwenke and the CCAT-p Project Director is Jim Blair. We started the day with a brief introductory meeting with project leaders and Etalon employees including team members Stephen Parshley, Mark Wissmann, Guido Natura, Jian Fang, Ronan Hiegns, and more.

At around 10:00 Central European Time (CET), Bob and I began setting up the robot in the Etalon facility with the help of Etalon Engineer Jian Fang. The router was successfully connected immediately, and, after pulling up the Control Team's User Guide for reference, I switched my computer onto the CCAT-p robot WIFI while Bob kept his on Etalon's WIFI. Etalon gave us a reflector, roughly the same as expected but heavier, and it was carefully mounted in the puck tower. The ball had a Roundness of 150 nm, and needed to be handled with a glove and cloth in order to avoid any smearing due to fingerprints or oils. The robot was massed at exactly 1.00 kg.

The transformer was then plugged in, but did not turn on. Several outlets and several converter blocks were tried with no success until the problem was identified as being in the power conversion from 230V to 110V, in other words, the problem was in the standard European to US power plug converter. While the plugs work excellently for less picky electronics like laptops and phone charge cords, the voltage does not actually change, rather the current changes so that the power reaching the electronics is about the same as it would on the designed for power. This did not work for our transformer, which only took standard US power input at around 110V. Since the voltage did not change, the transformer was overloaded and unable to get started. We solved this by finding an additional transformer that transformed the wall power 230 V voltage into US 110 V power voltage.

The second transformer imposed a maximum power limit of 500 W total power. In order to ensure we did not go over this limit for more than a millisecond, I wrote a new test plan to use a plug-in multimeter and test the fan power usage at different fan speeds.

1. Turn on robot.
2. Record power reading (wattage) and voltage from plug-in multimeter at 0% fan speed.
3. Turn fan power on to 10% fan speed using GUI.
4. Record wattage from plug-in multimeter at 10% fan speed.
5. Increase fan power in increments of 10% using GUI. Record wattage and

voltage from plug-in multimeter at each step. Continue until wattage is greater than 500 W or fan speed as 100%, whichever comes first.

6. Decrease fan power in increments of 10% using GUI. Record wattage and voltage at each step. Continue until fan speed is at 0%.

We completed the test twice for comparison purposes. The results were reproducible. The fans at full throttle drew about 525 W, while 90% throttle drew about 490 W and 10% throttle drew about 70W. With this data, we imposed a fan speed limit of 80-90% throttle.
Next, we did a short test on a separate workbench to ensure that at the new maximum throttle of 90%, the chassis would not deform in such a way that any of the screws would scratch the testing surface.
Then, we performed a repeatibility test driving the robot back and forth on the testing bench a few times and marking positional changes. There was a slight positioning change due to tether drag that was mostly accounted for in holding the cable up during subsequent tests.
Jian began calibrating the Etalon reflector (puck) to 4 Etalon lasers, with the calibration finished shortly after we returned from lunch.
We put some thin, metal plates on the testing platform to prepare for Eddy Current Sensor Testing. We noticed the sensor was a bit loose and tightened the hex nut, verified the sensor was not touching the ground, and proceeded with the sensor test. During this time, a wire from a Motor to the Teensy Board came loose, and we used the wiring diagram to re-attach the wire.
Following the earlier Repeatibility Test, that only had us, pencils, masking tape, and rulers tracking it, we ran another test, the Driving Vibration Test, with the laser tracking system active. We moved the robot back and forth at 10 cm/s over distances of 10, 30, and 50 cm with the fans off, then fans on between 10-60% in increments of 10%. During this time, Jiang collected the Etalon data, but we did not collect Eddy Current sensor data due to the long lead time in running the measurement. The Driving Vibration Test steps, which were the majority of the pre-written Etalon Test Plan, enumerated went as follows.

1. Place robot at starting point on testing surface.

2. Start taking Etalon data.

3. Using the GUI and with the fans at 0% fan speed, also known as fans off, drive the robot forward at 10 cm/s a distance of 10 cm.
4. As soon as the robot stops moving forward, drive the robot back at -10 cm/s a distance of 10 cm.
5. Stop taking Etalon data.
6. Repeat steps 2-4 for 30 cm and 50 cm.
7. Increase fan speed an increment of 10% throttle.
8. Start taking Etalon data.
9. Drive robot forward at 10 cm/s a distance of 50 cm.
10. As soon as the robot stops moving forward, drive robot back at -10 cm/s a distance of 50 cm.
11. Stop taking Etalon data.
12. Repeat steps 7-11 seven (7) times, i.e. 20%, 30%, 40%, 50%, 60%. 70%. 80%
13. Turn fans off.

