CCAT-prime Wall Climbing Robot
Project Report

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Abstraction:

This is a final for MENG project of Yuetong Liu. The main purpose of this project is to design a wall-climbing robot which has a ability to do the metrology on the CCAT-prime telescope in Ceero Chajnantor, Chile. The work covered in this report is completed and developing by Yuetong Liu through August 2019 to May 2020 which included the testing requirement protocols, pressure chamber test and PID control test. completion. As a team member in testing team, we worked with other Cornell University students in testing team, as well as students in Control and mechanical team.

Table of Contents

Introduction:

The CCAT-p wall climbing robot is a sub-project of a new observatory which is currently under construction in Chile. The telescope of the observatory has two mirrors, which are composed of 78 and 87 separate aluminum panels. Each mirror panel has four actuators behind its reflective surface to adjust the orientation and cancel the thermo-deformation of the panels. As a prerequisite of the mirror re-calibration procedure, the absolute orientation and location of each mirror needs to be measured. This is achieved by a laser based autonomous measuring system provided by Etalon, the company that is contracted to build the CCAT-p telescope. And the specific reflector needs to be used in order to reflect the laser. Thus, the climbing wall robot is used to carry the retro-reflective the puck specific measurement nodes across the mirror panels.

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 37 testing procedures need to be done, and the pressure chamber test need to be finished.

Testing Requirements:

The top-level requirements given by the CCAT-p project was gone throw and organized by the testing team.

CCAT-p wall climbing robot requirements

1. CCAT-p Environmental Requirements
    a. Operating air temperature: -21℃ to +9 ℃
    b. Survival air temperature: -30℃ to +25℃

c. Air pressure: 50 to 53 kPa
d. Relative humidity: 0 to 90%
e. The observatory provides single phase 230V, 50Hz 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
    (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 1g.

(k) The robot has a series of voltage dividers to prevent damage when it is tethered.

Test Plan:

Under 0.5 atmosphere, the fan will provide enough suction force.

Test Requirement ID	1
Requirement	3.7
Test Classification	Pressure Chamber Test
Author	Hansheng Zhang
Version	1
Number of people for testing	2
Location	Space Science Building, Ithaca

Objective

The ultimate goal is that the fan will provide enough suction force when the surrounding is 50 kPa air pressure (0.5 atmosphere).

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

This test will take place in the space science building room 210.

Required Materials

Robot (Connected by WIFI and powered by battery), PC, Stop Watch

Testing environment

0.5 atmosphere, temperature TBD (since nitrogen will be added into the testing facility)

Testing Facility

Figure 1&2: Pressure Chamber layout (platform and cover)

Here are the all functional requirement testing protocols that need to be finished.

1	Req. ID	Top Level	Functional Requirement
2	1	1, 3.7	The suction force of the fan must exceed the weight of the robot under 50kPa air pressure conditions
3	2	1,3.7	The electronic control systems will not be damaged by temperatures between -30°C and +25°C
4	3	1, 3.7	The electronic control systems will not be damaged by a 90% relative humidity enviornment
5	4	1	If tethered, the robot will have a series of voltage dividers/regulators to prevent damage to the microcontroller and other electronics.
6	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
7	6	2.1	The point locations to be measured on each panel must be standardized.
8	7	2.1	The robot will be told which of the two mirrors it is measuring and in which orientation.
9	8	2.2	The robot must be able to determine the puck's position on a panel to 1 cm accuracy.
10	9	2.2	The robot must be able to determine when it crosses onto each new panel.
11	10	2.3	If the puck is actuated, there must be feedback control on the actuators to ensure the .5 micron RMS requirement is satisfied.
12	11	2.3	Actuation of puck must place eddy current sensor off mirror surface between 0.35mm and 2mm
13	12	2.4	The robot must have speed of 150 mm/s (depends on how many measurement points and stopping time per measurement)
15	14	2.5	The robot will have a pre-planned path.
16	15	2.6	The microcontroller will have a procedure for troubleshooting communications.
17	16	2.6	The robot must be able to communicate with the Etalon multiline server (WiFi).
18	17	2.7	Reflector holder and tether must allow 180 degree of clearance around the reflector
19	18	2.8	The robot cannot vibrate surface more than 1 micrometer RMS of un-filterable vibration.
20	19	2.9	The robot will be able to measure multiple elevation angles without human interaction within a period of 12 hours.
21	20	3.1	The robot wheels must have sufficient grip with surface with no slippage in vertical configuration under -30° C and 90% humidity
22	21	3.1	The robot will be able to sense if it starts to detach from the mirror surface.
23	22	3.1	The robot will have a method of minimizing damage to itself if it falls from the vertical mirror.
24	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.
25	24	3.4, 3.8	For each failure mode there will be a corresponding troubleshooting or safe mode procedure.
26	25	3.4, 3.8	The robot will return to the base of each mirror in the event of an anomaly or failure.
27	26	3.4	The robot will know the fastest route to the base of the mirror as part of its pre-planned trajectory.
28	27	3.5	The robot must be able to traverse mirror surfaces, including surface gaps or defects
29	28	3.6	The robot must not damage surface of mirror
30	29	3.8	The robot must survive complete loss of observatory power
31	30	3.8	The robot must detect loss of observatory power
32	31	3.9	The robot must respond to Observatory Alarms/alerts
33	32	3.10.	The robot must operate safely during an earthquake with accelerations up to 1g.
34	33	4.1	Tether must retract faster than the robot's pendulum swing in case of robot detachment
35	34	4.1	Tether must be approximately parallel (allowed to be non-parallel up to 30 degrees to mirror) to the mirror surface to eliminate potentia
36	35	4.3	Robot shall be able to orient itself on corner of panel with turning within TBD seconds
37	36		Robot shall be able to orient itself on corner of panel without turning within TBD seconds
38	37		Robot shall be able to rotate 90 degrees with <TBD% error
39	38		

