Critical Design Review

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Abstract

Team P was to design and develop an Advanced Energy Vehicle to autonomously transfer people and resources between cities for the Smart City Columbus Staff. The AEV was designed to be as efficient as possible in terms of time, energy, and capital cost. Team P's AEV would first move towards the center of the track and stop at a gate for 7 seconds; it would then move to connect safely with a caboose at the end of the track and wait for 5 seconds; then, the AEV with the caboose would reach the gate once again and pause for seven second before returning to original position. The total cost of Team P's AEV when performing one full run was $534,014.04, with the capital cost being $148,540.

In the development process, research and development labs and performance tests were conducted. In the PreR&D labs, the AEV started moving on the horizontal track only after two smaller propellers were switched to larger ones at 35% power. In aR&D Lab1, a single propeller pulling at 50% power consumed 24.679J of energy to move the vehicle to 200 marks, which was the least amount of energy used compared to pushing and hybrid action. In aR&D Lab2, the AEV consumed the minimum energy of 25.285J when accelerating from rest to move the vehicle to 200 marks. In Performance Test 1 and 2, it was found that stop by coasting alone yielded unpredictable final position, which was then made consistent by applying supplementary power-braking. In aR&D Lab03, research showed that running the AEV at power increasingly higher than 50% (65%, 75%, 90%) yielded consistent decrease in power consumption and time use, though performance accuracy decreased.

From the experiments above, it was concluded that: first, larger propellers provide more thrust than smaller ones; second, pulling with the propeller provided more thrust than pushing at the same motor speed; third, when starting, accelerating to a given speed costed more energy and time than setting to the same speed directly; fourth, power-braking provided better braking accuracy than coasting, and the two should be combined to achieve maximum energy and time efficiency; last, operating the AEV at 75% motor power was the most consistent and energy-and-time efficient.

Therefore, it was recommended for Smart City Columbus to invest in development based on Team P's AEV design: on either side of the AEV, one large propeller was to be installed to maximize pulling thrust; it was also recommended for the vehicle to operate at high speed, and to make its stop using power-braking, in order to consume the least amount of energy and time.

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Introduction

Freshmen engineering Team P, under the company Koffolt Properties, was assigned to research, design, and develop an Advanced Energy Vehicle for Smart City Columbus. According to the Mission Concept Review, the vehicle would "be autonomous, electric-powered and travel suspended from a monorail system." (2019) A total budget of $500K was set for the AEV project, and Team P would be evaluated based on the energy and time cost, accuracy penalty, capital cost, R&D cost, as well as possible cost of safety violations, as listed in the Appendix B, Table B.1. The goal of Team P was to deliver a cost, energy, and time-efficient AEV model that could yield high performance accuracy, while maintaining safety. The roles of each member of Team P, as well as the project timeline, were attached in Appendix A.

Team P was required to perform five Preliminary Research and Development Labs, three Advanced Research and Development Labs, and three Performance Tests. The goal for Pre-R&D Labs was to introduced the team to the AEV model assembly, Arduino programming basics, the AEV data analysis MatLab tools, as well as methodologies use in creative design thinking process. Team P's goal in aR&D Labs was to design original controlled experiment to research on properties affecting the AEV performance, such as propeller size, propelling method, acceleration, and initial power. In the three performance tests, Team P were expected to apply previous findings to improve the AEV model, and quantitatively measure the time and energy cost of a single operation. In the first performance test, the vehicle model was to make it from the starting location to the gate and to stop for seven seconds, while two AEV designs were to be tested against each others in terms of general performance effectiveness. In performance test 2, the vehicle model was to continue on through the gate, to connect with the caboose at the other end of the track and wait for five seconds, while two sets of AEV control codes were tested against each other in terms of energy and time efficiency. In the final performance test, the finalized AEV of Team P will perform the entire autonomous right three times, and data would be recorded and analyzed for final evaluation, as well as for giving further recommendations on AEV design and testing.