Coming down to see how the test was going, Heinrich, Stephen, and staff requested we verify that the fan's air flow would not create a significant pressure change in the air that would affect laser beam. Using the robot and a second stationary puck beside the robot, we were able to confirm that the airstream does not affect the laser metrology on the stationary puck.
For our final test for day 1, we used the Etalon laser trackers to measure the vibration at 20% and 80% fan speed. The vibration was significant and far outside our requirements at both speeds, but worse at 80%.
Additional Notes:

- Etalon and Cornell agreed that the puck tower top would be titanium glued on by Etalon technicians with two part glue that could be accounted for with a multi-step calibration. This has since changed, as the design for the puck shows small slots at the equator that we can use to snap the puck into place.

- Wires were taped down beneath the height of the puck tower, with the electrical tape adding significant weight to the structure

5.3 Test Day 2: 5 December 2019

The morning of day 2 began with a lesson about the laser tracers, how they worked, and why and how they were calibrated. Then, the stationary vibration test from the end of day 1 was continued with the robot on the granite table top for 20% fan speed, 50% fan speed, and 80% fan speed, with three trials of each speed. Due to a shortage of hearing protection, of which Etalon did not have any extra, Bob ran the entire 80% experiment after learning the operation from Jian.

The steps were as follows.

1. "Ready" the Etalon system for measurement
2. Start the Fans through the GUI
3. Wait for Fans to run at speed for 3 seconds
4. Start Collecting Etalon Data
5. After about 10-15 seconds, Stop Collecting Etalon Data
6. Turn off the Fans. Jian re-enters room.

After the stationary vibration test, the driving vibration test from day 1 was continued at 70% and 80% fan speeds, again with only Bob in the room taking measurements with the Etalon system. One trial of the driving vibration test was taken at each speed. The steps were as follows, where it differed from the Data from day 1's test is the increase in speed and the first and last steps.

1. "Ready" the Etalon system for measurement
2. Start the Fans through the GUI. Increase to speed, 70% or 80%.
3. Wait for Fans to run at speed for 3 seconds
4. Start Collecting Etalon Data
5. Move robot forward 50 cm using GUI

