**Project 1 Final Report, Green Team, EECS 498, W17**

Michael Dobrowolski, Anvitha Paruchuri, Shariq Lalani, Paul Reggentin

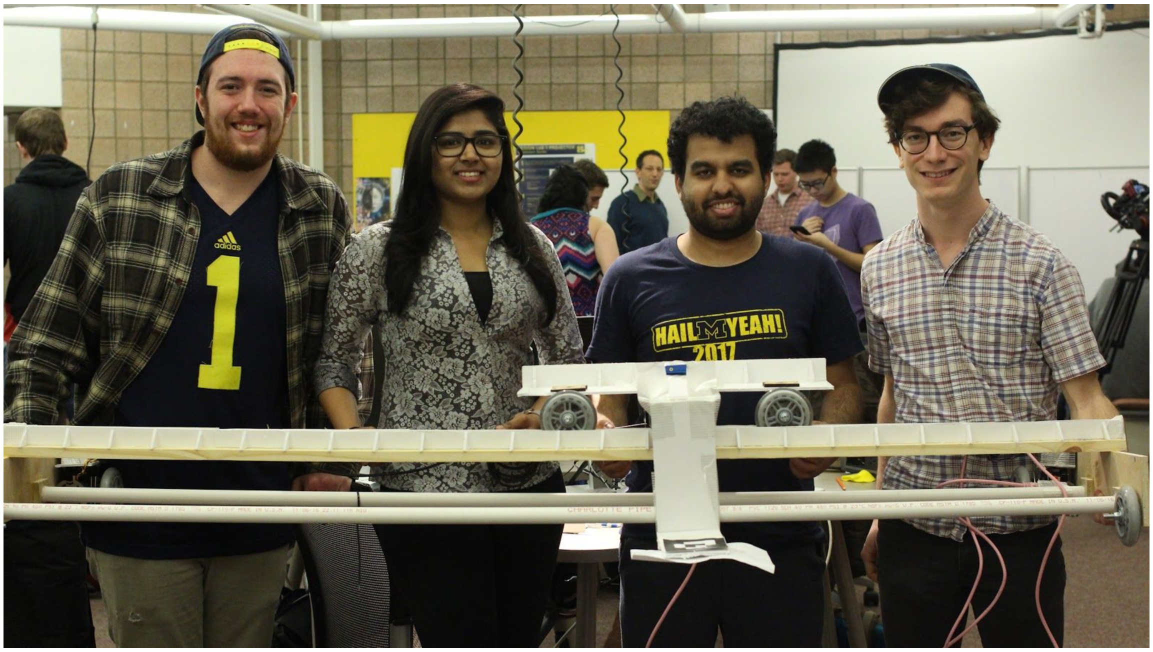


Table of Contents:

# 1 BACKGROUND

## 1.1 Project Description

Project 1 tasked us with the creation of a robot that travels around an arena to reach a sequence of waypoints, in specified order, while keeping a laser pointer (provided by the instructor) oriented along the positive Y axis  and projecting a dot on a screen. A network provided information about the sequence of waypoints to find, as well as distances from simulated lines connecting the waypoints. There were three requirements to pass: the robot tag stays in the arena, the robot reaches the final waypoint within 15 minutes, and the laser never illuminates in a direction with a negative Y component. The task was performed in a 2m x 2m arena as shown in *Figure 1.1* with edges delineated by eight tags. Waypoints were indicated by tags (10cm x 10cm) and the robot must carry a tag. A waypoint was reached once the robot tag is within a tag radius of the waypoint location. Each team was given two sensors, which returned the perpendicular distance between each sensors and the line segment connecting the previous and next tag in the sequence. This sensor data was the only information provided by the system about the robot's location; however, teams were free to use any auxiliary sensing that they wanted. If the team were unable to meet the pass/fail criterion, they could choose to manually drive the robot to the final waypoint and forfeit their chance of winning the competition.

