

CCAT-p Wall Climbing Robot M.Eng Project Report

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Table of content

•	List of terms	3
•	Abstract	4
•	Acknowledgement	4
•	Introduction	5
•	Background	5
•	Chapter 1 Testing Documentary	
•	1.1 Testing Requirement	7
•	1.2 Testing Instructions	8
•	1.3 Top Priority Tests	10
•	Chapter 2 Pressure Chamber Test	
•	2.1 Testing Preparation	11
•	2.2 Pressure Chamber Test with Rotation	13
•	2.3 Full Pressure Chamber Test	14
•	2.4 Other Tests in Fall 2019	18
•	Chapter 3 Sensor and control Test	
•	3.1 Eddy Current Sensor Test	18
•	3.2 Encoder and IMU Test	20
•	3.3 Simulation Test	22
•	Conclusion	25
•	Next Step	25
•	Reference	26
•	Appendix	27

List of terms

- Eddy Current Sensor: A kind of sensor, measuring the distance between the chassis of the robot and the surface of mirror panel on the telescope.
- IMU: Offered by Adafruit (Model type BNO055), IMU sensor is a combination of accelerometer, magnetometer and gyro sensor. By using a special algorithm, the position and orientation of the robot in 3D space will be determined.
- Etalon: A German company works together with the CCAT-p robot group, focusing on calculating position and orientation of the robot on the telescope.
- TCP/IP: The full name is Transmission Control Protocol / Internet Protocol. TCP/IP makes it possible to transmit information between several different networks, which acts a role of definition.
- FEA: Full name is Finite Element Analysis. FEA is a kind of simulation, which widely used in solid and fluid mechanical engineering analysis. By using this method, engineers could foresee the mechanical behavior of the target object in certain environment.
- PID: It is a kind of control algorithm, combining proportional, integral and differential methods together. It is one of the most mutual control methods and has a wide application.

Abstract

As a part of the MAE6900 research project, this final report describes the work finished by Hansheng Zhang from August 2019 to May 2020 in the CCAT-p wall climbing robot team. The ultimate goal for this project is to design, build and test an autonomous robot, which will be used to operate metrology on the surfaces of a telescope. This CCAT-p telescope locates in Cerro Chajnantor, which is the northern part of Chile. Currently, the CCAT-p telescope is expected to start operating in 2021. In this CCAT-p project team, four sub-teams are established, which are control, mechanical, testing and tethering team. As a member in the testing team, Hansheng Zhang is in charge of modifying testing requirements, compiling testing instructions, implementing top priority tests, supporting tests in Germany, analyzing testing results, collaborating with control and mechanical team. In the following report, three main topics will be discussed. First of all, the testing requirements and top priority tests will be discussed. Secondly, three trials of pressure chamber tests will be reviewed. Last but not least, tasks, which are collaborating with control's team, will be described. Relative results and findings are discussed in the mean time. The whole project is overseen by Professor Dmitry Savransky, Dr. Hunter, Mr. Stephen Parshley, who is the CCAT-p project engineer and faculty members in the Department of Astronomy. This report will be helpful for later students to continue working on this project.

Acknowledgement

When talking about the acknowledgement, I would like to say thank you to Professor Dimitry Savransky, acting as the supervisor in this CCAT-p Wall Climbing Robot team. Professor Savransky gives a lot of suggestion, guidance and resources to help us and students learned plenty of knowledge and skills. At mean time, Mr. Stephen, Dr. Thomas, who helps us to run pressure chamber test, and Department of Astronomy, providing this great project. What's more, thanks to Control, Mechanical, Tether's team and other students in Cornell University who have worked with us.

Introduction

This CCAT-prime telescope has a diameter of 6 meters, which is currently under construction and expected to operation in 2021. The construction project is processing by Vertex Antennentechnik GmbH. This telescope locates at Cerro Chajnantor with an altitude of 5600 meters in the north of Chile (ccatobservatory.org, 2020). By utilizing the ALMA array, the CCAT-p telescope is able to map the sky with high resolution and efficiency. The observing wavelength will achieve a minimum of 350 micrometer and 200 micrometer during ideal weather condition.

In this telescope, two aluminum mirror surfaces (primary mirror M1 and secondary mirror M2) are designed. Primary mirror M1 consists of 87 aluminum panels and secondary mirror M2 consists of 78 aluminum panels. Each mirror panel has a dimension of 675 mm x 675 mm and its orientation can be adjusted individually by four actuators behind each panel. The goal for these adjustable aluminum panels with high accuracy is to achieve a desirable shape of two mirror surfaces, which will be utilized in observatory. The CCAT-p wall climbing robot will be able to measure the orientation and location for each aluminum panel with high precision, which the basic elements for the observatory telescope. During the measuring process, a kit of laser equipment will be utilized, which is provided by Etalon company. The puck on the robot will receive lases from Etalon's laser emitters. In this way, the data created by laser measurements will be analyzed. In the end, the location and orientation of the aluminum panel will be calculated.

Background

During the summer semester in 2018, a prototype robot was created by two Master of Engineering students in Cornell University. This prototype was an autonomous mobile robot and was used to do deformation analysis for the CCAT-p telescope in Chile. After building and testing this robot, the position of the puck was defined. This puck would be utilized to reflect laser, which was emitted by the Etalon measuring system. As a result, the deformation of two mirror surfaces was defined.

Then, a project group was formed with two sub-teams, including control and mechanical. In the initial stage of the project, the goal was to design and build a robot that can meet a series of strict and meticulous requirements. These requirements included survival environment, route accuracy, measurement precision, potential damaging risks and safety issues. A second prototype of CCAT-p wall climbing robot was built before August 2019 and ready to be tested in German with Etalon measuring system.

From 2018 to 2019, the control's team focused on developing functional algorithm for the robot and relative sensors, including route planning, running accuracy, GUI for control and corresponding assembly for electronics. The mechanical team was responsible for CAD design, FEA analysis, thermal simulation, choosing suitable materials for the robot and operating some mechanical tests. Testing team was in charge of preparing testing instructions and perform top priority tests, especially the pressure chamber test.

In the end of 2019, the robot was sent to Germany, performing measurement test with Etalon AG. In the future, a backup robot, which is the same as second prototype will be built. In 2020, the robot will be shipped to Germany, performing further tests with Etalon AG.

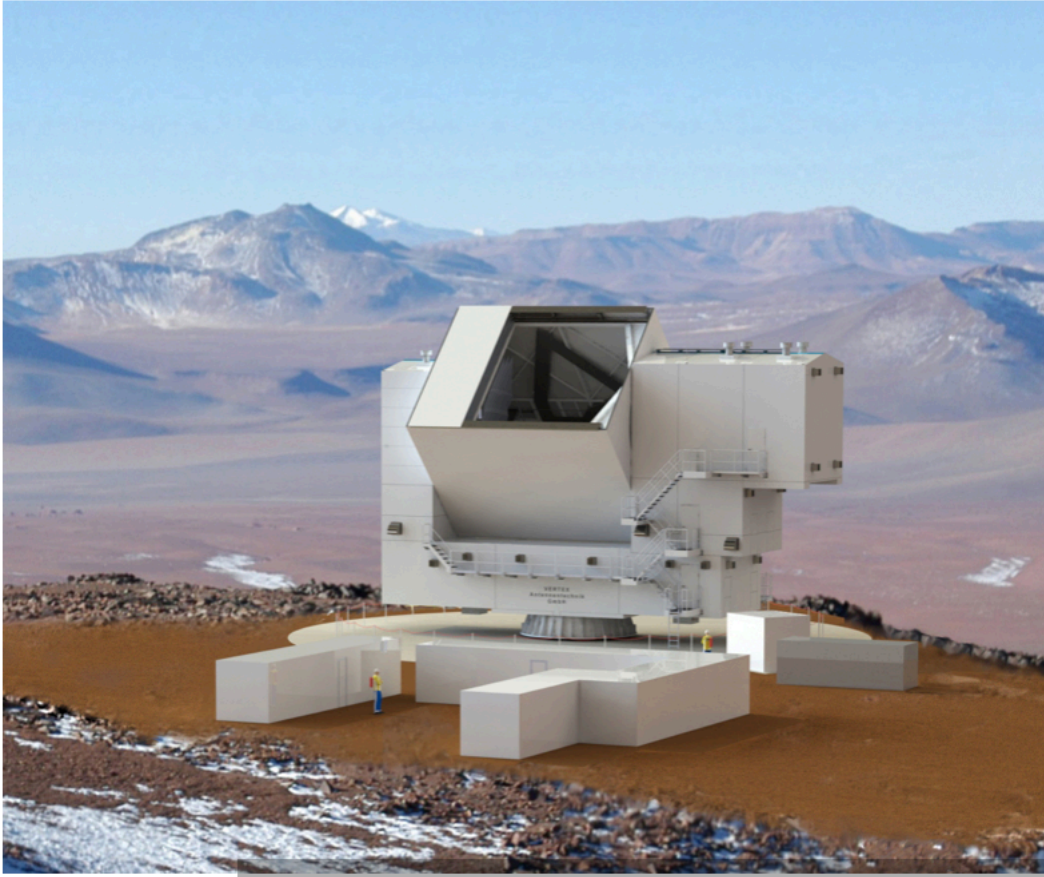


Figure 1 The appearance of the CCAT-p telescope [1].