Tol Stack.JPG

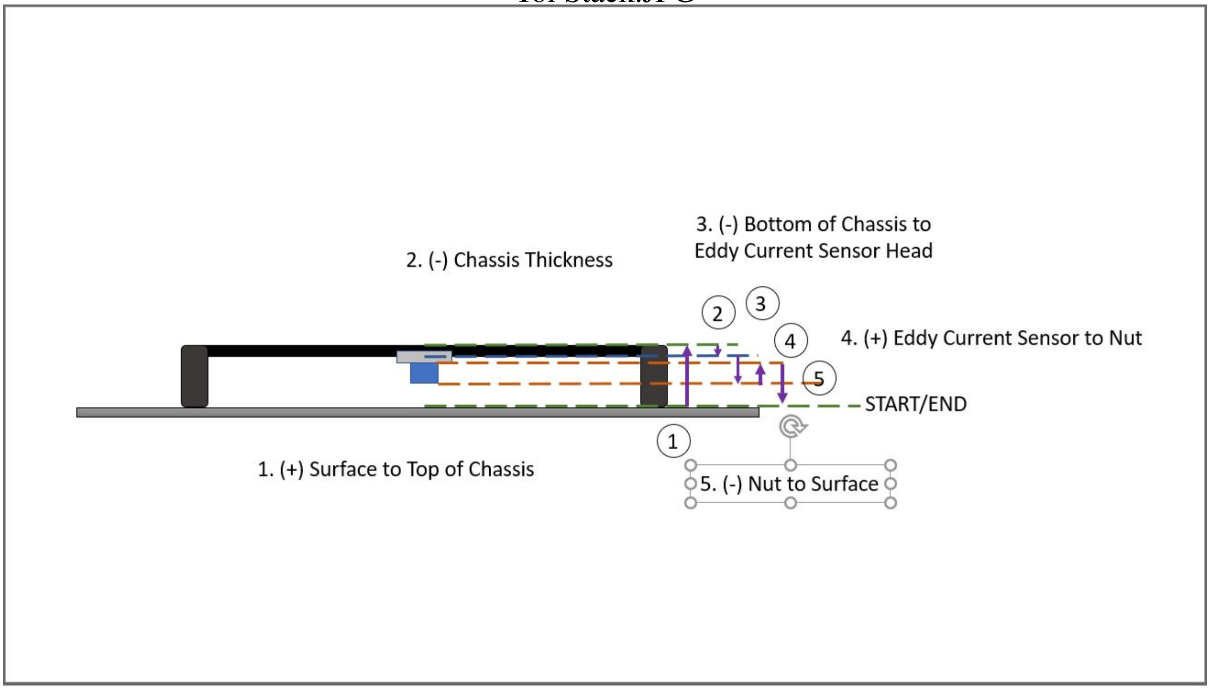

Figure 5: Measuring the Height of the Eddy Current Sensor

6. Move robot backward 50 cm using GUI
7. Stop Collecting Etalon Data
8. Turn off the Fans. Jian re-enters room.

This concluded the main results of the morning. Following lunch, changes were made to the Eddy Current Sensor in order to correct data readout to something that made sense physically. First, we lowered the Eddy Current Sensor from 3400 micron above the platform to about 1 mm. In order to measure the distance between the sensor in the ground and because of the awkward placement, we used a series of measurements with a caliper to determine the current height, which you can see in Figure 5 and the list below.

- (+) Surface to Top of Chassis
- (-) Chassis Thickness
- (-) Bottom of Chassis to Eddy Current Sensor Head
- (+) Eddy Current Sensor to Nut

- (-) Nut to Surface

When changing the height of the sensor, we had to remove the puck from the tower and the tower from the robot. In doing this, we found both a stripped wire and a loose wire. We corrected the stripped wire with electrical tape and checked the wiring diagram for the loose wire. Data immediately following the fix was a bit noisy but straightened out. Further trials showed that the noise limit rose with fan speed to the point where fanspeed covered the entirety of the expected sensor range. That said, the values recorded by the eddy current sensor were inconsistent in their centerline between trials by a significant amount. The only major change in these trials were the location of the robot, so that may or may not have caused it.

6 Results

The following table shows the power results from the first trial. The second trial results were comparable.

Fan Speed (%)	T1: Wattage(W)	T1: Voltage(V)	T2: Wattage(W)	T2: Voltage(V)
0	27.1	50.7	26.6	48.7
10	71.5	108.3	71	102
20	141.8	202.9	141	202
30	213.3	298.2	212	296
40	284.2	394.4	284	392
50	339.2	466.1	340	462
60	386.6	527.2	387	524
70	423.4	571.7	425	569
80	454.1	599.2	454	605
90	506.2	957.8	507	672
80	448.3	589.5	453	603
70	416.1	550.3	419	563
60	382.3	516.1	383	517
50	336.1	457.5	336	457
40	281.7	389.1	282	388
30	211.1	294.0	211	297
20	140.7	200.3	141	201
10	71.0	106.3	71	104
0	26.7	50.7	26.6	49.7

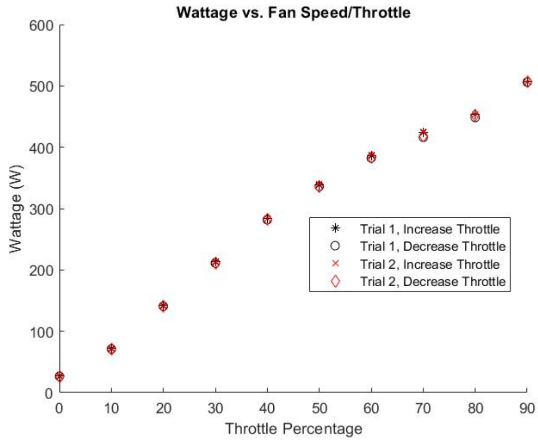

Figure 6: Wattage versus Fan Speed

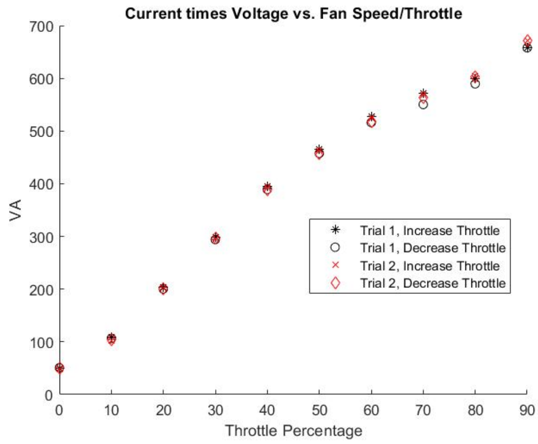

Figure 7: Current times Voltage vs Fan Speed

The following charts show some of the data taken by the eddy current sensor on day 1 and before and after the eddy current sensor was changed on day 2