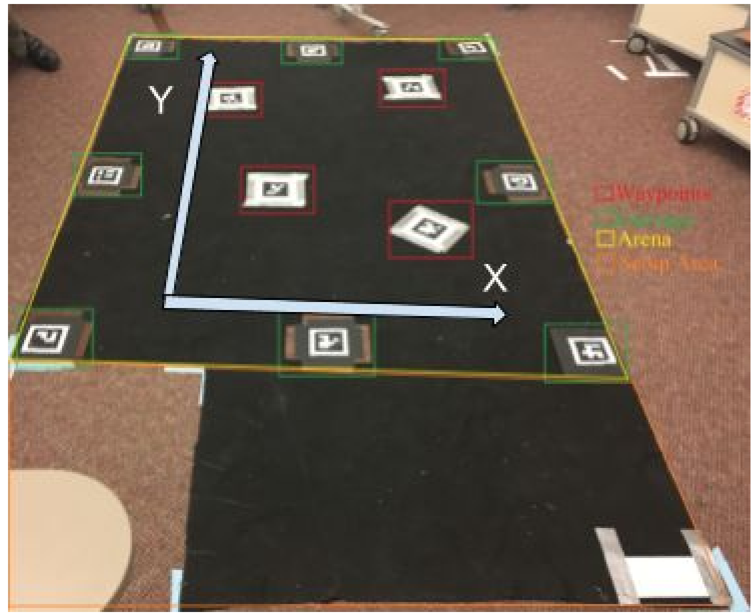



***Figure 1.1:*** *The arena used for the competition on P-Day*

The robot had to meet several design constraints. It had to be set up in a 2m x 1m area within five minutes. During this time, the robot tag had to remain in the within this area.  Additionally, the team could use a maximum of six Dynamixel motors and the laser dot must be at least 25cm above the arena. The screen on which the dot was projected was between 50cm and 100cm away from the arena.

## 1.2 Brainstorming

Our team started the research by reviewing previous years projects and their brainstorming presentations. The previous year's projects were useful because they demonstrated what had worked and what had not for the same task with the same timeframe and available materials. We also did research on robots outside the class. All of the references that we considered during the brainstorming stage are included in our Resource Document. During the initial brainstorming stage, we compared the following three possible designs for our robot.

### 1.2.1 Design 1

The first design was inspired by 2016 Blue team. The design consisted of two orthogonal rack and pinion gear mechanisms, one mounted on the other. It required either two or four motors: one for each rack and pinion mechanism, and two more to drive the body if it were shorter than the arena. The advantages of this design were that the laser could be mounted with the tag on the top rack and pinion, and the tag only moved in the X direction and positive Y direction via the two rack and pinion gears and wouldn't rotate, thus the laser would always point in the positive Y

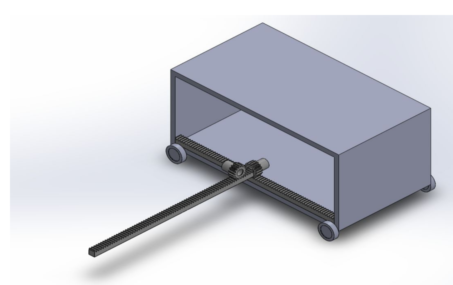


***Figure 1.2.1:*** *Orthogonal view of Design 1 robot*

direction. The robot could also scan the entire arena without determining the position of waypoints. However, the mechanical aspects, such as two interacting rack and pinion mechanisms as well as an arm that could extend unsupported over the arena, would have been very difficult to build.

### 1.2.2 Design 2

The second design we considered was a crane robot which is inspired by the [2014 Maize Team](). It consisted of a main body with a crane arm connected to a smaller car which held the tag. The main body would control the y-motion and the car would control the x-motion of the tag. This design required four motors: two motors for main body for front/back wheels, and two motors for wheels on smaller box attached to arm. The motions of both the main body and the car would be guided by fixed rails. The advantages of this robot were that the discrete x and y motion made it possible to scan the entire arena without worrying about sensor data, and the fixed orientation of the small car allowed for fixed orientation of the laser in the positive Y direction. Some disadvantages were that the robot would be difficult to manufacture, and the crane arm would be vulnerable to hysteresis. Our final design was a variation on this idea.