Chapter 1 Testing Documentary

1.1 Testing Requirements

During the Fall semester of 2019, one of the major tasks for the testing team is to review and modify all existing testing requirements, which are created by previous students. After adjusting the testing requirements, the total testing requirements are 30. All of these requirements are divided into 4 categories, including survival conditions, control algorithm, electronic equipment, damage test and insurance of safety.

For survival conditions

1. Operating pressure: 50kPa air pressure
2. Operating temperature: -30°C to 25°C
3. Operating humidity: up to 90% humidity

For electronic equipment:

4. Voltage dividers or regulators will convert 110 volts from power supply to 12 volts and 6 volts under tethering condition.
5. Eddy current sensor is placed above the mirror surface 2 mm to 0.35 mm.

For control algorithm:

6. The distance between robot's edge and puck center should be less than the one between measuring points and mirror's edge.
7. On each panel, the measuring points have same locations.
8. Robot is able to percept which mirror it is measuring.
9. Robot can achieve a path accuracy with 1 cm.
10. When crossing two panels, robot will have perception.
11. The running speed for robot needs to achieve 150 mm per second.
12. Robot's path is planned in advance.
13. Robot is able to measure elevation angles for 12 hours without effects of human.
14. If robot detach from the mirror surface, it can percept.
15. The pre-planned path is the shortest route for the robot to run.
16. Robot can orient itself (with turning) when it is on mirror's corner.
17. Robot can orient itself (without turning) when it is on mirror's corner.
18. Robot can turn an angle of 90 degrees.

For damage test:

19. If the robot falls from the mirror, it is able to find a way to minimize the damage.

For insurance of safety

20. Troubleshooting communications are established for microcontroller.
21. The puck tower will leave 180-degree clearance for the tether.
22. Wheels on robot can provide enough friction under temperature of -30°C and humidity of 90% with vertical status.
23. If any failure happens, the robot will have a trouble solving function or enter safety mode.
24. If any abnormal condition happens, the robot will return to the bottom of each mirror.
25. The robot will not drive over mirror's edge.

- 26 Robot is able to traverse defects on the mirror surface.
- 27 Robot will not hurt mirror surface.
- 28 If robot's power is lost, it can percept automatically.
- 29 Robot is able to run during earthquake with 1g vertical acceleration.
- 30 Robot's surface will not vibrate over 1 micrometer RMS of unfilterable vibration.

1.2 Testing Instructions

Each testing requirement will have a corresponding testing instruction, which is a standard operating procedure (SOP). In each testing requirement, a format is designed, including testing requirement ID, requirement number, test classification, author, version number, testing location, objective, scope, safety equipment, required materials, testing environment, testing procedure and results table.

The following document is a sample of testing instruction.

The robot is able to determine the puck position with 1cm accuracy

Test Requirement ID	8
Requirement	2.2
Test Classification	Demonstration on test panels
Author	Hansheng Zhang
Version	1
Number of people for testing	2
Location	Ithaca

Objective

The ultimate goal for this test is to see that the robot is able to determine the puck's position with 1 cm accuracy on the panels.

Scope

When the robot is running following the designed route on the test panels, it can determine the puck position with about 1cm accuracy. On both straight lines and curves, the accuracy should satisfy the requirement.

Safety Equipment

Safety glasses
Insulating gloves

Required Materials

Robot, Power source, PC, [Stop.Watch](#), Digital Caliper

Testing environment

Room temperature (25°C), Room humidity

Testing Procedure

1. Tethering the robot with the power source / Power by the battery.
2. Turn on the power source and let the robot running under normal conditions.]
3. Record the difference between reference position and actual position based on GUI. The time interval for this part is 0.5 seconds.

Results table

Trial 1	Time Span (seconds)	Track type (straight line / curve)	Displacement	Does the displacement value satisfy the requirement? (Y/N)
	0.5			
	1			
	1.5			
	...			
	9.5			
	10			

Figure 2. A sample of testing instruction.

1.3 Top Priority Tests

Among all of these 29 testing requirements, top priority tests are defined.

- Pressure chamber test
- Eddy current sensor test
- IMU test

The reason why choosing these tests are the top priority is that these are the basic survival requirement for the CCAT-p robot. If these tests are not finished, the rest part of the testing requirement can't be progressed. Also, eddy current sensor test is one of the most important part in the December test in Germany.

For the pressure chamber test, the robot needs to be running under half atmosphere with different rotation angles from (0 degree to 180 degree) for an hour. This test takes place in the space science building and Dr. Thomas is in charge of the pressure chamber testing platform. In the chapter 2 of this report, the pressure chamber test will be discussed in detail.

For eddy current sensor test and IMU test, these two tests are software tests. Eddy current sensor tests the distance between the mirror surface to the bottom of the chassis. This measured distance will be used by Etalon company to calculate the position of the robot in the whole mirror surface. The IMU measures the acceleration and orientation of the robot, which will be used to analyze position, velocity and orientation angle of the robot. It is an essential sensor to measure the local position of the robot. In the chapter 3, these two tests and other software tests will be mentioned. All of the above tests are co-worked with Wenbo Lou and Xiaotian Liu in the control's team. For pressure chamber test, it is implemented under Dr. Thomas's instruction.

Chapter 2 Pressure Chamber Test

2.1 Testing Preparation

The pressure chamber locates in the room 210 in the Space Science Building. Dr. Thomas (tn46@cornell.edu) is in charge of this testing facility. By utilizing this pressure chamber, 0.5 atmosphere environment will be simulated.

Figure 3 displays the pressure chamber in space science building. The blue cylinder on the right is the pressure chamber. It has an inspection window on the side. The frame of this pressure chamber enables the rotation from 0 degree to 180 degree with pitch angle of five degrees. The box on the left is the pump, which will extract the air in the pressure chamber.

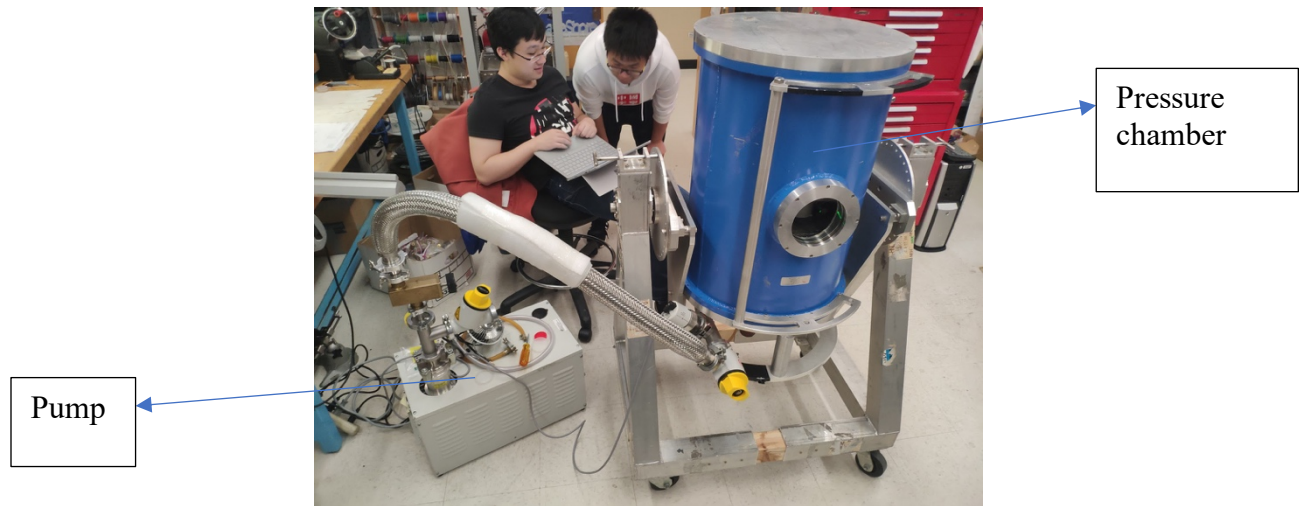


Figure 3. Pressure chamber in Space science building.