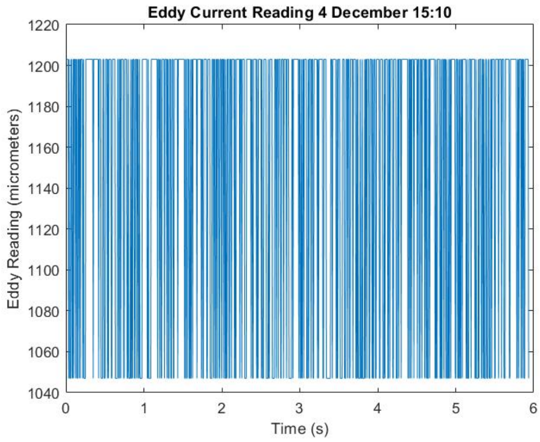

Figure 8: Eddy Current Reading Day 1 0% fan speed, 15:10

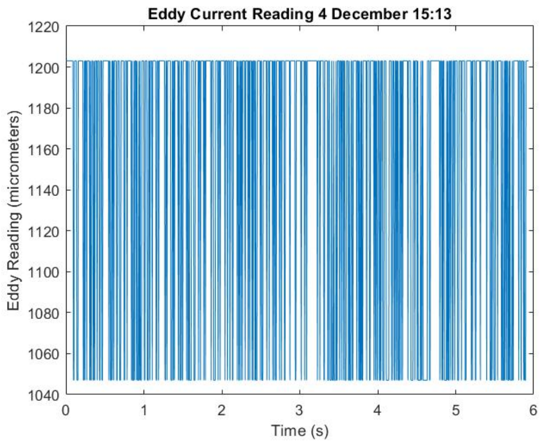

Figure 9: Second Eddy Current Reading Day 1 0% fan speed, 15:13

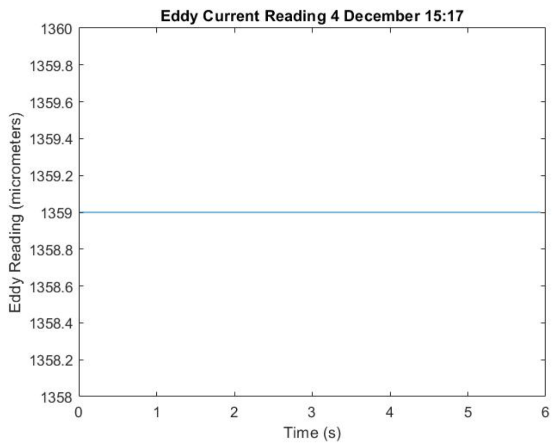

Figure 10: Eddy Current Reading Day 1 20% fan speed, 15:17

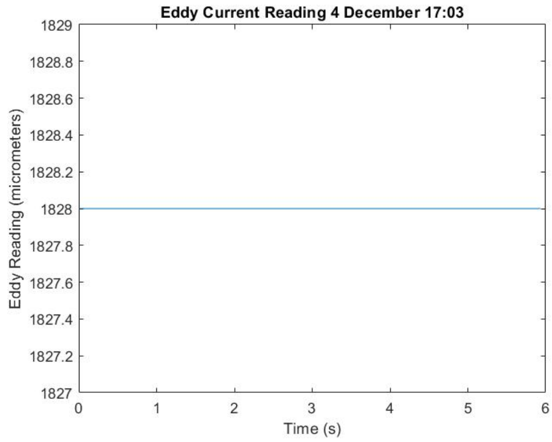

Figure 11: Eddy Current Reading Day 1 80% fan speed, 17:03

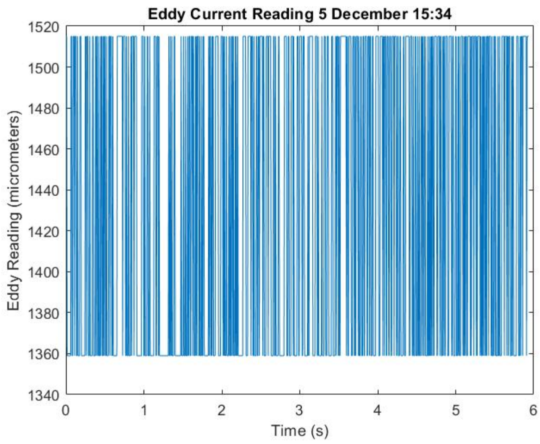

Figure 12: Eddy Current Reading immediately before changes were made, Day 2, 15:34