Experimental Methodology

Main Equipment for AEV Labs

During the development progress, models of AEV had been designed, built, and tested by Team P on a track simulating autonomous transportation between Easton and Linden. The AEV model would first move towards and stop at a gate located halfway along the track; it would then wait for seven seconds before moving over to the other side of the track to pick up a caboose using magnet; the AEV would then wait five seconds and proceed to the gate once more; after stopping for seven seconds, the AEV would return to its original position with the caboose. Parts of the track would be inclined, and its general dimensions is shown as below:

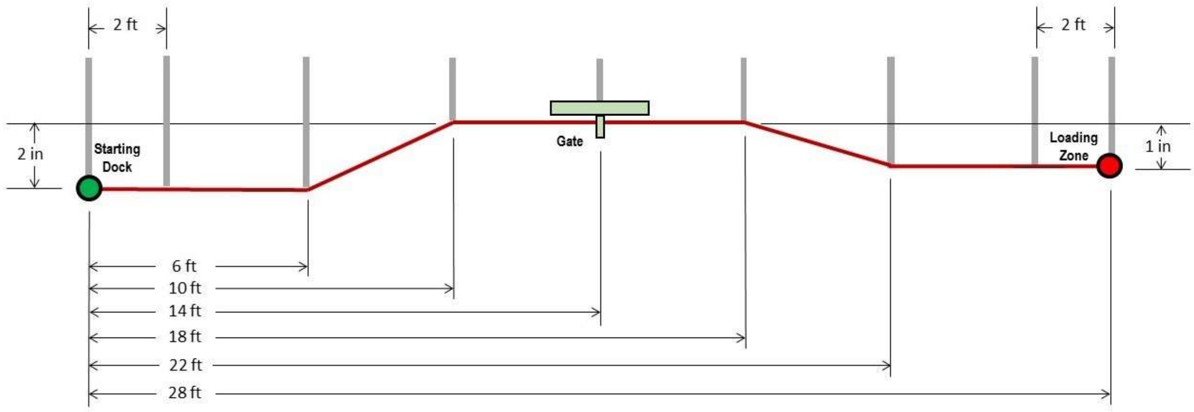


Figure 1.0 Dimensions of the AEV Test Track

Methodologies for Preliminary Research and Development Labs

The first five labs were named Preliminary Research and Development 1, and all had different and specific goals relating to the Arduino and the AEV. The first lab with the AEV was to learn about the Arduino itself, and the code required to run it. The tools that were given were the Arduino, a set of two motors, a battery, a cable, and a 3D printed housing for all of it. The task was to become familiar with coding the Arduino, which would turn out to be the most important task in the future. A couple sets of test codes (C.1) were given in the PR&D 1 document posted on Carmen. Before coding anything, the wires had to be connected from the motors and battery, to the Arduino. All of the group members practiced with coding the Arduino, but the people in the group who are majoring in CSE took precedence. There were no issues with learning how to code, or remembering the different possible codes that could be written.

The second lab was the first time that the group dealt with a physical AEV instead of a stand to hold everything. The sample AEV was constructed according to the example on that was listed on the Carmen page. This AEV included everything that was used in the stand plus the arm that the AEV will hang from and the nuts and bolts to secure everything. The other main thing that this AEV included was reflective sensors, which was what the focus of PR&D 2 was about. The reflective sensors are the way that the AEV can tell where it is on the track, and how far to move. The group learned that a reflective sensor test will be required before every test track run to ensure that the sensors are working properly. In the future, code would be created using "goToRelativePosition" which is only accomplished by using the reflective sensors.

The third lab was the first one where the members of the group were able to actually put their ideas on paper. The goal was to brainstorm an idea for a possible AEV design that would meet all of the criteria laid out in the Mission Concept Review(MCR). The AEV would most importantly have to be as efficient as possible in energy as well as the cost of the materials. The other considerations that would have to be taken into consideration were the time on the track and also the aesthetics. The way that each team member did this was by sketching out a multiview drawing of their idea on a grid paper. The sketch had to be dimensioned by the overall width, height, and depth of the AEV.

The next PR&D lab, number 4, had the goal of learning how to extract the data off of the AEV after a run on the track. The group members would use the same sample AEV that was assembled during the second lab day, and upload test code (C.1) that was given in the PR&D document. The code that was uploaded created a graph of the data and also gave an amount of total power that was used during the run. This was one of the most important preliminary labs, because throughout the labs, every group will have to be able to read the data in order to make the most efficient AEV.

The last preliminary research and development lab's goal was to make a final decision on what AEV that will be moving forward in the stages of development. The way that each group was able to do this was by using screening and scoring tables. These were two different tables that evaluated all of the important pros and cons of each different AEV design. The first table that was completed was the screening table, which was the more broad of the two. The main criteria were laid out along the left column and each design was given a +, -, or 0 based on how well each described them. This gave each group a good idea of the front runners in design and also the designs that were falling behind. The next table, the screening table went into much more detail about each criteria. This table gave a weight to each category because something like aerodynamics is much more important than aesthetics. This would leave the most important criteria with the most weight, and allow the most promising one to be found.