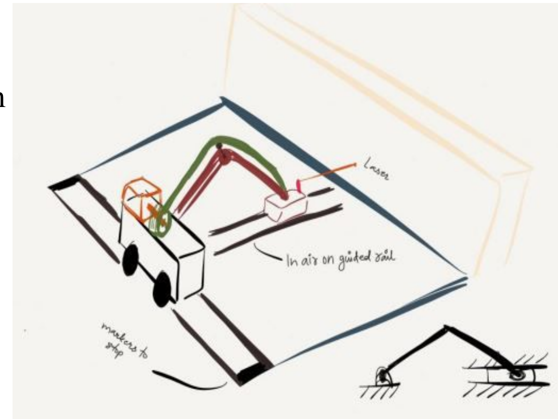


***Figure 1.2.2:*** *Orthogonal view of Design 2 robot*

### 1.2.3 Design 3

The final design we considered was inspired by the [2014 Blue Team ](). It consisted of two wheeled legs that could lift and rotate to control the direction of the robot without changing the orientation of the center platform, where the tag and laser were mounted. It required five motors: two motors for driving the front and back wheels, two motors for lifting these wheels, and one motor for rotating the entire body of the robot over the platform. The advantages of this design were that it was optimized for straight-line motion along waypoint lines, and that it could search for waypoint lines without moving by rotating the legs. However, wheeled motion would be liable to drift error and there would be no way to correct if the laser alignment were changed.

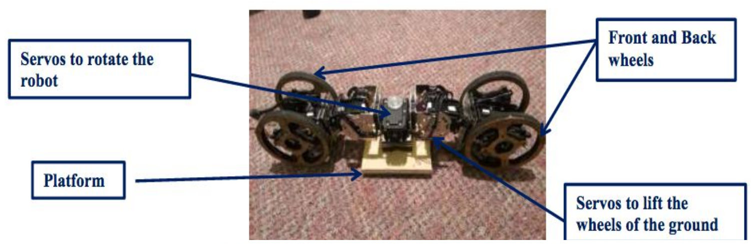



***Figure 1.2.3:*** *Side view of design 3 robot*

### 1.2.4 Final Selected Design

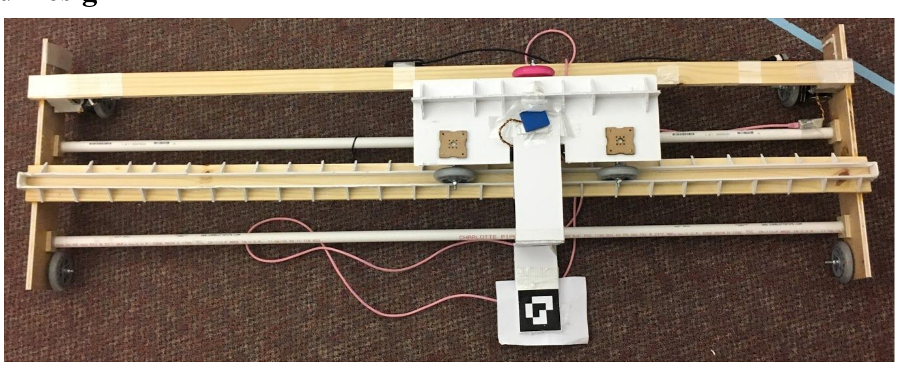


***Figure 1.2.4:*** *Top view of our final robot*

Alternative viewing angles of the final robot: [Orthogonal View]() [View in X-direction]() [View in Y-direction]()

### 1.3 Final Design Iterations

Our team decided to prototype a design which was 2m x 1m and implemented a 2m track along the X axis which supported a gantry carrying the robot tag. Our track consists of a 2m wooden board with foam core walls to keep the wheel moving in a straight line. We designed this robot using three motor, two for the driving (rear) wheels and one motor for a wheel on the track. We decided to use this design due because it would be able to scan the entire arena with relatively simple software. The gantry on top of the track could traverse the entire x-axis, moving a tag diameter in the y-direction after each x-traversal. This motion can be seen in this video and this chart of the tag position from P-Day. This scanning motion would be repeated until all four waypoints have been found. Some problems we foresaw for this design was the sagging or slipping of the gantry motor on the track and the slipping of the wheels on the chassis from the carpet. We decided to pursue this design for demo day, focusing on improving the mechanical design.

We found the mechanical design to be more difficult than expected, and were not able to present a functional robot at the Demo Day 2. There were two primary problems that caused this. First, our design was large and required a long rigid track. Foamcore would bend under such conditions, even when we stacked multiple boards together, so we decided to construct the robot out of PVC pipes and wood. However, these materials required special tools such as a bandsaw and a dremel which were not present in the Design Lab, so it took us longer than we expected to fabricate the chassis and track. Our second problem was that the wheel on the gantry tilted slightly because the gantry was unbalanced. When the wheel tilted, its sides would catch on the guiding walls and lock its motion, preventing it from moving. Due to these problems, our robot was not functional at Demo Day 2.