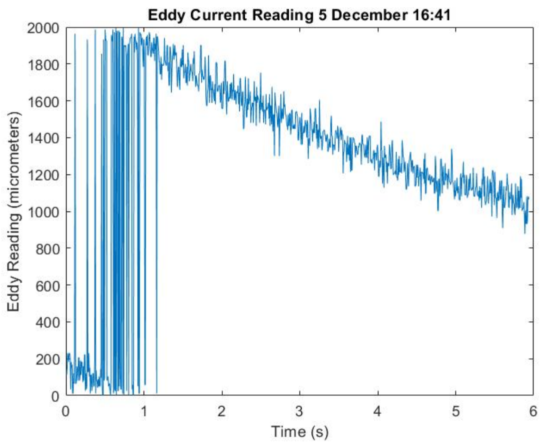

Figure 13: First Eddy Current Reading after changes were made, Day 2, 16:41

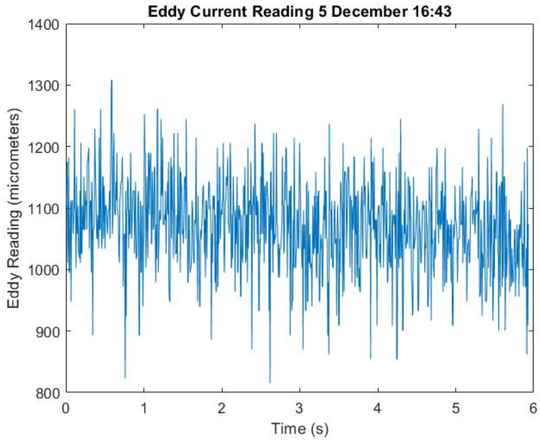

Figure 14: Second Reading after changes. The value has now evened out. Day 2, 16:43

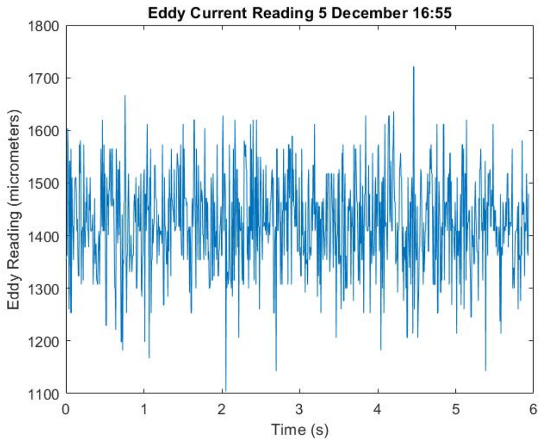

Figure 15: Eddy Current Reading after robot has moved to starting position, 0% fan speed, Day 2, 16:55

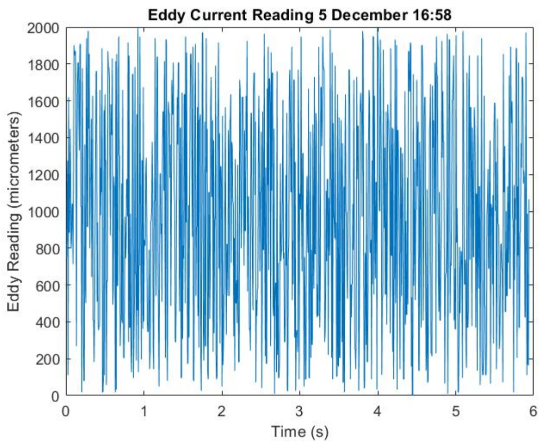

Figure 16: Same position as Figure 15, 10% fan speed, Day 2, 16:58

7 Next Steps

Some next steps for the robot will be to complete the tests already written and identify new tests for any changes of top-level or functional requirements.