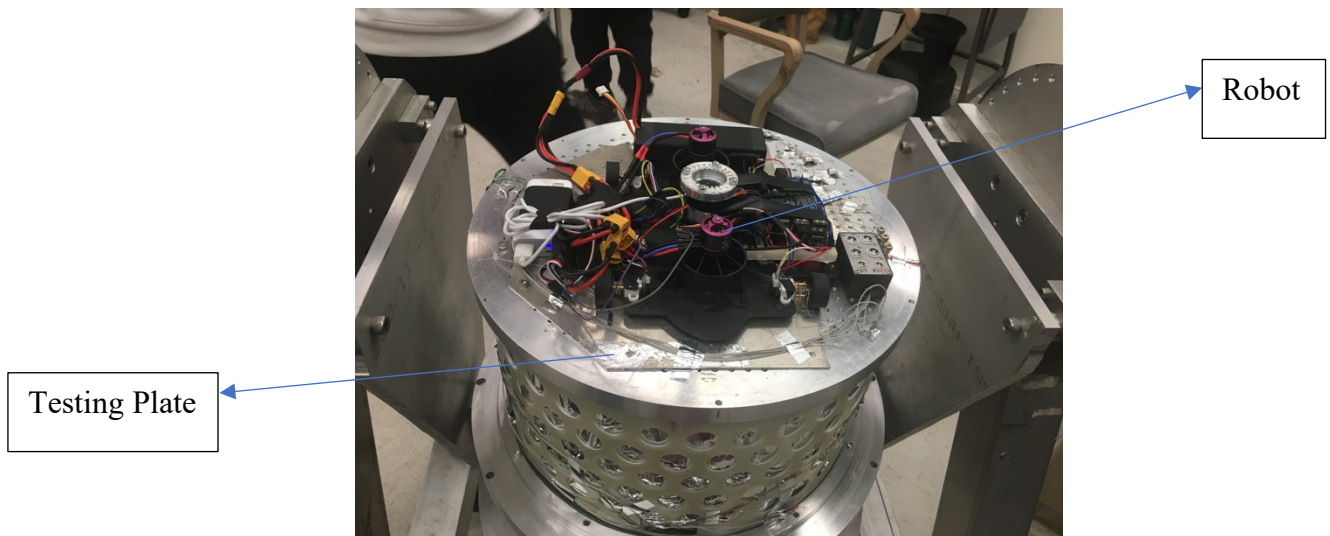


Figure 4. Inside view of the pressure chamber.

Figure 4 displays the inside view of the pressure chamber by removing the outer blue cover. Between the robot and the testing platform, there is a testing plate. Since there are many screw holes on the original testing platform, which will be used to fix testing targets, a smooth and flat aluminum plate is required. Because the fans on the robot will provide suction force to make the robot attach on the testing platform and the robot will be able to move 5-7 cm by using this testing plate. Figure 5 is the drawing of the testing plate with dimensions. This testing plate uses a piece of recycle aluminum in the CCAT-p lab.

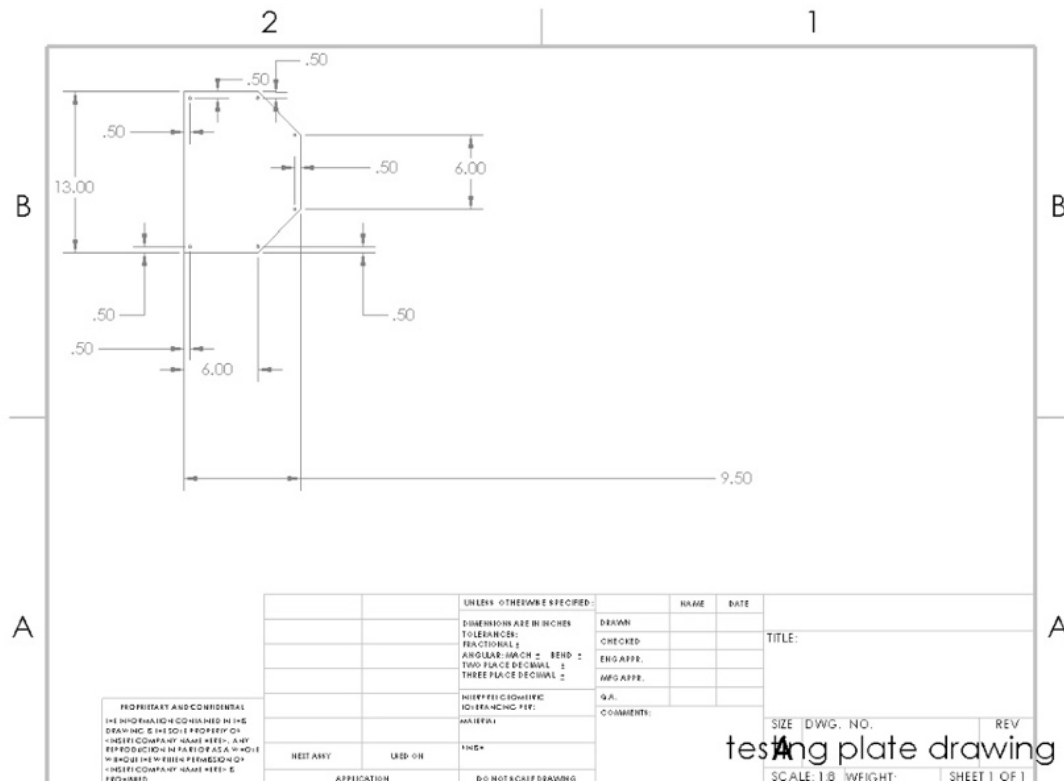


Figure 5. Drawing of the testing plate.

The first pressure chamber test takes place on 10/23/2019. Wenbo Lou (White hoodie in figure 3) and Xiaotian Liu (black T shirt in figure 3) from control's team also attend this test, helping testing to on the control side. During this test, the robot is powered by a battery. What's more, the power can be supplied by tethered power as well and detailed information will be discussed later. After fixing the robot on the testing platform with testing plate, the first step before the real test is to set up TCP/IP, which establish the communication between the robot inside the pressure chamber and outside control algorithm. For this test, the TCP/IP is set manually and this manually setting is improved in later tests, which means that the TCP/IP is set automatically.

Then, the pump starts pumping out air gas from the pressure chamber until achieving half atmosphere condition. This test indicates that all of the electronics on board work without failure in the 0.5 atmosphere surroundings. In addition, the robot can move forward and backward with several centimeters. The moving distance is restricted to the space in the chamber. During this test, the testing platform is not being rotated because fans are updated and not on board at that time.

2.2 Pressure chamber test with rotation

On 11/13/2019, the second pressure chamber test is operated. In this test, the latest fans are assembled on board and each fan has an output power of 500 watts. For the power supply, a bigger capacity battery is used and can provide a short working window for the robot with 100% power of both fans.

During this test, fans on the robot can provide enough suction force to let the robot attach on the testing plate and the rotation is from 10 degrees to 80 degrees. However, fans' speed start to decreasing at 50 degrees and both fans are out of power at 80 degrees. The reason is that two fans require a power of 1000 watts but the battery only supply a power of 8000 mA. The working window for the robot is less than 1 minute. In order to solve this problem, a tethered power will be used instead of using a heavy battery. Also, in the December test, tethered power will be used.