To fix the tilt of the gantry wheel, we decided to add a second 2m wooden block (second track) that ran parallel to the first track. We then connected the motor to a U-bar via snap lock. The U-bar was connected to a second wheel that ran on the second track. The heights of both tracks and the wheels were the same which allowed us to counterbalance the motor and keep the wheel perpendicular to the track. We also connected these two wheels by a foam core ceiling which we planned to use as a mount for our tag. By testing the movement of this system, we found that as we rotated the motor the ceiling would also rotate along with it causing it to hit the foam core walls beneath it. To correct this, we added two more free wheels on the first track, one in front of the powered wheel and one behind it and connected them to U-bars which then connected to the foam core ceiling. The principle behind this was the same as when adding the first free wheel to counterbalance the sag of the motor. These additional free wheels were used to balance the foam core ceiling since they held the foam core ceiling up from both sides, thus stopping the rotation of the ceiling as the powered wheel moved. This final gantry design is detailed in our assembly instructions in our How-To folder.

After we finished building a moving robot, we began testing the robot to determine how much the slipping of the wheels will affect the linear motion of the robot. Our initial tests showed that our robot moved 4 inches to the right of its initial position after moving forward a distance of 2m and we also found that our drive wheels were loose, thus wobbling as they moved. We taped the motors in tension to the wooden frame to fix the motors in place and found the robot moved straight across a distance of 2m. Finally, we programmed the robot to move forward in the positive Y direction in increments of 10cm via the drive wheels and then moved the powered wheel in the gantry 2m to the left and right. Upon testing the code, we added walls at the end of the foam core bridge to stop the gantry from falling off the bridge as it moved in the X direction. These iterations resulted in our final design shown in *Figure 1.2.4*.

### 1.3.1 Code Design

Our code was constructed using the JoyApp library following the structure from 2016 Blue Team's code due to their robots similarity to ours. Our design consists of a manual and an autonomous mode. Our manual mode allows a user to control the robot via the arrow keys on the keyboard. Considering the tag side of the robot as the front, the up arrow moves the robot forward, down reverses the robot, and left and right move the gantry respectively. This is accomplished using the *set_torque*() function in the JoyApp library which we use to cause the wheels to rotate in a direction upon a "key-down" event and stop upon a "key-up" event.

Our autonomous mode actives when the user presses the "a" key and continues operating until the program is terminated. Due to our mechanical design, we were able to employ a successful autonomous mode without the need to use the line sensing data. Our autonomous mode is of a cycle consisting of 2 steps: gantry movement and body movement. In the gantry movement step, we move the gantry 6 full wheel rotations to the right or left starting with movement to the right. The movement direction of the gantry alternates every cycle. In the body movement step, we move the body forward or backwards one wheel rotation starting with movement forward. The movement direction of the body alternates every 6 cycles in order to cover the length of the arena. This process allows us to scan the entire area of the arena making it possible to find all the tags without the need to sense them.

In order to sense the wheel rotations, we used the syncmx library, but we had complications using any commands that set the motor to a state. To mitigate this issue, we stored the initial angle of the wheel and used the *set_torque*() function to rotate the wheel while continuously polling the motor to get its current angle using *get_ang*(). We added an error of 10 degrees to the starting angle and checked for the current angle to leave this threshold to avoid counting a rotation early or double counting a rotation. When the current angle reentered this threshold, we counted that wheel as making 1 rotation and reset the wheel to the initial state.