Figure 3: Finished Testing Requirement protocols

Pressure Chamber Test:

The pressure chamber test is to guarantee if the suction force of the fan exceeds the weight of the robot under half atmosphere conditions. And the pressure chamber needs to rotate different angle 0 to 180 degree to check if the robot can attach on the testing plate. It was done by using the pressure chamber in space science. Last semester, with the help of Dr. Thomas and Dr. Chuck, two trails were done and succeeded.

Figure 4: Pressure chamber test trial 1

This trial was done by the cooperation of the control team and testing team. It proved that the robot can move forward and backward under half atmosphere. Due to the installation of the fans, this trial did not do the rotation test.

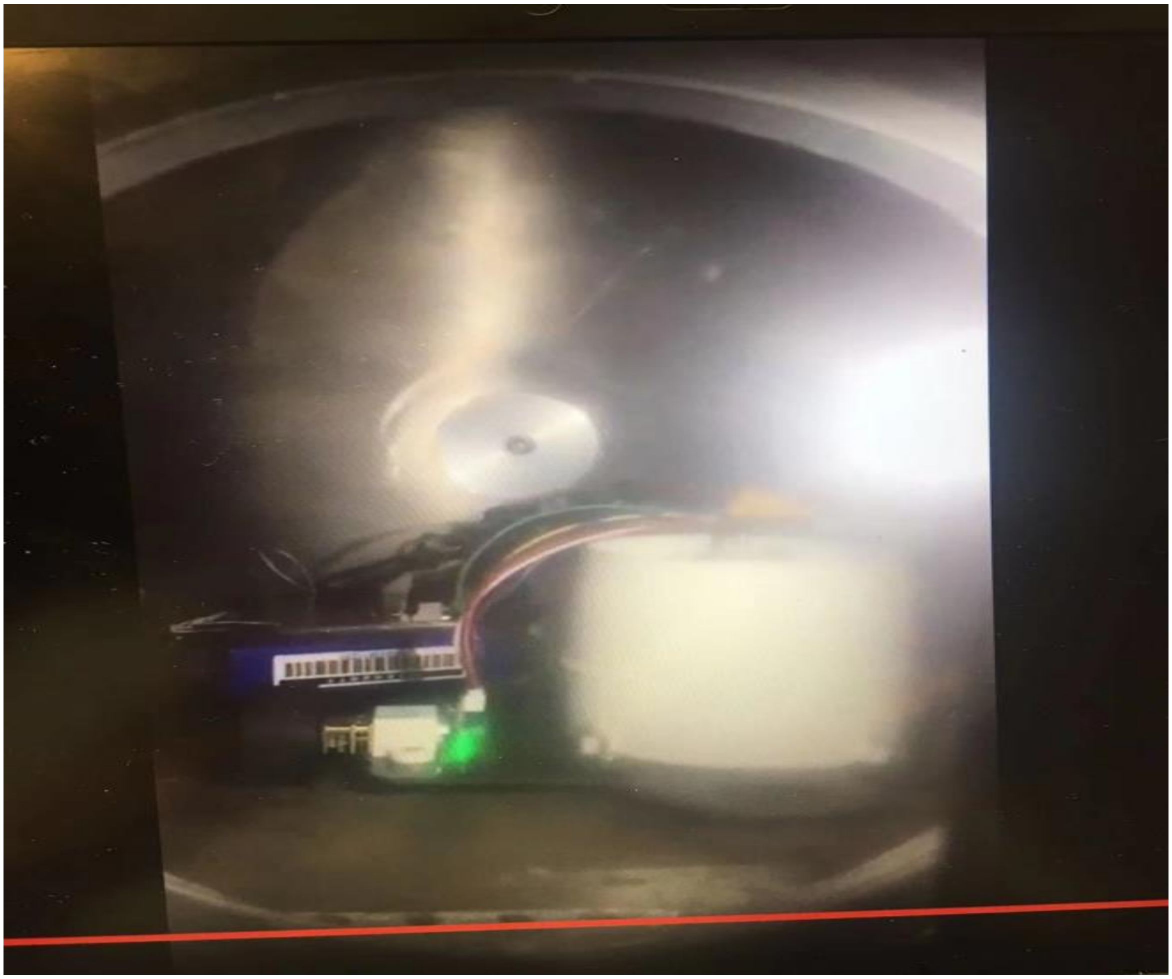

Figure 5: Trail 2 for last semester

The second trail was to test if the robot can attach on testing plate when rotate 0 to 180 degree. The robot was placed on the testing plate, and the pressure chamber was rotated from 10 degree to 80 degree and the robot performed perfect. However, for the further rotation, the fans stopped running due to the outage of the battery. It is because two fans need 1000w power, but our battery is only 8000 mA. For the December test, the more powerful and long lifetime battery will be used for the robot.

Thus, the team decided to rearrange another pressure chamber test and used tether instead of power bank.