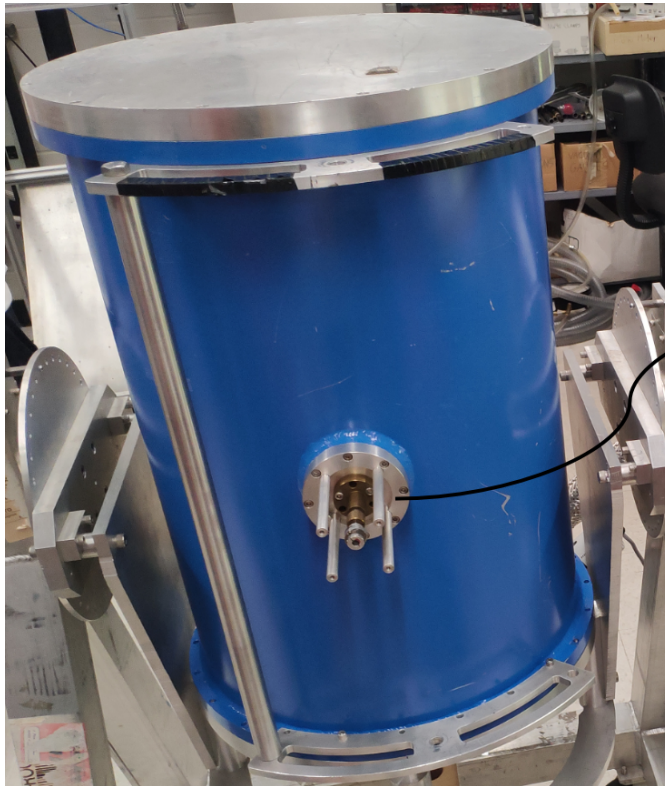
Figure 6 is a screen shot from the testing video. The full video is in the testing folder under CCAT-p's group shared doc. In this video, the noise of the fans starts decreasing at 50 degrees. What's more, the rotation of the fans become slower and slower. These two facts indicate that the battery runs out of power. Later, the team decides to use tethered power instead of battery.



Figure 6. Robot is in the pressure chamber with rotation.

2.3 Full Pressure Chamber Test

In the February and early of March in 2020, the most essential task for testing team is to run the robot in the pressure chamber with tethered power. In this way, the robot is able to work an hour in the pressure chamber, which satisfy the ultimate design requirement. To satisfy this target, the robot needs a tethered power in the pressure chamber.



Need to create an adaptor under the outside ring.

Figure 7. Picture for the connecting ring on the cover of the pressure chamber.

Before doing this test, an adaptor is needed for this test. Since the existing adaptor in the lab only has one hole on the center, the robot has two cables to supply power and needs two holes on the adaptor. As displayed in the figure 8, the aluminum outer ring with screws will fix the inside adaptor to the pressure chamber and create a vacuum environment. In addition, the adaptor requires a smooth and rigid surface. In the figure 8, the red prototype of the adaptor has a diameter of 3 inch and 0.354 inch of the thickness. If the thickness of the adaptor is less than 0.354 inch, vacuum environment will be not established and air will leak from the gap between the adaptor and the outer ring. In the figure 12, the gap is displayed if the adaptor is thinner than 0.354 inch. The red prototype adaptor is made of acrylic by using laser cutting machine in the basement of Upson. On the surface of the adaptor, two holes are drilled with a diameter of 0.375 inch. This number is the diameter of the cable, connecting transformer and robot. Later, an aluminum adaptor for the experiment will be created by Bob Qian.

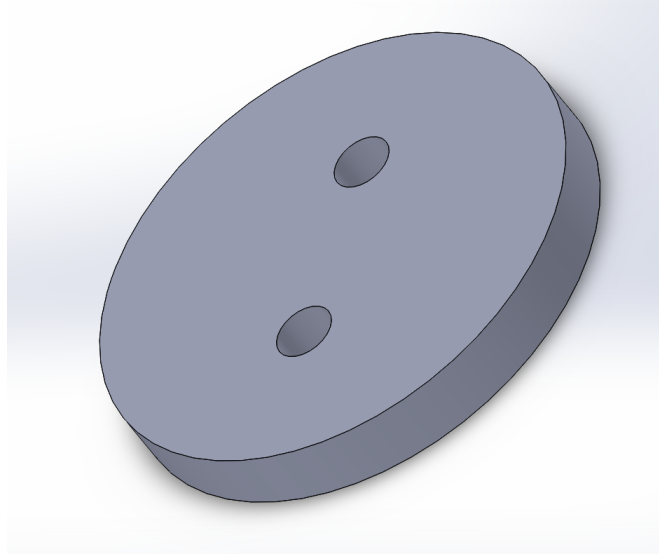


Figure 10. Overview of the adaptor.

Figure 10 is the appearance of the adaptor. The raw solidwork file is the shared folder under testing team. Figure 11 displays how adaptor works and the connecting map of the cables. In the black dotted box, this is the precast part. On the left side of the adaptor, two red cables connect fans on the robot. These two cables will go through the adaptor to the outside of the pressure chamber. At the end of these two cables, two female connecting parts are attached. On the right side of two yellow connectors, another two cables will connect to the transformer. One comment is that the cable between the robot and the adaptor need to leave a free moving length. Currently, the design is to leave 1.5 m and the robot is able to move in the pressure chamber and other normal tests.

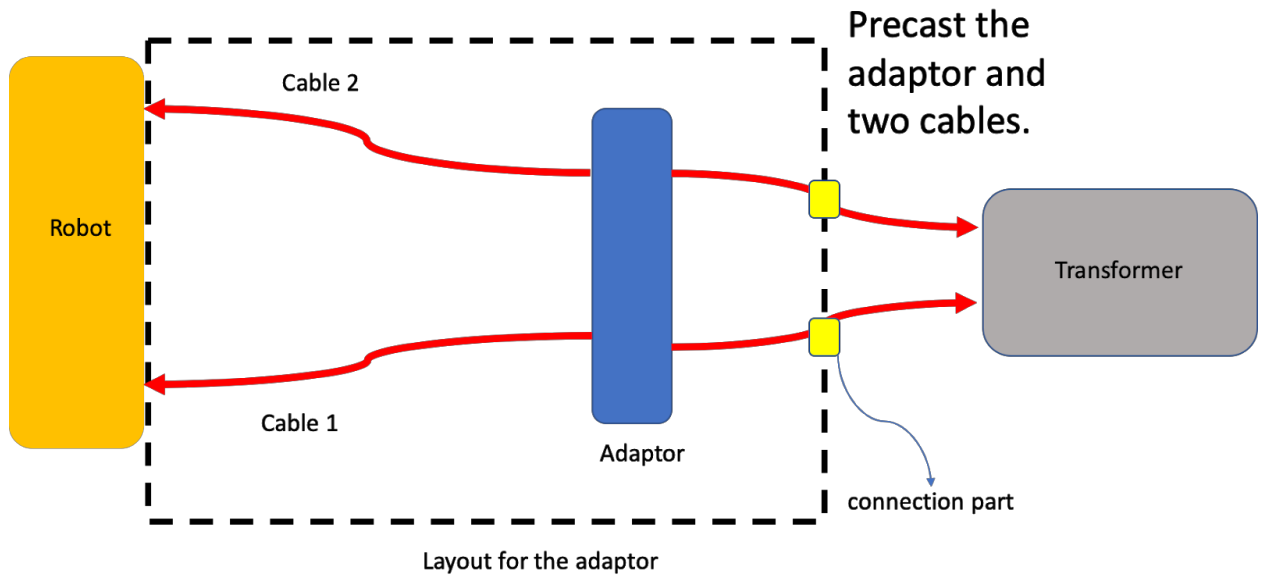


Figure 11. Layout of the adaptor.