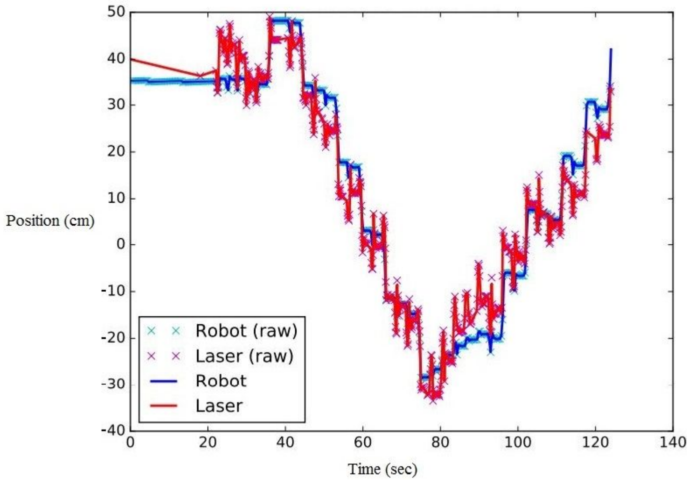
# 2 RESULTS

P-day had one recorded competition. Each time was granted five minutes to set up their robot in the deployment area. Next, they were required to manually move their robot to waypoint 0, the first waypoint. Upon reaching waypoint 0, the robot had to move autonomously towards waypoint 1, 2, and 3 respectively while keeping their laser oriented in the positive Y direction. If a robot was unable to reach a waypoint autonomously, they could forfeit the competition and manually reach the waypoints to reach the pass/fail criteria. They were given 15 minutes to finish. The times were recorded by humans with stopwatches. Times were recorded when the robot reached waypoint 1, 2, and 3. Timing started when the robot reached waypoint 0.

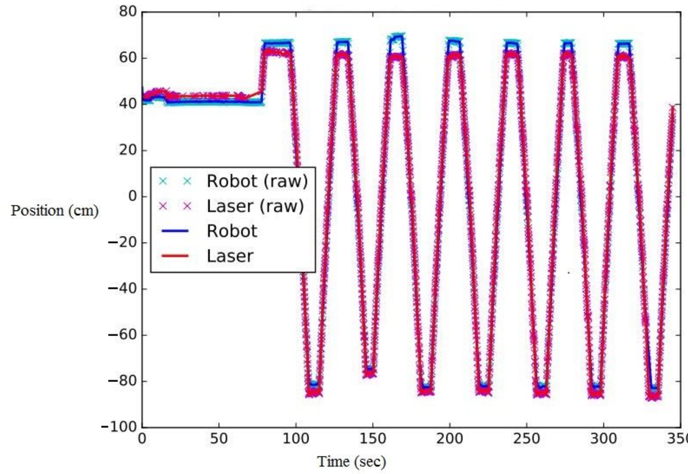
## 2.1 P-Day Results

| Team | Waypoint 0 – 1 | Waypoint 1 - 2 | Waypoint 3 - 4 | Total Time |
|---|---|---|---|---|
| Maize | 01:00:32 | 00:28:16 | 01:10:00 | 02:38:16 |
| Blue | 00:39:12 | 00:12:47 | 00:31:89 | 01:23:48 |
| Green | 01:10:53 | 01:46:51 | 01:35:29 | 04:32:33 |
| Red (DQ, manual) | 00:24:07 | 00:18:35 | 00:22:11 | 01:04:53 |

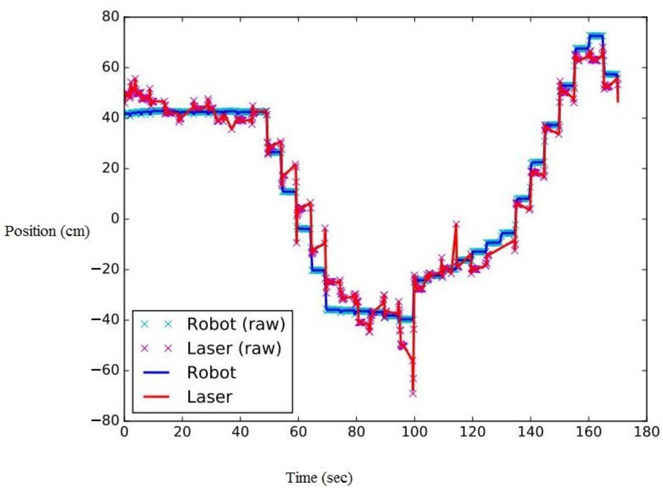
***Table 1:*** *Table of waypoint navigation times on P-Day. Times are listed in minutes (minutes:seconds:milliseconds)*