However, the diameter of original hole for external cable on pressure chamber is smaller than our tether cable. The testing team decided to manufacture an adapter for the test.

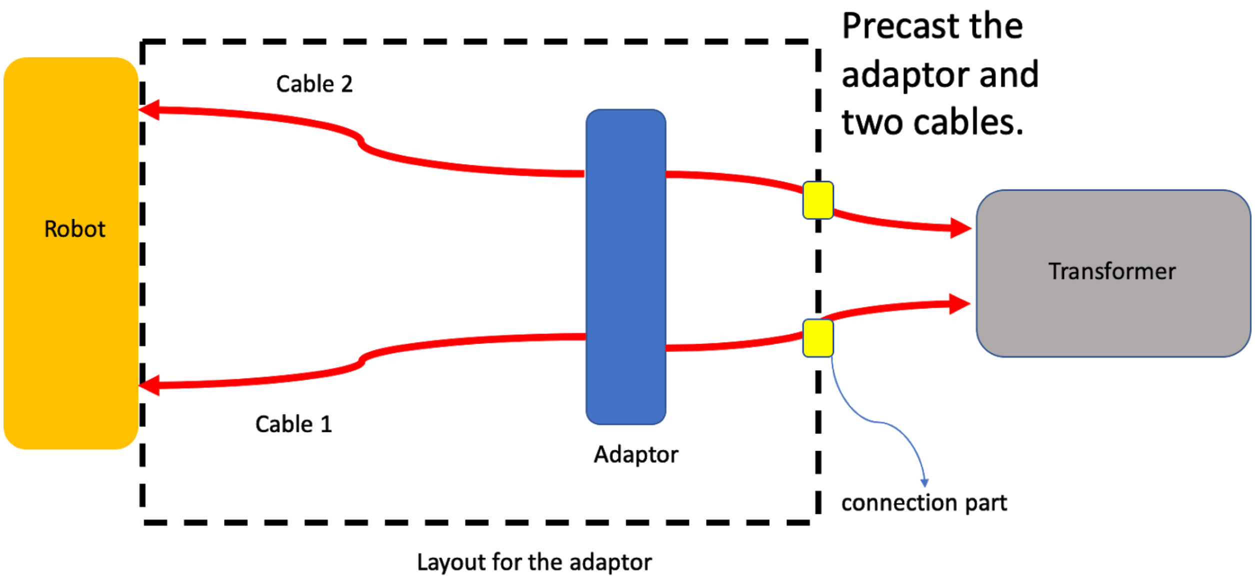

Figure 6: Layout for the adapter

The team used CAD to draw the adapter design sketch, used acrylic as material, and fabricated use laser cutting.