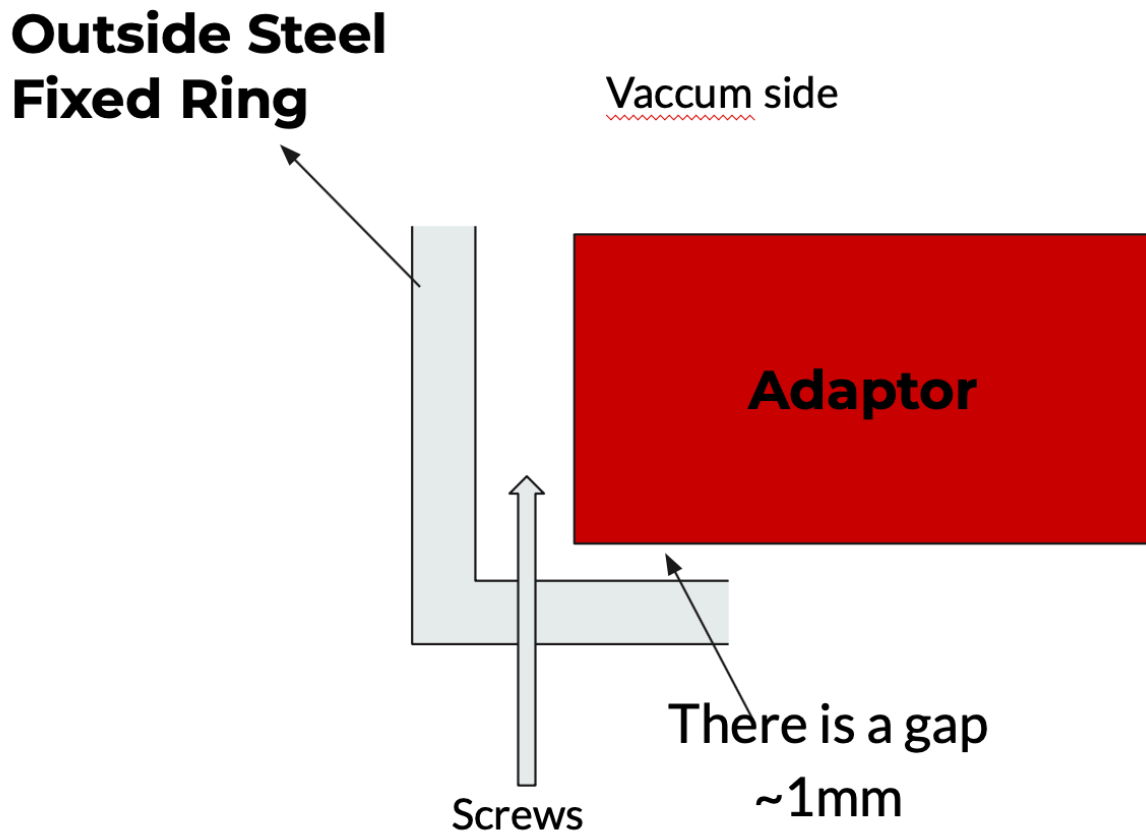


Figure 12. Explanation of the gap between the adaptor and outer ring.

2.4 Other Test in Fall 2019

In December 2019, the robot was sent to Germany for testing Eddy current sensor and Etalon measuring system. For more details, please check Becca's report (the link is in the reference [2]). Also, in her report, information about humidity test is mentioned.

Chapter 3 Sensor and Control Test

3.1 Eddy Current Sensor Test

Eddy current sensor measures the distance between the surface mirror and the bottom of the chassis. By combining this distance and Etalon's data, the position and orientation of the robot on the whole mirror surface will be calculated, which will be used to monitor and adjust the orientation of each mirror panel. Figure 12 displays the location of the Eddy current sensor and the puck tower locates above it.

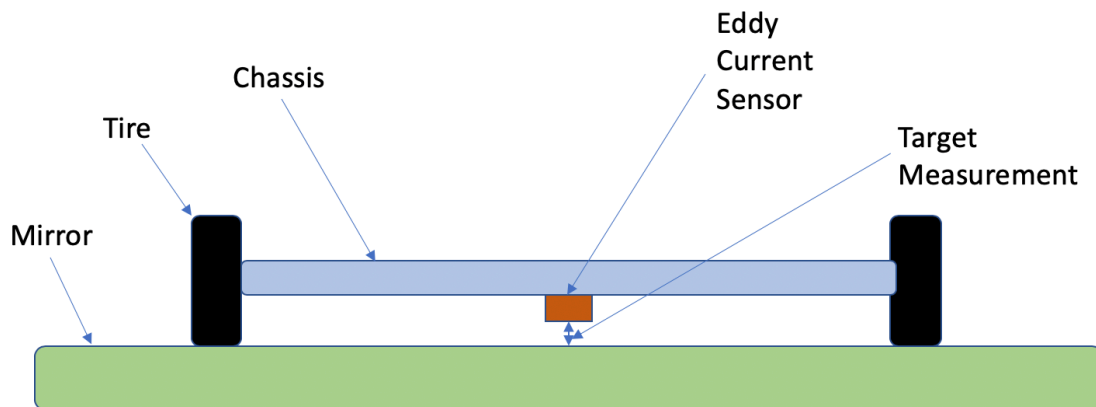


Figure 13. Location of the Eddy current sensor.

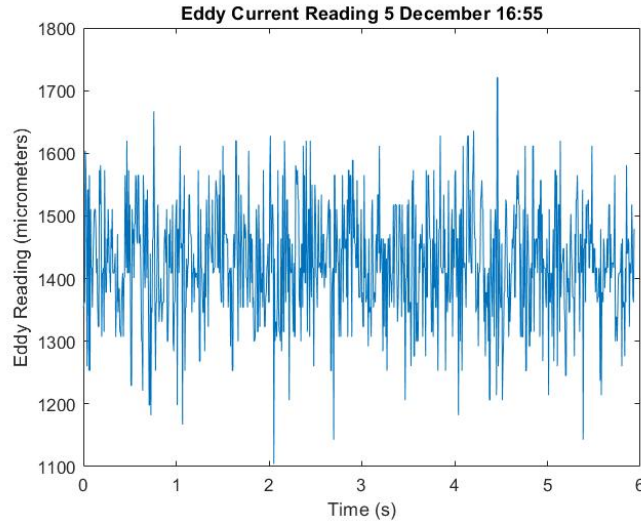


Figure 14. Reading from Eddy current sensor without fan running [2].

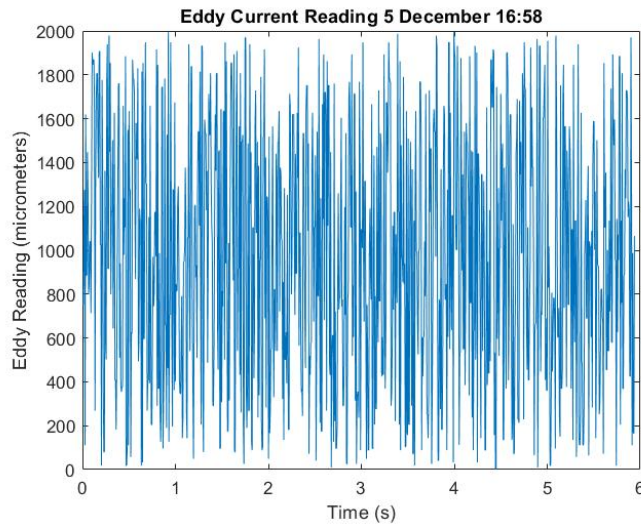


Figure 15. Reading from Eddy current sensor with 10% power of fan [2].

The measuring range for the Eddy current sensor is 2 mm. Figure 14 displays the measurement when the fans are not running. The reading ranges from 1.1 mm to 1.7 mm. Figure 15 displays the measurement when the fans run at 10% throttle. The reading ranges from 0 mm to 2 mm. Both two graphs show a large vibration and the one with fan on has even worse vibration. Even if the measurement reasonable, the vibration of the readings is not ideal. Right now, the group is still working on this sensor and try to eliminate the noise.

3.2 IMU Test

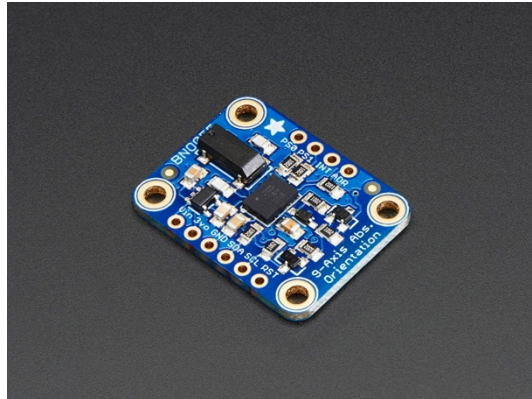


Figure 16. IMU sensor used on robot [3].