Methodologies for Advance Research and Development Labs 1 and 2

The next phase of the AEV process was the two Advanced Research and Development labs. Each group chose their own topics to test and try to make the AEV more efficient. The groups could've chose anything from testing the motors to the batteries themselves. The group decided to chose to test whether a pulling or pushing motor would be more efficient. The materials that were used for this experiment was the fully assembled AEV with the code (C.2-C.7), a track, and a computer to extract the test data from the runs. The results were all compared to each other to see what motor configuration was the best.

The second test for the AR&D process was also focused towards the AEV's motors. The idea tested was to see if adding acceleration would decrease power consumption. After each previous run, there was an initial power spike noticed, which was the AEV overcoming the static friction between the wheels and track. The test runs added a gradual acceleration to the start of each run. The first test added 1 second (C.5), the second test added 2 seconds (C.7), and the third test added 0.5 seconds (C.6) of acceleration.

Methodologies for Performance Test 1

After completing both of the Advanced Research and Development tests, all of the groups were ready to apply what they learned to an actual graded run. This run was Performance Test 1 which was the base for all of the other tests. The goal was to start the AEV and have it run until it stops between two sensors. Some possible approaches were to only rely on coasting or to add power braking. Coasting would be more energy efficient, but less precise. The best option was to find a way to coast for a little and then power brake. After stopping in the sensors, the AEV had to pause for seven seconds and then depart from the gate. Code used for performance test one met those ideas of coasting and power braking (C.9) Once all of these tasks were completed, performance test was completed.

Methodologies for Performance Test 2

The next task was to complete the second performance test which was just an addition to the first one. In addition to all of the tasks of the last performance test, all groups had to now move out of the gate towards a caboose at the other end of the track. The AEV had to gently connect to the caboose and then pause for 5 seconds. Once the five seconds were up, the AEV had to move out of the dock with the caboose attached. This would complete the second performance test. Similar code with the added requirement was used for performance test 2 (C.10). The materials needed would only be the fully assembled AEV, the track, and the caboose.

Methodologies for Advance Research and Development Labs 3

aR&D 3 focused on the difference in energy used with different motor speeds. This was determined to be further tested because our current code did not use high motor speeds and led to high energy usage and slower performance times. The group wanted to be more energy efficient now that energy and time used was a factor for the final performance test. Therefore, many trials of performance test 2 were run with 4 different motor speeds in order to compare time used and energy used. The first motor speed used was 50% (C.12.1). Additionally, during aR&D 3, a simpler code was introduced as the complicated codes from the first two performance tests proved to be unnecessary and detrimental. Next, performance test two was run using 65% motor speed (C.12.2), 75% motor speed (C.12.3), and 90% motor speed (C.12.4). These runs each used the same outline of code with differing gotoAbsolutePosition values and motor speed values. The motor speed continually increased because the AEV's runs became more efficient as the motor speed increased. After running tests with performance test 2, the group began testing motor speeds for the final performance test. The ideal goal was to use the highest motor speed that provided the greatest accuracy and consistency. Therefore, 75% motor speed was used as it fit that criteria. Code was developed for the final performance test that used 75% motor speed for the whole run (C.13). This code entailed an initial position to travel to and coast for 1.875 seconds, then brake at 35% motor speed in between the two sensors before the first gate. Once the AEV stops in between the two sensors, it waits for seven seconds, then passes through the gate to a position that allows it to coast into the loading zone and connect to the caboose without recoil. Then, the AEV waits for five seconds and travels to a position that allows it to coast for 1.875 seconds, then brake at 50% motor speed to stop in between the two sensors. After the AEV stops in between the two sensors, it waits for seven seconds then travels to a position that allows it to coast for 6.25 seconds then brake at 50% power to safely land in the final zone. This code was developed to use large amounts of coasting to minimize energy used, while implementing braking to remain precise.

Methodologies for Final Performance Test

The final performance test was an add-on to the previous performance tests. After completing the required criteria for performance test 2, the AEV was to return to the gate with the caboose, wait seven seconds, and then return safely to the starting location. Code used for the final performance test was modified during testing day in order to account for battery voltage. The starting point for final performance test code (C.13) utilized 75% motor speed throughout. Additionally, it used different braking powers throughout the test. 35% braking power was used when the AEV was not attached to the caboose and 50% braking power was used when it was connected to the caboose. This increase in braking power was necessary to stop the AEV and caboose combination due to the increase in momentum from the mass of the caboose.