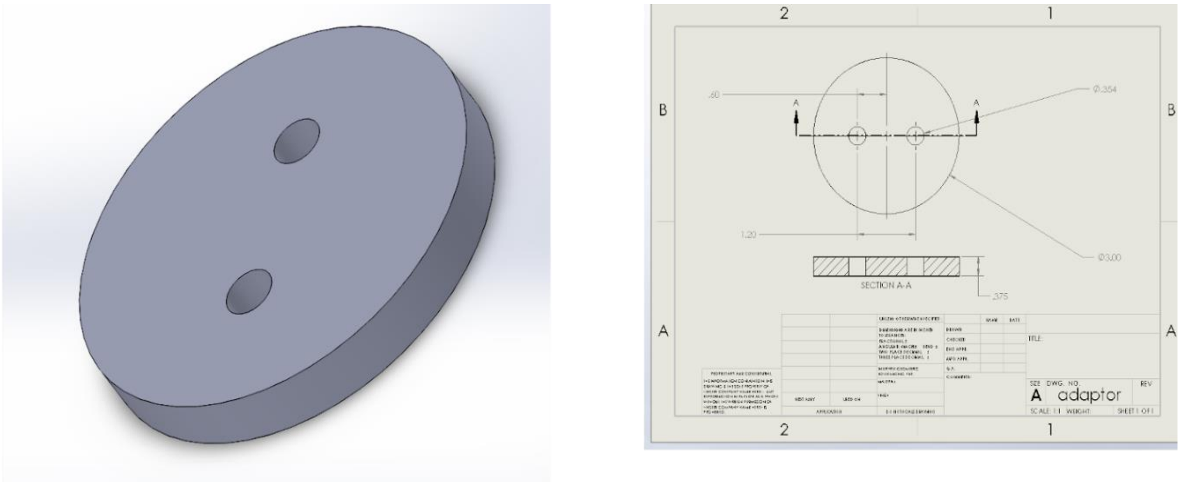

Figure 7: 2D and 3D sketches

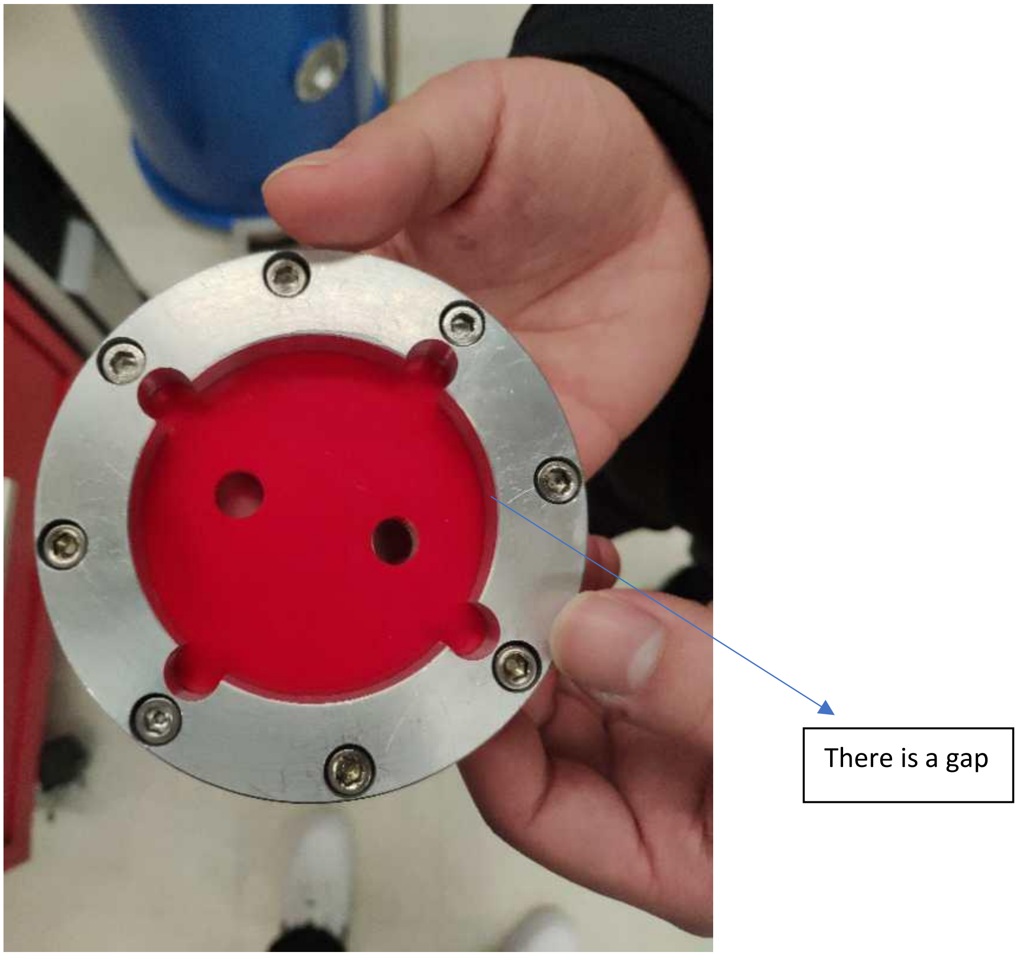

Figure 8: Laser cutting adapter

The testing team found that the thickness of first version of the adapter is not enough, thus it caused a gap between the adapter and the outside steel fixed ring. The second version of the adapter was decided to use the aluminum and will be fabricated by mechanical team.

PID control

In order to let the robot can move both forward and backward 30cm, the PID controller need to be used for the motor. With the collaboration of the control team, the wire connect for the encoder was finished, and the reading from the encoder was also tested.

Eddy Current test

Eddy current test was done in German by Becca, a former teammate in testing group, more detailed can refer to Becca's final report. Here is one of the testing results shown below.