The IMU sensor used on robot is provided by Adafruit (Model BNO055). This sensor is a combination of accelerometer, magnetometer and gyro sensor, which calculates the orientation of an object in 3D space by using a special algorithm. In this project, IMU sensor will be used to determine the orientation, velocity and position of the robot on the surface mirror. For the orientation, this IMU will give three axis orientations. What's more, BNO055 could provide acceleration data on three axis and the acceleration is a combination of gravity and local linear acceleration. In addition, angular velocity with units of rad/s is also provided by this IMU. All of the data above are measured with a frequency of 100 Hz.

For the IMU test, control's team and testing team works together. Figure 17 displays the result of the first trial of IMU test. In this test, the robot is moving along a straight line and the moving distance is about 0.2 meters. The moving speed is set at a constant speed of 0.06 m/s. In figure 17, the encoder's acceleration is also plotted as comparison. The acceleration for encoder is 8.5929×10^{-4} m/s² and for IMU is 0.0840 m/s². Since the acceleration readings from IMU have too much noise, comparing to the almost flat line of encoder's reading, the result is not ideal.

Later, a Kalman filter is added to the IMU readings and encoder, which decreases the original noises. As figure 18 displays, the error between the IMU reading and encoder is decreased to about 0.01 meters. However, some points have error of 0.012 and 0.014 meter. The reason may due to the sensitivity of the IMU sensor.

For this test, the MATLAB code is attached in the appendix.

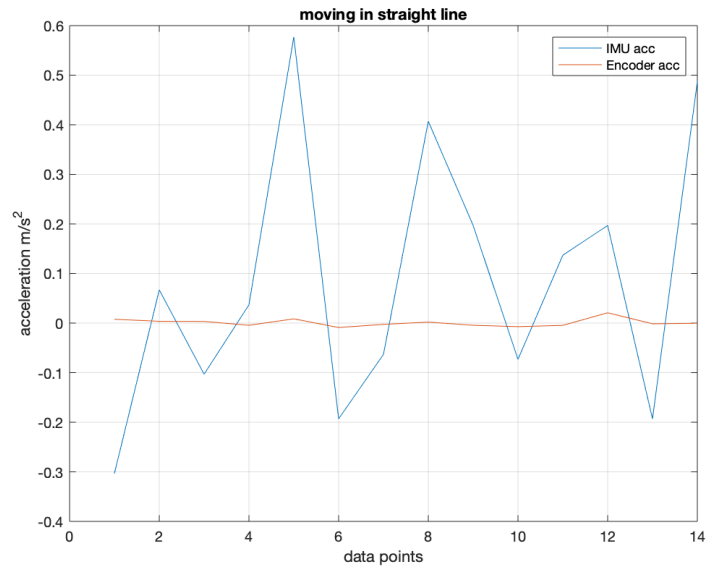


Figure 17. First trial of IMU test.

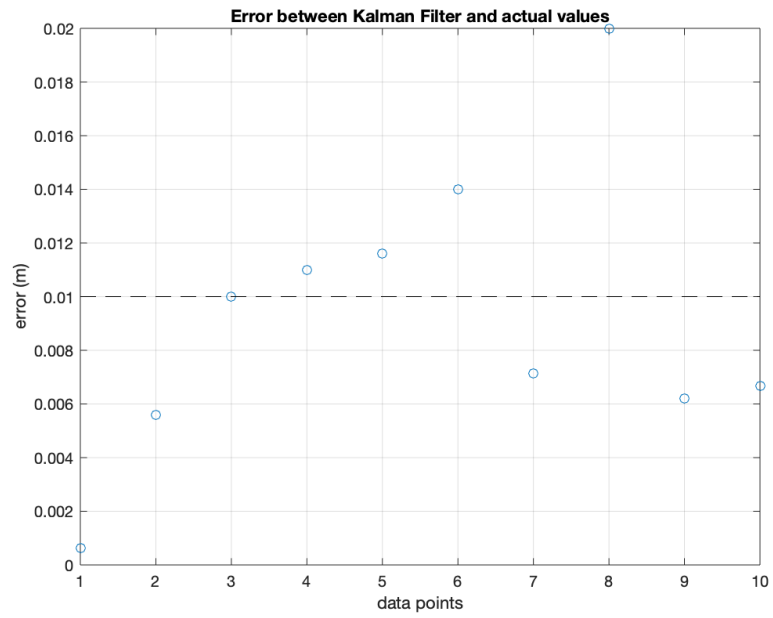


Figure 18. Add Kalman Filter to the IMU readings.

3.3 Simulation Test

In this simulation test, the robot is running on a testing panel, which is made up of four sub-mirrors. Later, this panel can be expanded to more mirrors. In the simulation, the robot will have a pre-planned path and an algorithm to return to the base of the testing panel. When talking about the localization of the robot on this testing panel, the Kalman filter is used, which optimizes the IMU's data by utilizing encoder's data. Also, linear and angular PID methods are used to control the robot to run more accurately. In this simulation, the robot will measure 36 points on the panel with a designed route as figure 19 displays.

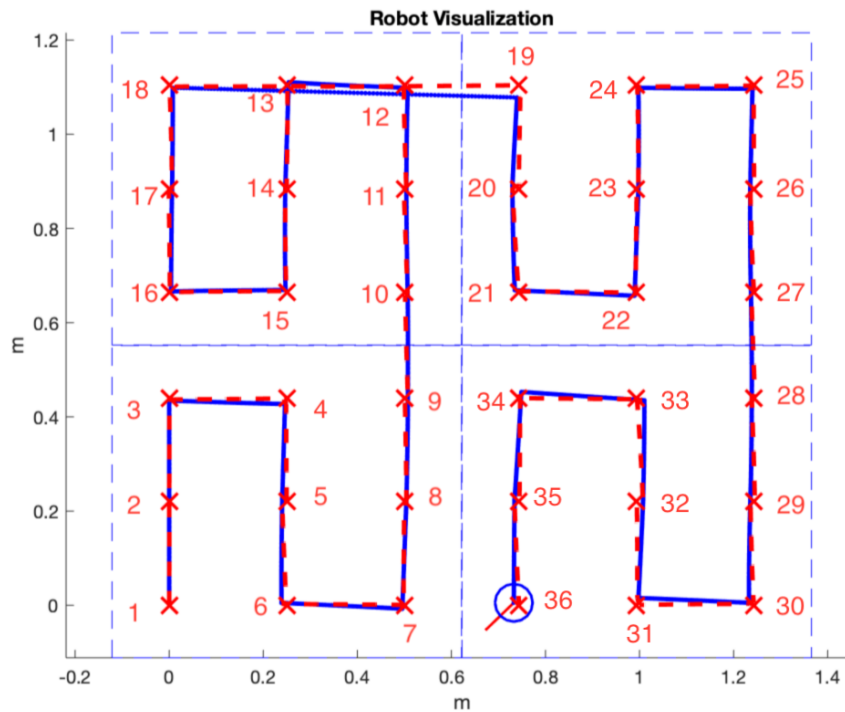


Figure 19. Simulation test.

After running this simulation, the error between the robot position and measurement points are calculated and plotted. In the figure 20, the dotted black line is the threshold line with 1 cm and the blue line is the error of the simulation. Five trials are finished for this test. For most of the robot's position, the error is less than 1 cm. However, due to the turning angles and relative orientation, the error will exceed 1 cm sometimes.

The simulation file is under the control's group in the google drive. Before running the simulation, a couple add-on packages need to be installed, including mobile robotics toolbox, PID controller for a DC motor and navigation toolbox.

For this test, a MATLAB code is attached in the appendix.