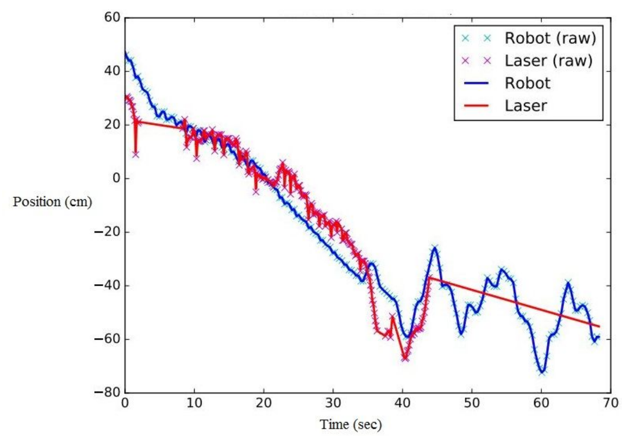

Blue Team RMSE Error  = 4.71




Green Team RMSE Error = 3.84




Maize Team RMSE Error = 5.58




Red Team RMSE Error = 8.85

***Table 2:*** *Laser Tracking Results. RMSE stands for root mean squared error*

# 3 DISCUSSION AND FUTURE WORK

## 3.1 Discussion and Improvement of Our Robot

Our robot was the winner of the competition because it completed the task with the lowest root-mean-squared error between the robot tag's y-position and the laser's y-position. Our robot's laser was placed at the same y-coordinate as the robot tag and aligned parallel to the y-axis. Both laser and tag were mounted on the gantry, so they moved together. This meant that the laser would stay in alignment for translations in both the x and y directions. A rotation of the chassis would have caused the laser to go out of alignment with the robot tag; however, we fixed all four of the chassis wheels parallel to the y-direction, which prevented the robot from rotating.

Our design was able to find the tags successfully in 4:30, as seen in this video. This was the slowest time of the three teams that succeeded autonomously, and was slower than the Red Team's manual run. Our design did not use sensor data; instead, it scanned the entire arena. This meant that it often moved farther than necessary, such as at the 3:50 mark of the video, where it locates Tag 2, then moves away from Tag 3. It does not return to Tag 2 until 4:30, resulting in a delay of 35 seconds.

We considered incorporating waypoint sensors to give the robot information about which direction to scan, but we did not have time to implement such a system. We believe that this would have decreased our run time significantly by preventing motion away from waypoints as described in the previous paragraph.

Our robot had a few design flaws that did not affect its performance on P-Day, but could have. For one, we did not secure two of the ethernet cables: the one connecting the robot to the USB and the one connecting a chassis wheel to the gantry. In the video of our robot at P-Day, the robot can be seen running over the cable that connects it to the USB. This had the potential to disconnect the robot or push it out of its alignment with the y-axis, which, as discussed earlier, would have put our laser out of alignment. Additionally, the gantry can be seen running over its ethernet cable, which could have either disconnected the gantry or pushed it off the track. This did not happen during either of our two runs, but we did not do anything to prevent it from happening.

Another potential problem for our robot was the presence of "blind spots," areas of the arena that our robot did not cover during a scan pattern. Because we were working on the mechanics of the robot until the day before P-Day, we did not have time to rigorously test the software. In this video of our first run, the robot misses its target tag because it travels too far in the y-direction between x-traversals. We were able to complete an autonomous run on our second attempt, but with a different arrangement of waypoint tags it is possible that we would not have been able to locate all tags. This would be a very easy problem to fix, though, as we would simply have to decrease the y-motion in between x-traversals.

Another improvement that we could have made would have been increasing the speed of motion of the robot. As shown in our test data document, our robot had an average x-traversal time at P-Day of 12.03 seconds. Although it did not perform a continuous y-traversal, data from testing shows that it took an average of 35.54 seconds to travel along the entire y-axis. In a worst-case scenario, with each successive tag at the opposite y-coordinate of the arena, our robot would have to make 3 full scans of the arena (assuming no blind spots) to complete the autonomous task. Our robot needed 8 x-traversals to complete a full scan of the arena, so the total worst-case time would be $3*(8*12.03+35.54) = 395.3$ seconds, or 6:35.3 minutes. This is within the time limit of 15 minutes, but in the spirit of competition, we believe that we could have increased the torque applied to the powered wheels to decrease this worst-case time.