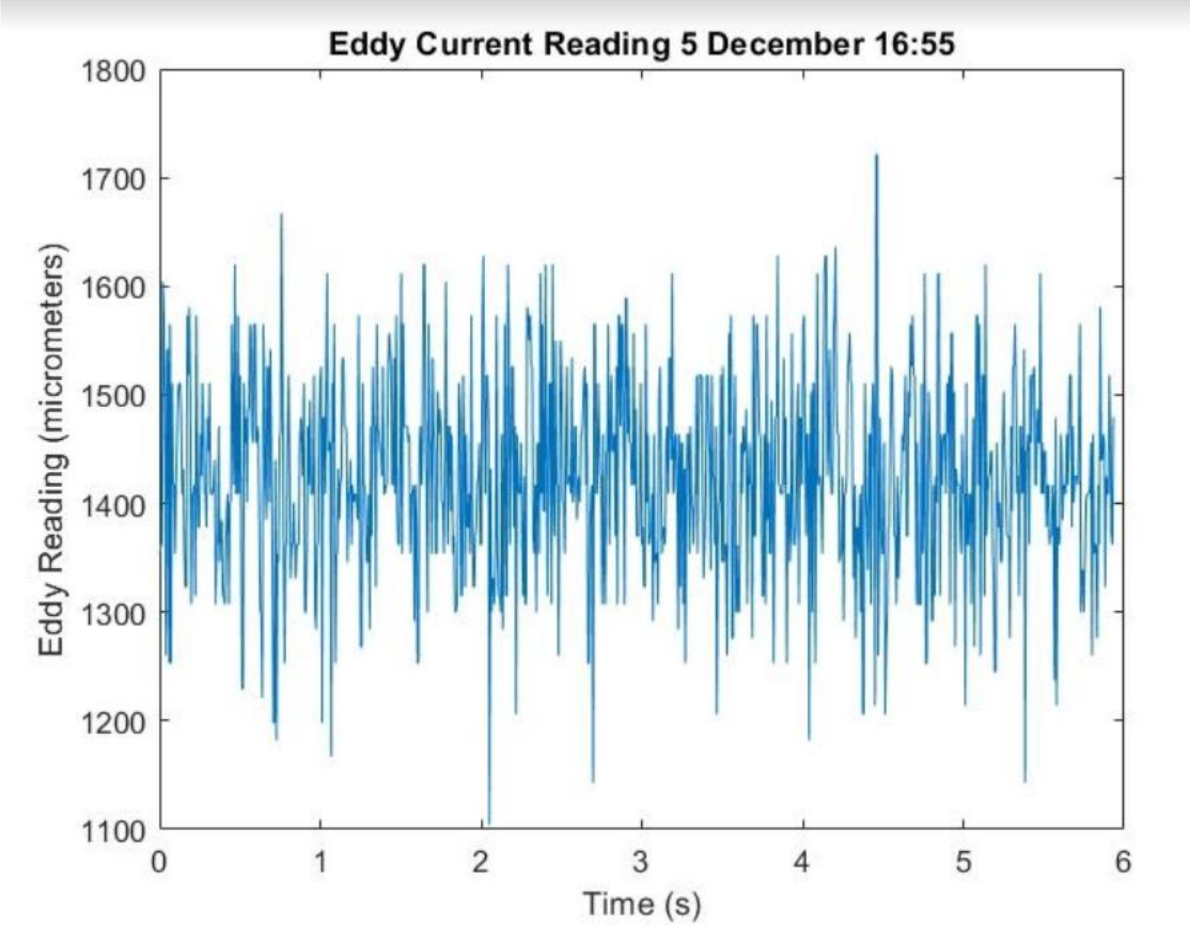

Figure 9: Eddy current test: Second Reading after changes. The value has now evened out. Day 2, 16:43

Simulation test

The goal of the simulation test is to compare the points that were run in the simulation with the points that were supposed to be reached. The code of simulation test was written by MATLAB, and the method of it was to compare the distance of two points using the formula:

$$d = \sqrt{(x_1 - x_2)^2 + (y_{1-}y_2)^2}$$

Equation 1

The process of the simulation test was:

1. Running the simulation code, the robot supposes to reach to 35 points.
2. When the robot reached to the point, the coordinates (x1, y1) will be indicated.
3. Comparing the (x1,y1) with the coordinate (x2,y2) of these 35 points.

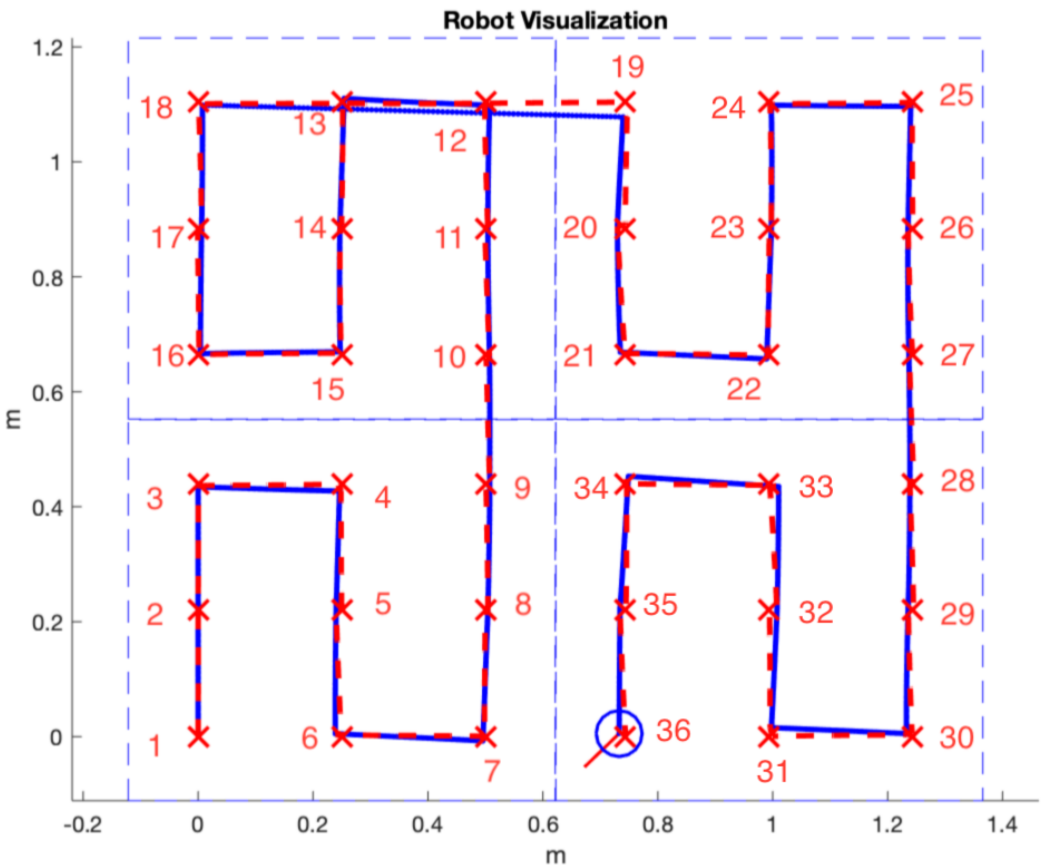

Figure 10: The route of the robot running (35 points)

The team ran five trails for the simulation test in order to avoid the coincidence, and they almost could prove that the distances of positions robot reached and the position of the point were in range of 0.01m:

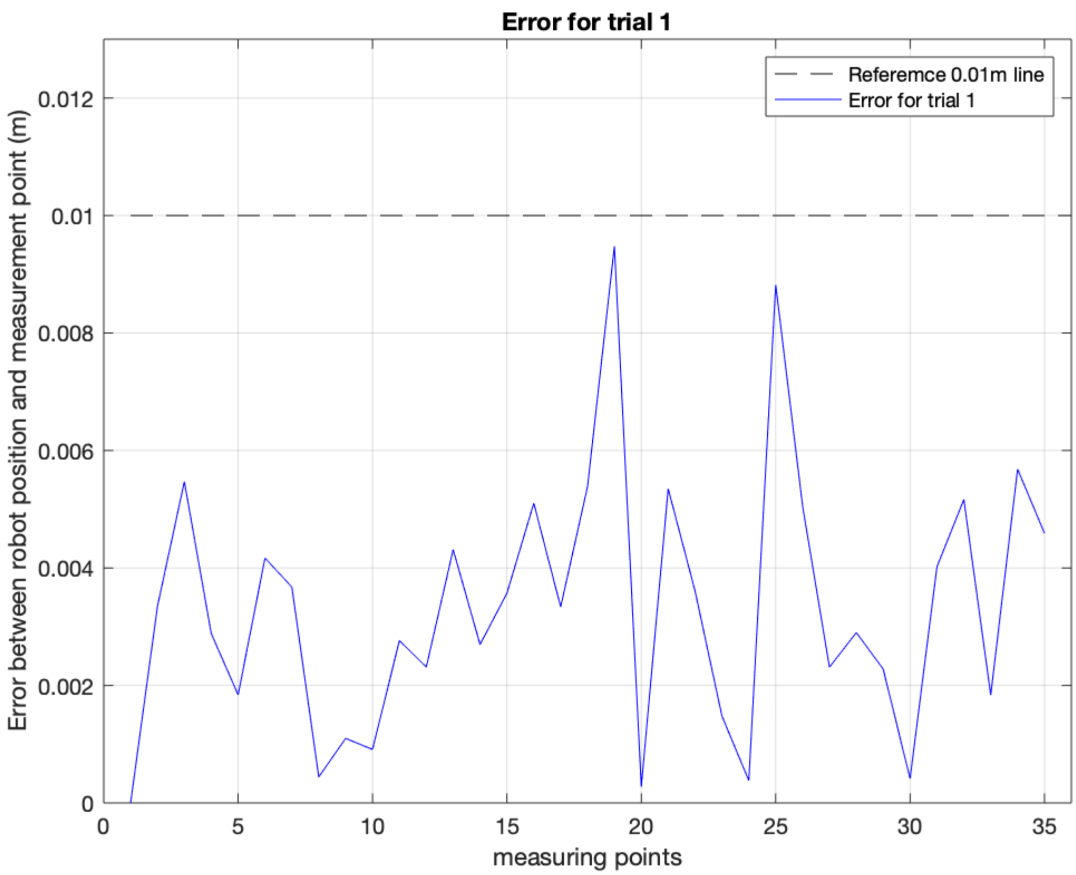

Figure 11: Simulation test Trail 1

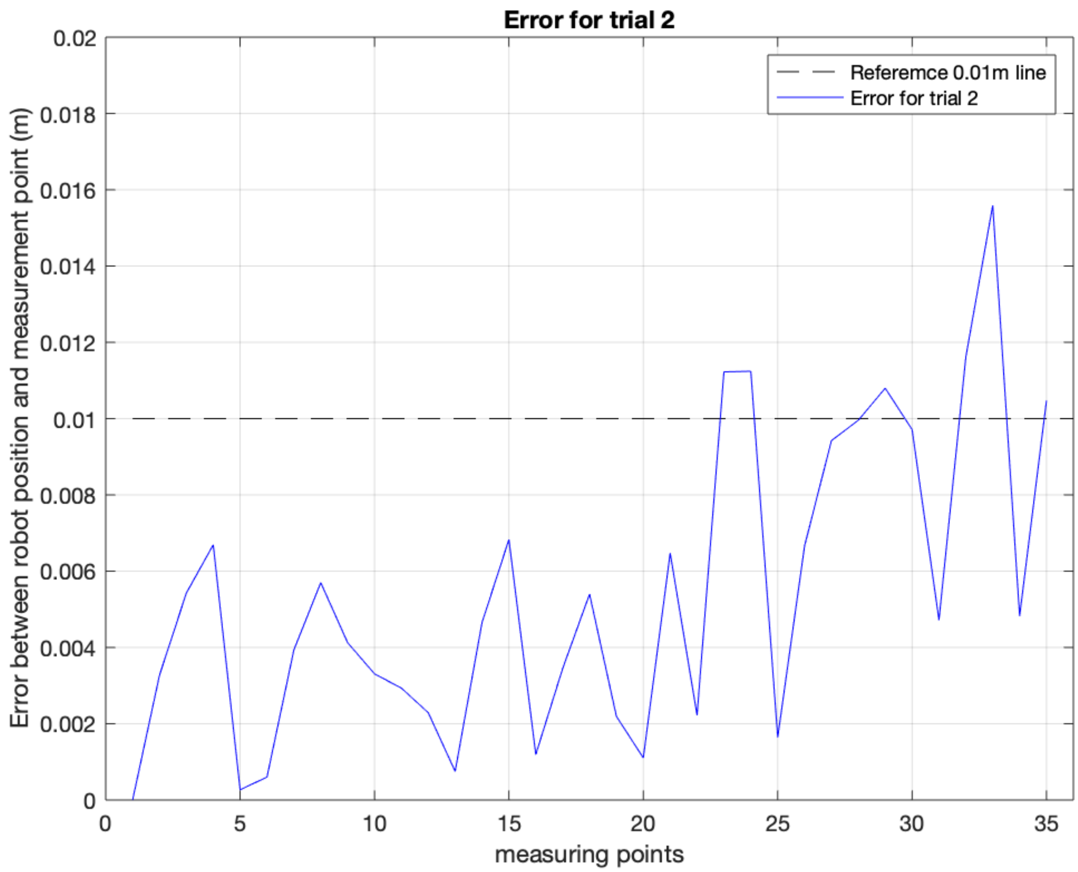

Figure 12: Simulation test Trail 2

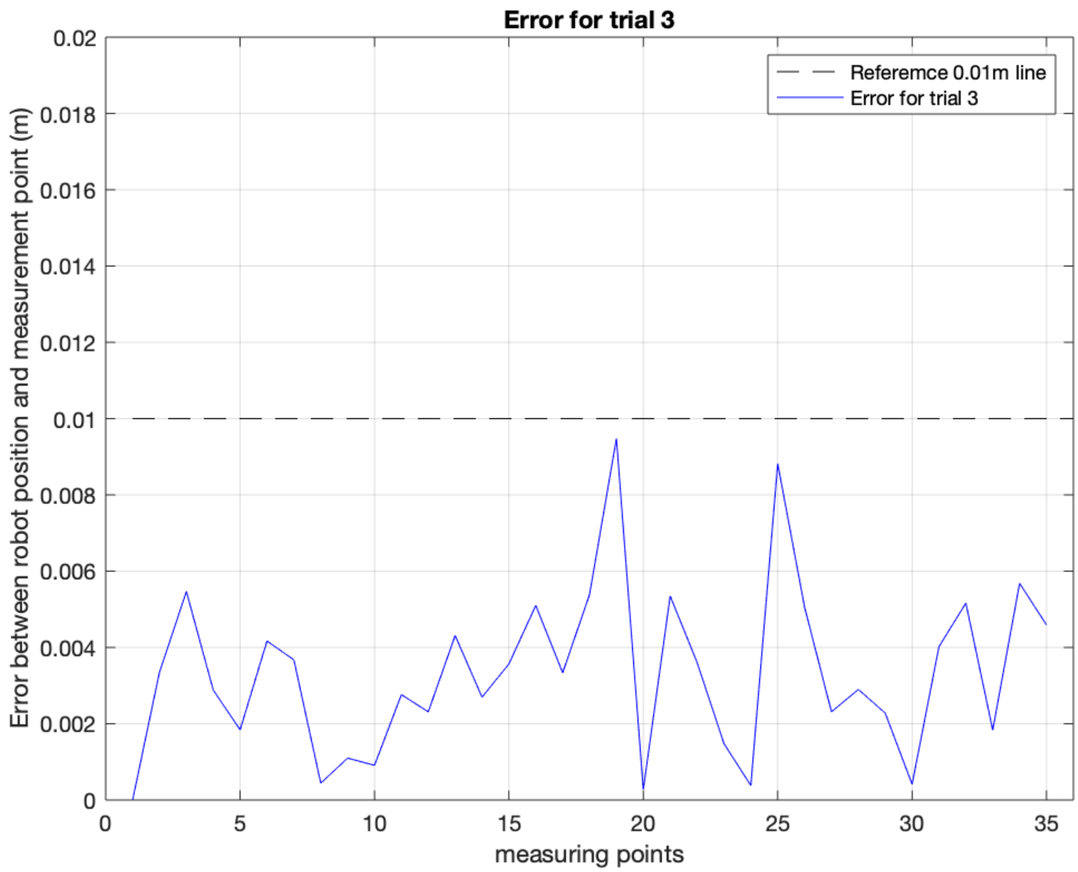

Figure 13: Simulation test Trail 3

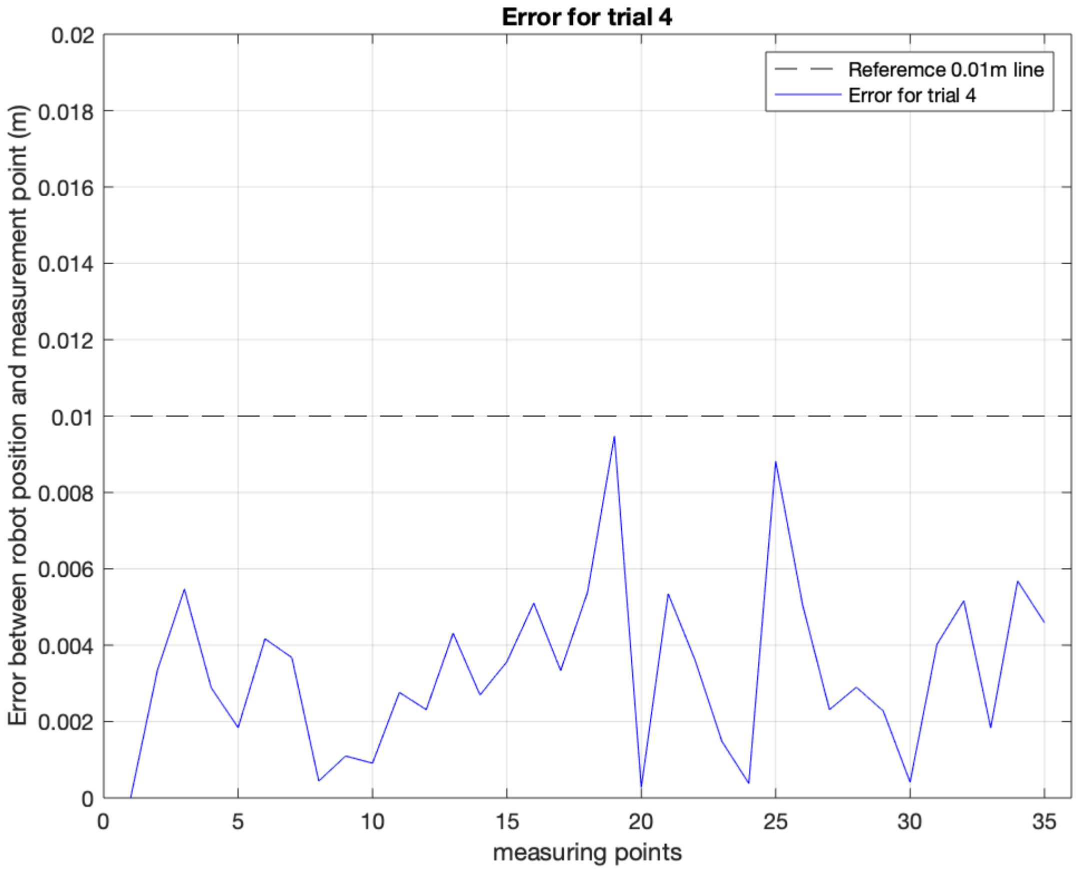

Figure 14: Simulation test Trail 4

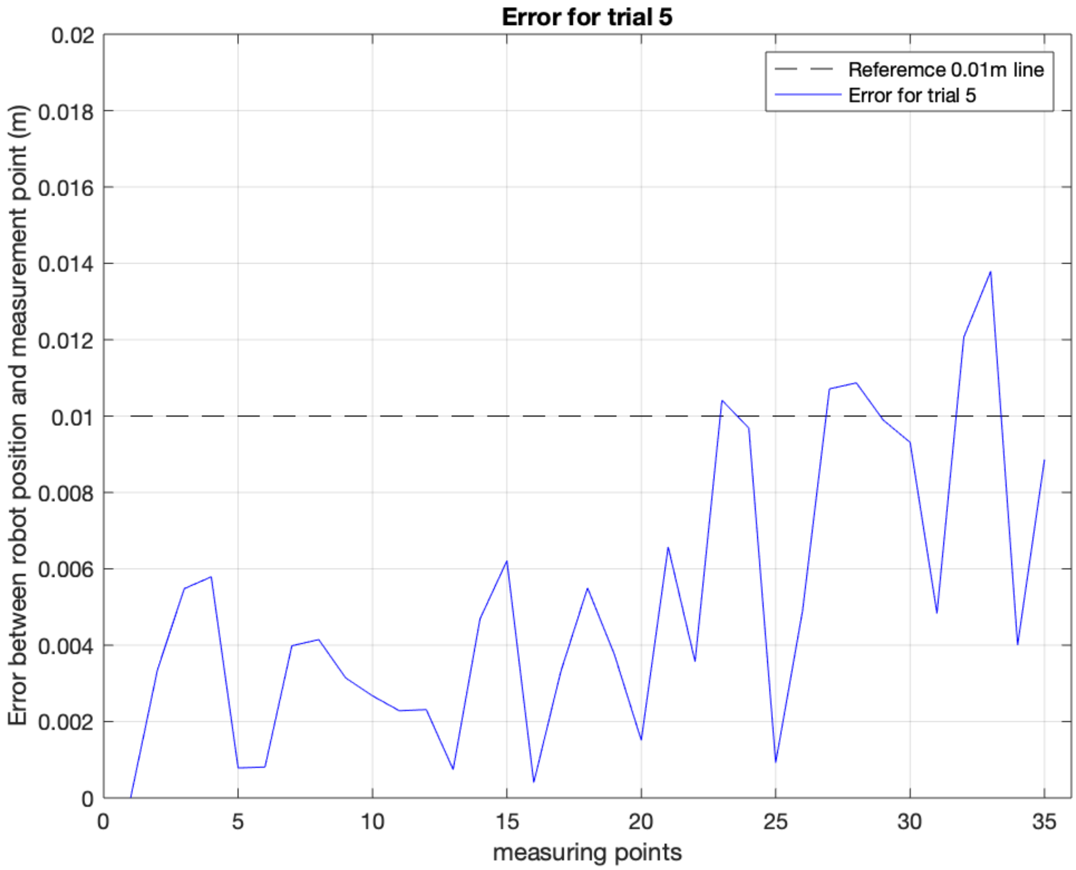

Figure 15: Simulation test Trail 5

Conclusion:

From August 2019 to May 2020, this project works smoothly. Based on the initial project objective, the physical prototype is built and tested by control, mechanical and testing team. As a member of testing team. The main goal is to finish all the testing instructions and do the testing according to the test requirements. The testing instructions were all finished and the eddy current sensor test, PID controller test, pressure chamber test and simulation test were almost done, all other tests were on going.

All the materials covered above was the work that was done by the author. For more detailed which were not covered in this report, please refer to other students' report.