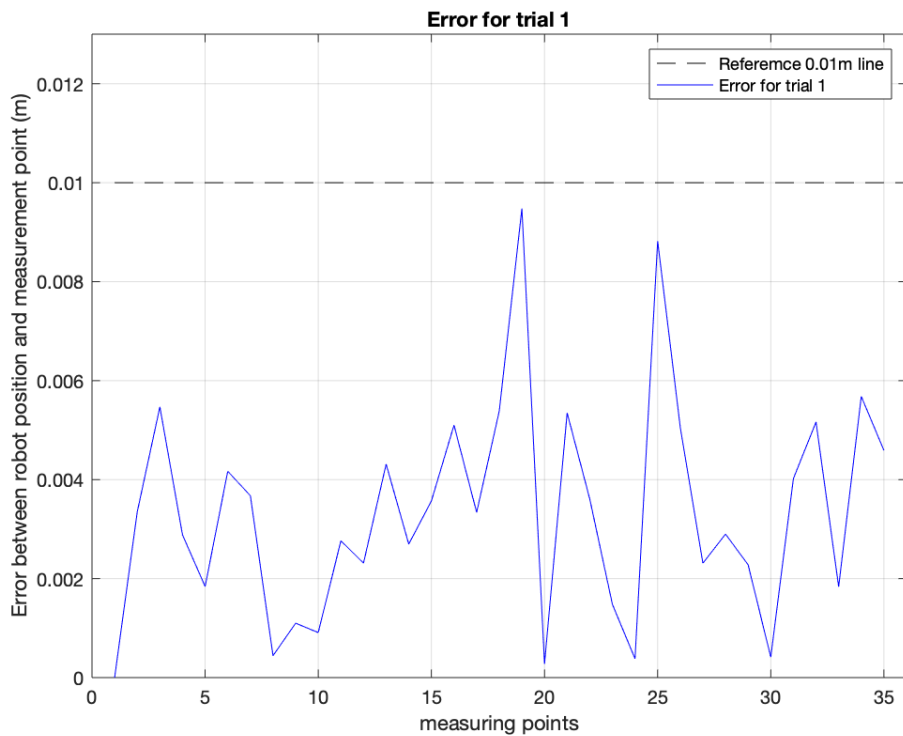


Figure 20. Error between robot position and measurement points.

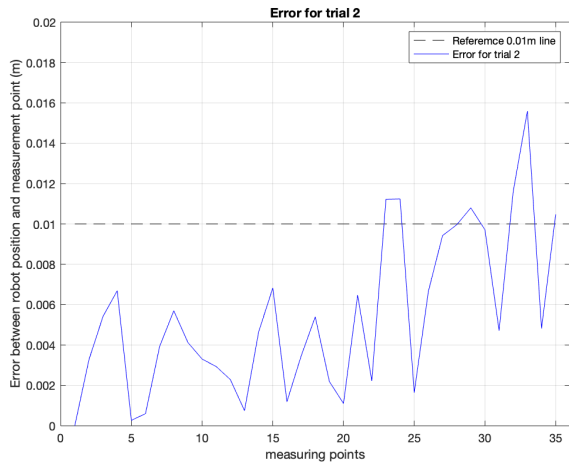


Figure 21.

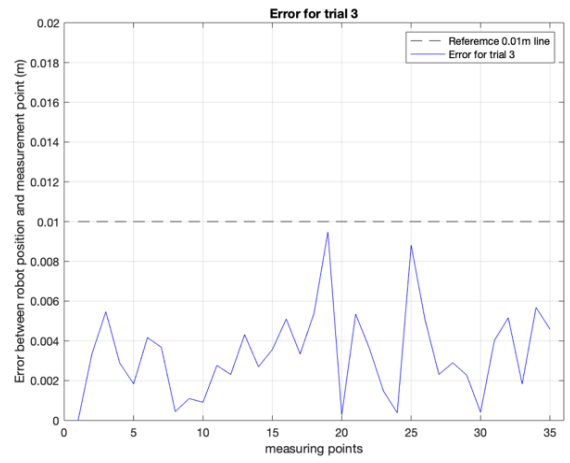


Figure 22.

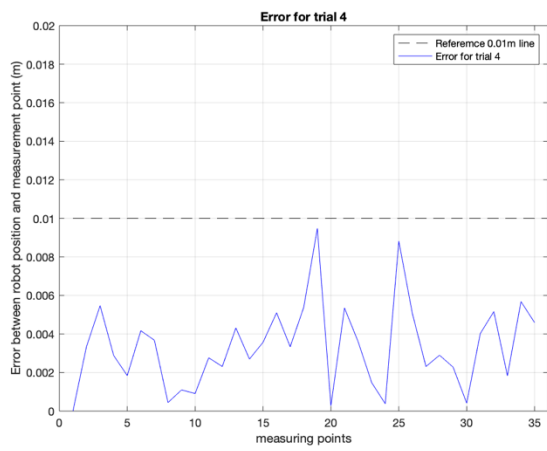


Figure 23.

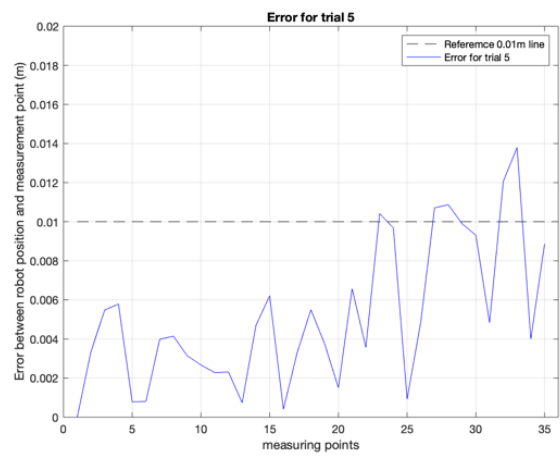


Figure 24.

Figure 21 – 24. More trials for error plots.

Conclusion

From Fall semester 2019 to Spring semester 2020, the testing team finished writing all testing instructions based on robot's operating requirement. The total number of testing instructions are 30 and all of them are uploaded to the google drive. In addition, two trials of pressure chamber tests are finished and the third trial is prepared. For the first two trials, the robot is able to fully rotate and move forward/backward in the 0.5 atmosphere environment. For the third trial, the design of the adaptor is done and the adaptor is under constructing. Furthermore, testing team co-work with control's group and finished sensor tests and simulation loop tests. Eddy current sensor and its algorithm is being improved currently. First round of IMU test and simulation loop tests are done.

Next Step

The third trial of pressure chamber tests need to be completed. In this test, the robot will be able to run an hour in the pressure chamber with tethered power and full rotation of the testing platform will be implemented. In addition, more tests will be done for the eddy current sensor and get ready for another Etalon test in Germany. Also, more simulation tests will be done in the future.

Reference

1. CCAT prime . (n.d.). Retrieved from http://www.ccatobservatory.org/index.cfm/page/observatory/telescope_details.htm
2. Lublin, B. (2019). *Ccat-P Wall Climbing Robot Testing Team*. Retrieved from https://sioslab.com/wp-content/uploads/2019/12/Lublin_Becca_2019_Final_Report.pdf
3. Adafruit Industries. (n.d.). Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055. Retrieved from <https://www.adafruit.com/product/2472>

Appendix

Part 1. A list of test instructions.