## 3.2 Discussion and Improvement of Other Teams' Robots

### 3.2.1 Blue Team

The Blue Team employed a design which had four wheels, one parallel to each side of a square chassis. These wheels were square, so they restricted the robot to discrete amounts of motion at each step. The laser was mounted on a rotating platform at the top, which used gyroscopic sensing to preserve its orientation in the y-direction. The tag extended out from the body on a foamcore board, which allowed the tag to lie closer to the ground than it would be able to if it were attached to the chassis.

The Blue Team performed very well. It completed an autonomous run in 1:26 minutes, the fastest time of any autonomous run. They placed second in the competition because their root-mean-squared-error between robot tag and laser y-coordinate was 4.71, which was higher than our team's score.

The plot of the robot tag vs. laser y-positions shows regular sharp jumps in the laser position. These jumps correspond to steps taken by the robot. When the robot took a step, the chassis was lifted up from the flat sides of the wheels to the corners of the wheels and dropped back down in the span of approximately 0.7 seconds. This motion resulted in the chassis being jolted, and, since the laser was at the end of a foamcore tower extending out from the chassis, its deviation was magnified. Although the laser came to rest in between steps at a consistent orientation, its position during the step motion was uncontrolled. Besides these jumps, the laser position tracks the tag position very closely, so they were most likely a large contribution to the mean-squared error. It is possible that a wheel design with a smaller difference between apothem and circumradius would have reduced the jolt to the chassis during steps. This could be achieved by a regular polygon with more sides, or a circular wheel. Such a design would likely improve the robot's laser score.

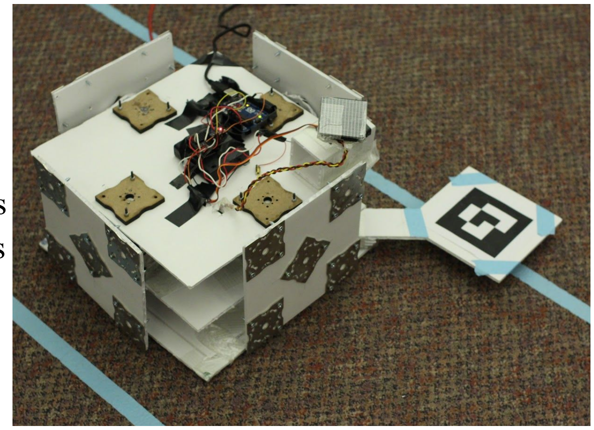


***Figure 3.2.1:*** *Blue Team Robot*

One significant problem that the Blue Team had was cabling. They did not come into P-Day with a plan for cable placement, intending to let it hang free onto the ground beside the robot. This became a problem because the metal plates at the corners of the wheels were sharp enough to cut and damage the ethernet cables that tethered the robot to the computer and power supply. The Blue Team was able to improvise a solution by draping the cable over the Design Lab 1 light fixtures, but had those fixtures not been present, they would have been in a very risky situation.

### 3.2.2 Maize Team

The Maize Team had a design very similar to that of the Blue Team. It also had a square chassis with regular polygon wheels. However, its wheels were pentagons instead of squares. The structure of the wheels also differed in that the edges of the wheels were reinforced with a foamcore board on all sides, instead of by metal plates at the corners. Its tag was mounted at the center of the chassis, several inches from the ground. The laser, which is not visible in the above picture, was mounted on a tower on the chassis. It was fixed in relation to the robot's chassis, and was therefore unable to correct its orientation if the chassis rotated.

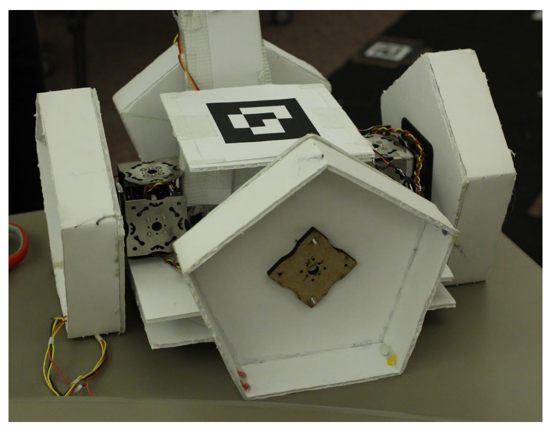


***Figure 3.2.2:*** *Maize Team Robot*

The Maize Team was able to complete the task autonomously. Its root-mean-square error of the laser vs. the robot tag y-coordinate, 5.58, was the highest of all teams that completed the task autonomously. It took 2:38 minutes to complete the task, which was the second-fastest autonomous time.