Results

Preliminary Research and Development Lab 1-5 Results

After running multiple tests on the straight tracks, group members realized that a large factor in the success of the AEV is propeller size. A test was run on the straight track with the initial testing code (C.1). This was concluded because the sample AEV would not move at 35% power and smaller propellers. However, once the smaller propellers were swapped for the larger ones, the AEV moved. The scoring and screening tables and the weighted criteria needed to maximize AEV success were now able to be formed from these results (B.3, B.4).

Table 2.0 - Scoring Table

		Reference (Sample AEV)		Keming Design		Jon Design		Zach Design		Nick Design	
Success Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Weight	25%	3	0.75	4	1	2	0.5	4	1	4	1
Propeller	25%	3	0.75	2	0.5	3	0.6	2	0.5	2	0.5
Aerodynamic	20%	3	0.6	3	0.6	2	0.5	4	0.8	3	0.6
Cost	20%	3	0.6	4	0.8	2	0.5	3	0.6	2	0.4
Aesthetic	10%	3	0.3	3	0.3	2	0.5	1	0.1	2	0.2
Total Score			3		3.2		2.6		3		2.7
Continue?					Yes		No		No		No

Table 3.0 - Screening Table

Success Criteria	Reference	Keming Design	Jon Design	Zach Design	Nick Design
Propeller	0	"-"	"+"	0	"-"
Weight	0	"+"	"-"	"+"	"+"
Aerodynamic	0	0	"0"	"+"	“+”
Cost	0	"-"	"-"	0	0
Aesthetic	0	"+"	0	"-"	“-“
Sum +’s	0	2	1	2	2
Sum 0’s	5	1	2	2	1
Sum -‘s	0	2	2	1	2
Net Score	0	0	-1	1	0
Continue?	Combine	Yes	No	Yes	No

Using the tables above, all of the designs were rated and the best design was chosen to move forward in the development process. It would’ve been much more difficult to determine the most promising design without them These tables were the goal of PR&D Lab 4 which was completed on 02/06. The design that was decided to be the most promising was the one with an aerodynamic design (B.5). Another reason this was chosen was because the design had a motor on each side of the AEV. Having propellers on each side of the design allows for a pulling motion which is a more effective than pushing. Two tests were also created in order to further confirm the ideas of power efficiency. The first was to test and confirm that the motor in the pulling configuration is more efficient. The second test was created in order to see if the aerodynamic shell was actually worth adding to our design.

Description of First Team AEV Design

The teams first AEV design focused on three main factors: aerodynamics, lightweight, and pulling. Each factor of the AEV design contributed to maximizing each of these three elements. First, the bottle shell was designed in order to provide an aerodynamic shape, while remaining lightweight. Next, one motor was placed on each side of the AEV in order to always use a pulling motion. Finally, the team’s custom support arm was created as one, lightweight piece that supported the bottle and allowed for a motor on either side of the arm. Additionally, the battery could be held in place on the face of the support arm. The model of the design is shown below.