Req.	Top Level Requirement	Functional Requirement	Test	What Part	Who is Writing
1	1, 3.7	The suction force of the fan must exceed the weight of the robot under 50kPa air pressure conditions	Pressure Chamber Test	Full	Hansheng
2	1,3.7	The electronic control systems will not be damaged by temperatures between -30°C and +25°C	Thermal Test	Electronic Control System	Becca
3	1, 3.7	The electronic control systems will not be damaged by a 90% relative humidity environment	Humidity Test/Specification	Electronic Control System	Becca
4	1	If tethered, the robot will have a series of voltage dividers/regulators to prevent damage to the microcontroller and other electronics.	High Voltage Test	Electronic Control System	Hansheng
5	2.1	Distance between center of puck and edge of robot must be less than the distance between edge of mirror and measurement points	Demonstration on Test Pa	Full	Yiqian Zhang
6	2.1	The point locations to be measured on each panel must be standardized.	Demonstration on Test Pa	Full	Yiqian Zhang
7	2.1	The robot will be told which of the two mirrors it is measuring and in which orientation.	GUI Demonstration	Software	Hansheng
8	2.2	The robot must be able to determine the puck's position on a panel to 1 cm accuracy.	Demonstration on Test Pa	Full	Hansheng
9	2.2	The robot must be able to determine when it crosses onto each new panel.	Demonstration on Test Pa	Software/Full	Hansheng
11	2.3	Actuation of puck must place eddy current sensor off mirror surface between 0.35mm and 2mm	Demonstration on Test Pa	Sensors	Hansheng
12	2.4	The robot must have speed of 150 mm/s (depends on how many measurement points and stopping time per measurement)	Data from IMU	Full	Hansheng
14	2.5	The robot will have a pre-planned path.	Demonstration on Test Pa	Full	Hansheng
17	2.7	Reflector holder and tether must allow 180 degree of clearance around the reflector	Static Measurements	Full	Yuetong
18	2.8	The robot cannot vibrate surface more than 1 micrometer RMS of un-filterable vibration.	Vibration Test	Full	Hansheng
19	2.9	The robot will be able to measure multiple elevation angles without human interaction within a period of 12 hours.	Demonstration on Test Pa	Full	Hansheng
20	3.1	The robot wheels must have sufficient grip with surface with no slippage in vertical configuration under -30° C and 90% humidity	Wheel Drive Test under W	Full	Becca
21	3.1	The robot will be able to sense if it starts to detach from the mirror surface.	Demonstration on Test Pa	Full	Hansheng
22	3.1	The robot will have a method of minimizing damage to itself if it falls from the vertical mirror.	Fall Damage Mitigation Te	Full	Yiqian Zhang
23	3.3	The robot will be able to sense if there is not another mirror panel past a panel edge it was intending to drive over.	Demonstration on Test Pa	Full	Yuetong
24	3.4, 3.8	For each failure mode there will be a corresponding troubleshooting or safe mode procedure.	Demonstration on Test Pa	Software	Yiqian Zhang
25	3.4, 3.8	The robot will return to the base of each mirror in the event of an anomaly or failure.	Demonstration on Test Pa	Full	Hansheng
26	3.4	The robot will know the fastest route to the base of the mirror as part of its pre-planned trajectory.	Demonstration on Test Pa	Full	Hansheng
27	3.5	The robot must be able to traverse mirror surfaces, including surface gaps or defects	Surface Test	Full	Yuetong
28	3.6	The robot must not damage surface of mirror	Surface Test	Full	Yuetong
29	3.8	The robot must survive complete loss of observatory power	Battery Testing	Full	Hansheng
30	3.8	The robot must detect loss of observatory power	Signal Test	Full	Hansheng
32	3.10.	The robot must operate safely during an earthquake with accelerations up to 1g.	Shake Table Test	Full	Yuetong
35	4.3	Robot shall be able to orient itself on corner of panel with turning within TBD seconds	Demonstration on Test Pa	Full	Yuetong
36		Robot shall be able to orient itself on corner of panel without turning within TBD seconds	Demonstration on Test Pa	Full	Yuetong
37		Robot shall be able to rotate 90 degrees with <TBD% error	Demonstration on Test Pa	Full	Yuetong

Part 2. MATLAB code for the simulation test.

```
clc,clear all
close all
data=xlsread('simulation test.xls')
x_ref=data(6:41,3);
y_ref=data(6:41,5);
d_ref=sqrt(x_ref.^2+y_ref.^2);

x_sim_1=data(6:41,4);
y_sim_1=data(6:41,6);

x_sim_2=data(47:82,4);
y_sim_2=data(47:82,6);

x_sim_3=data(88:123,4);
y_sim_3=data(88:123,6);

x_sim_4=data(130:165,4);
y_sim_4=data(130:165,6);

x_sim_5=data(171:206,4);
y_sim_5=data(171:206,6);

d_sim_1=sqrt(x_sim_1.^2+y_sim_1.^2);
d_sim_2=sqrt(x_sim_2.^2+y_sim_2.^2);
d_sim_3=sqrt(x_sim_3.^2+y_sim_3.^2);
d_sim_4=sqrt(x_sim_4.^2+y_sim_4.^2);
d_sim_5=sqrt(x_sim_5.^2+y_sim_5.^2);

diff_1=abs(d_ref-d_sim_1);
diff_2=abs(d_ref-d_sim_2);
diff_3=abs(d_ref-d_sim_3);
diff_4=abs(d_ref-d_sim_4);
diff_5=abs(d_ref-d_sim_5);

j_1=0; % error < 0.01m
p_1=0; % error >= 0.01m
for i= 1:35

    if diff_1(i) < 0.01

        j_1=j_1+1;

    else

        p_1=p_1+1;
```

```
    end
    i=i+1;

end

j_2=0;
p_2=0;
for i= 1:35

    if diff_2(i) < 0.01

        j_2=j_2+1;

    else

        p_2=p_2+1;

    end

    i=i+1;

end

j_3=0;
p_3=0;
for i= 1:35

    if diff_3(i) < 0.01

        j_3=j_3+1;

    else

        p_3=p_3+1;

    end

    i=i+1;

end

j_4=0;
p_4=0;
for i= 1:35

    if diff_4(i) < 0.01
```

```

    j_4=j_4+1;

else
    p_4=p_4+1;

end
i=i+1;

end

j_5=0;
p_5=0;
for i= 1:35

    if diff_5(i) < 0.01

        j_5=j_5+1;

    else

        p_5=p_5+1;

    end
    i=i+1;

end

stand=[0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;...
    0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;...
    0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;...
    0.01;0.01;0.01;0.01;0.01;0.01];

figure(1)
plot(stand,'k--')
hold on
plot(diff_1(1:35),'b-')
grid on
title('Error for trial 1')
xlabel('measuring points')
ylabel('Error between robot position and measurement point (m)')
axis([0 36 0 0.013])
legend('Referemce 0.01m line','Error for trial 1')

figure(2)
plot(stand,'k--')
hold on
plot(diff_2(1:35),'b-')

```

```
grid on
title('Error for trial 2')
xlabel('measuring points')
ylabel('Error between robot position and measurement point (m)')
axis([0 36 0 0.02])
legend('Reference 0.01m line','Error for trial 2')
```

```
figure(3)
plot(stand,'k--')
hold on
plot(diff_3(1:35),'b-')
grid on
title('Error for trial 3')
xlabel('measuring points')
ylabel('Error between robot position and measurement point (m)')
axis([0 36 0 0.02])
legend('Reference 0.01m line','Error for trial 3')
```

```
figure(4)
plot(stand,'k--')
hold on
plot(diff_4(1:35),'b-')
grid on
title('Error for trial 4')
xlabel('measuring points')
ylabel('Error between robot position and measurement point (m)')
axis([0 36 0 0.02])
legend('Reference 0.01m line','Error for trial 4')
```

```
figure(5)
plot(stand,'k--')
hold on
plot(diff_5(1:35),'b-')
grid on
title('Error for trial 5')
xlabel('measuring points')
ylabel('Error between robot position and measurement point (m)')
axis([0 36 0 0.02])
legend('Reference 0.01m line','Error for trial 5')
```

Part 3. MATLAB code for the IMU test.

```
clc, close all
```

```

a=0.26162403-0.261; %0.261m
b=0.278603325-0.273; % 0.273m
c=0.4171353825-0.41; % 0.41m

d=0.449198385-0.443; % 0.443m
e=0.477668895-0.471; % 0.471m

f=0.394-0.384; %0.384m
g=0.403-0.389; %0.389m
h=0.3996-0.388; %0.388m
i=0.397-0.386; %0.386m
j=0.432-0.412; %0.412m

refer=[0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01];

y_plot=[a,b,f,i,h,g,c,j,d,e];
%x_plot=[0.261m,0.273m,0.384m,0.386m,0.388m,0.389m,0.41m,0.412m,0.443m,0.471m];

figure
plot(y_plot,'o')
hold on
plot(refer,'k--')
%legend('0.261m','0.273m','0.384m','0.386m','0.388m','0.389m','0.41m','0.412m','0.443m','0.471
m')
xlabel('data points')
ylabel('error (m)')
title('Error between Kalman Filter and actual values')

%text(1,a+0.001,'0.261m')
%text(2,b+0.001,'0.273m')

hold on
grid on

```