The Maize Team's design worked well; it was able to complete the task autonomously without making motion away from its target waypoints. However, its laser score could have been improved upon. As seen in the plot of laser vs. robot tag y-coordinate, the laser had regular sharp deviations from the tag position. These deviations correspond to steps taken by the robot. As seen in the video of the Maize Team's run, it was subject to the same jolts during steps that the Blue Team was. Their steps took only .2 seconds, approximately 30% of the time that the Blue Team's steps took. As discussed in the Blue Team section, involving a regular polygon with more sides or circular wheels could mitigate this problem. Another problem that the Maize Team encountered was that its robot relied on preserving its orientation throughout the arena run to keep the laser and robot tag in line. If the orientation were lost through a rotation of the robot's chassis, the robot did not have a method to sense or correct for the rotation. As seen at the end of this video, the robot began to rotate just before it reached the final tag, which corresponds to the large gap between the lines at around 160 second in this plot. There are a number of ways the Maize Team could have dealt with this, including a laser orientation correction system similar to the ones the Blue and Red Teams used, as well as a method to sense the orientation of the robot and mechanical controls to adjust it.

### 3.2.3 Red Team

The Red Team was the only team to not complete the task autonomously. They also had the highest root-mean-squared error between the robot tag and laser y-coordinates, with a score of 8.85 on their best run.

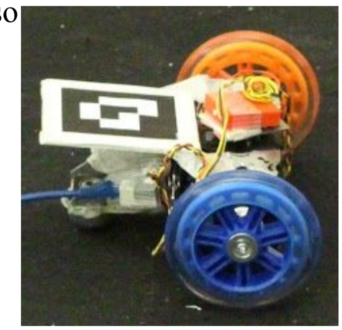


*Figure 3.2.3: Red Team Robot*

One significant reason that they could not complete an autonomous run was their algorithm for transitioning from one waypoint to the next. Their robot relied on sensor data to guide the robot from one tag to the next along the simulated line segments between tags. As seen in this video, after the robot located Tag 1 it continued to circle Tag 1 instead of following the waypoint line to Tag 2. The recovery plan was not able to scan the arena to locate the next simulated line segment.

Another major flaw in the Red Team's design was their method for keeping the laser oriented parallel to the y-axis. Their robot was the only one to incorporate planned rotation into its motion; all other teams attempted designs that kept the robot oriented in one direction the entire time. As seen in these three plots(1, 2, 3) of the robot tag vs laser position, the laser was prone to high-frequency noise, which is present especially at the beginning of each run. This noise may have been in part due to latency between the robot chassis turning and the laser mount sensing the amount of turn. Another possible source of noise was the tilt of the chassis. The ball bearing on the back of the robot can be seen and heard lifting off the ground when torque is applied to the motors, especially at the beginning of the second run. Each time the ball bearing lifted off the ground, the chassis of the robot was jolted, which most likely contributed to the noise in the laser positioning.

# 4 REFERENCES

[1] Project 1 Description: https://wiki2.eecs.umich.edu/hrb/index.php/Projects#Project_1_--_Waypoint_navigation
[2] Dynamixel Modules: https://wiki2.eecs.umich.edu/hrb/index.php/Dynamixel_modules
[3] Brainstorming_Presentation_P1_17Green:https://wiki2.eecs.umich.edu/hrb/index.php/File:Brainstorming_Presentation_P1_17Green.pdf
[4]Brainstorming_Resources_P1_17Green: https://wiki2.eecs.umich.edu/hrb/index.php/File:Brainstorming_Resources_P1_17Green.pdf
[5]How_To_P1_17Green.zip: https://wiki2.eecs.umich.edu/hrb/index.php/File:How_To_P1_17Green.zip
[6]Prior Projects: https://wiki2.eecs.umich.edu/hrb/index.php/Project_Base#Project_1_-_Waypoint_Navigation
[7]Brainstorm_Final_14Blue: https://wiki2.eecs.umich.edu/hrb/index.php/File:Brainstorm_Final_14Blue.pdf