- Go through current testing instructions to find any that need to be altered due to design or requirement changes
- Purchase a voltage transformer than can step down from a European Voltage of 230 V to 12 V or at least the American voltage of 110V
- Add cable ties
- Rework wiring diagram to cut down on unnecessary connections and make neater.
- Alter robot cover to account for wire bend radii
- Alter Puck Tower design to be self-supporting but not fully dense, i.e. design for additive manufacturing with minimized material.
- Cut out unneeded breadboards
- Identify equipment and contacts and get in touch with them. Schedule tests well in advance.

8 Appendix: Pictures!

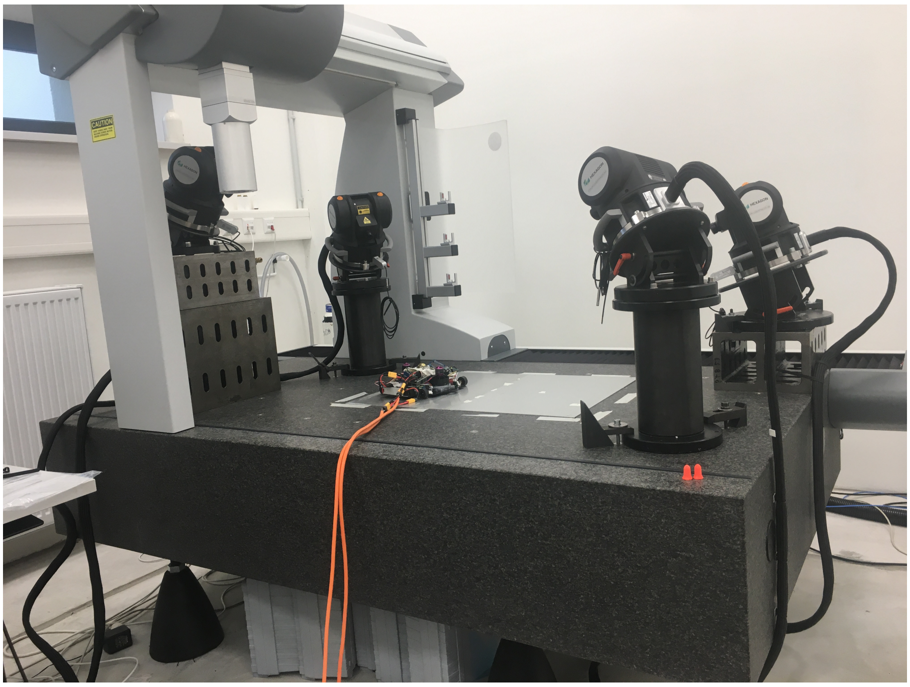

Figure 17: Laser Tracking System

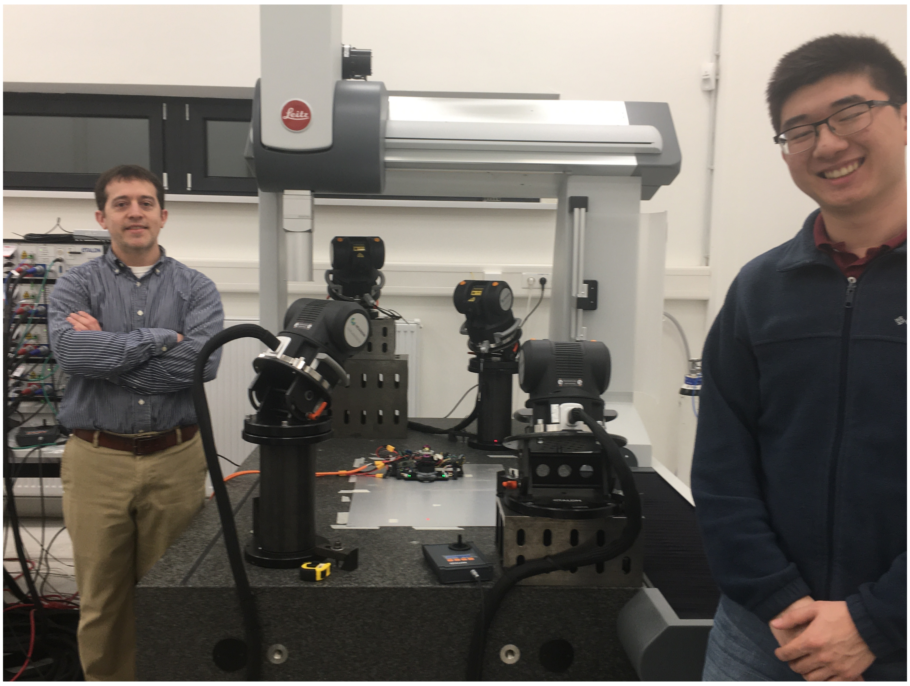

Figure 18: Bob and Stephen by test setup

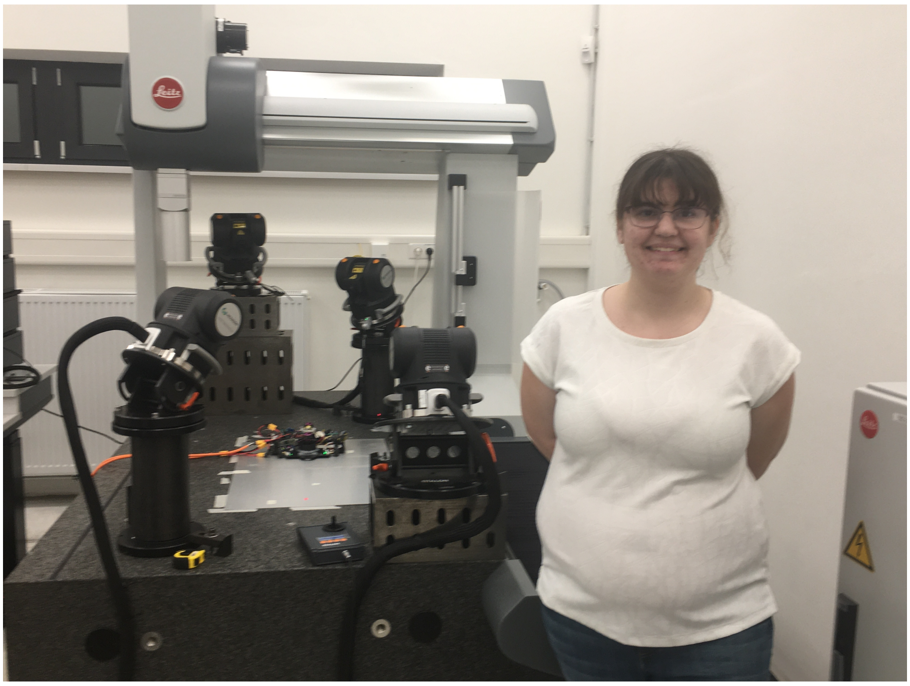

Figure 19: Me by test setup

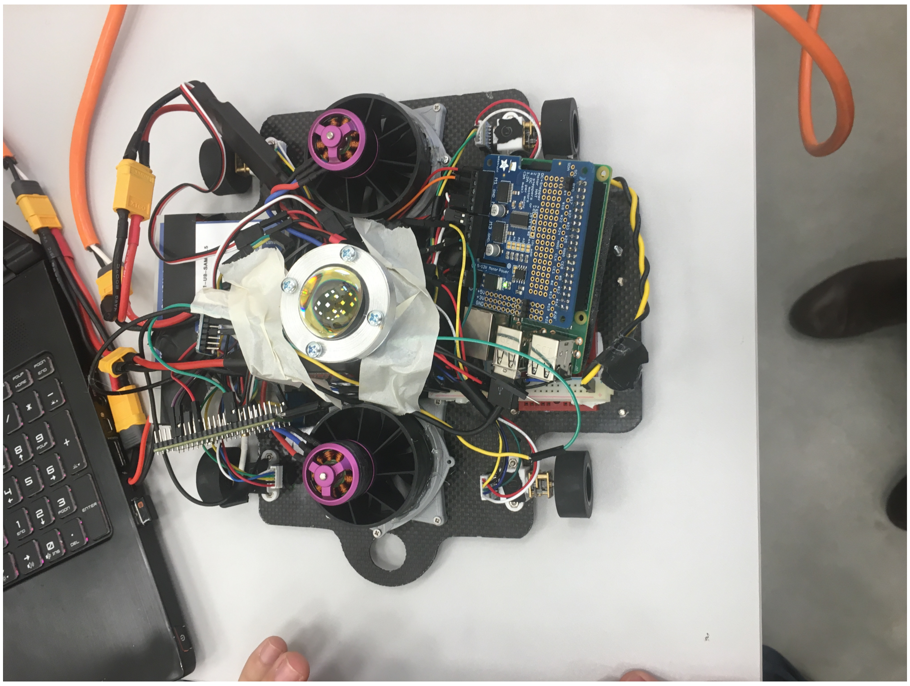

Figure 20: Robot now named Fran Friction

Figure 21: Me and Bob by Test Set Up

Figure 22: Puck

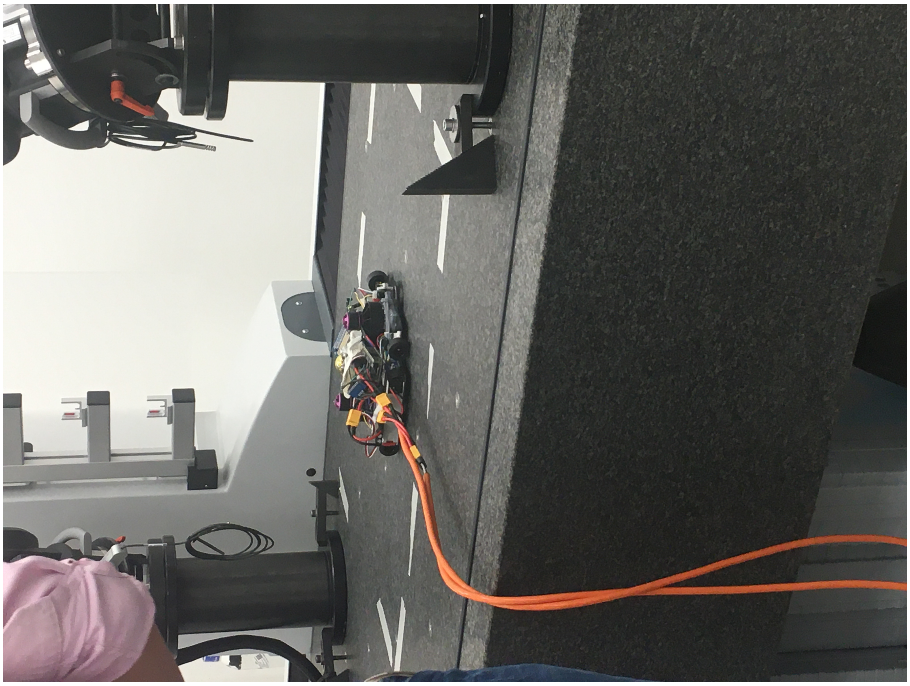

Figure 23: Robot on Test Bed

Figure 24: Multimeter

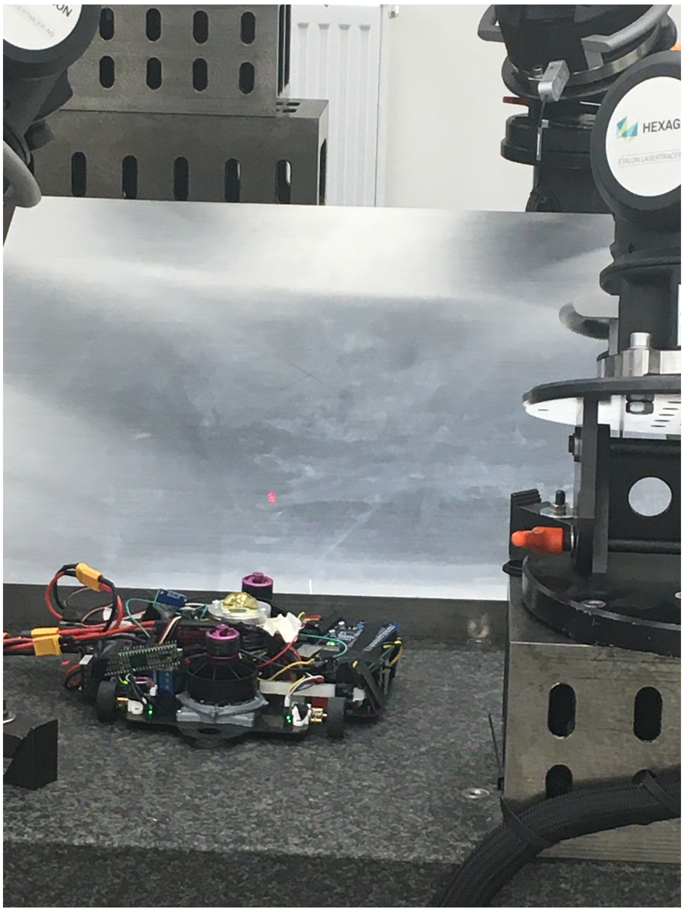

Figure 25: Driving across mirror panel