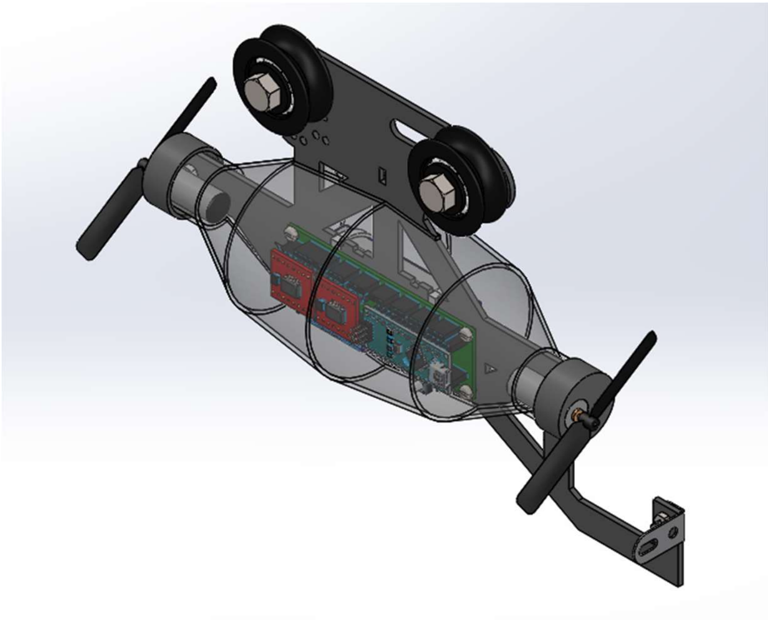


Figure 4.0 - Initial AEV design

Advanced Research and Development Lab 1 Results

Creating a combined graph of all three runs for each type of method proved that the runs were relatively consistent. The three graphs for the pushing tests (B.6), pulling tests (B.7), and hybrid tests (B.8) are shown below. First, the three pushing tests using the team's determined code (C.2) provided an average energy usage of 35.764 Joules. The range of these set of values is 6.227 Joules. Next, the three pulling tests using the team's determined code (C.3) provided an average energy usage of 24.679 Joules and a range of 0.537 Joules. Finally, the three hybrid tests using the team's determined code (C.4) provided an average energy usage of 53.373 Joules and a range of 3.747 Joules. These results clearly indicate that a pulling method is much more energy efficient, while using the most consistent amount of energy based on its significantly lower range value. Additionally, the pulling method was also the fastest of the three methods. Since two of the most important factors for the team's AEV design are energy efficiency and time, the pulling method proved to be the most successful method and will be carried out in future aR&D testing. A table highlighting the data from aR&D 1 is shown below.

Table 5.0 - aR&D Lab01 Result

Method of Movement	Energy Used (J)	Time (seconds)
Pushing	35.764	4.44
Pulling	24.679	3.20
Hybrid	53.373	8.30

Advanced Research and Development Lab 2 Results

The team determined it would be beneficial to determine a way to eliminate that spike of energy at the start of each run. Therefore, the acceleration tests were introduced. It was hypothesized that an initial acceleration achieved by celerate(), as opposed to only using the motorSpeed() function, would help eliminate the spike. A pulling method was used for all acceleration tests. Three different types of acceleration tests were compared to the initial pulling test data in order to determine if this was a viable method or if the team's initial code would suffice. The first acceleration tests used code (C.5) with three trials for consistency. This test was a one second acceleration from 0 motor speed to 50 motor speed. The combined graph of all three trials (B.9) proved consistency throughout the three tests. The average energy used for these tests was 25.285 Joules. The second type of acceleration test used the same code as the first type of acceleration test with the only difference in the time it took to accelerate (C.6). Instead of one second acceleration time period, this test was a one-half second acceleration time. Only one trial of this test was recorded (B.10) with an energy used of 27.307 Joules. This test was only analyzed once due to the clear fact that it is less efficient that the previous acceleration test and can be eliminated as an option. The final acceleration test used code (C.7) with a longer acceleration time period of two seconds. Again, only one trail of this method was recorded (B.11) with an energy used of 27.680 Joules. Similar to the second acceleration test, only one trial was analyzed because of it being less efficient than any of the first acceleration test results. Comparing the first acceleration test to the initial pulling test, the energy used is roughly 0.7 Joules less for the pulling test. Also, the time required to travel the same distance was roughly one-half of a second less for the pulling test. Additionally, the spike of energy was still present in all the acceleration tests as an elongated spike based on the time it took to accelerate. Therefore, it was concluded that adding acceleration to the team's code is unnecessary and makes the AEV less efficient. A table highlighting the data from aR&D 2 is shown below.

Table 6.0 - aR&D Lab02 Result

Acceleration time	Energy used (J)	Time (seconds)
1 second	25.285	4.21
0.5 seconds	27.307	4.50
2 seconds	27.680	5.40

Performance Test 1 Result and AEV Support Arm Changes

During Performance Test 1, the custom-made support arm of Team P's AEV model was changed from the former design (B.12.1) to the current design (B.12.2). The former design featured two extrusion on each end of the support for securing motors; with the tip of the 3in propeller having a 0.25in clearance in respect to the metal track. However, at the start of performance test 1, an unexpected extruding screw fixed to the side of the track interfered with the propellers. Team P therefore re-designed the support arm for the AEV model, and provided 1.00in clearance between the tip of the propeller and the metal track. The second AEV design assembly proved to outperform the first, because there was no interference between the propeller and the metal track. The second support arm design was carried forth into all future labs and tests. Furthermore, two SolidWorks assemblies of the two AEV designs were also included in the appendix (B.12.3, B.12.4). The capital cost of AEV with the former and higher support arm was $149,310 (including $770 grant), and the cost of AEV with current support arm was $149,288 (including $748 grant).

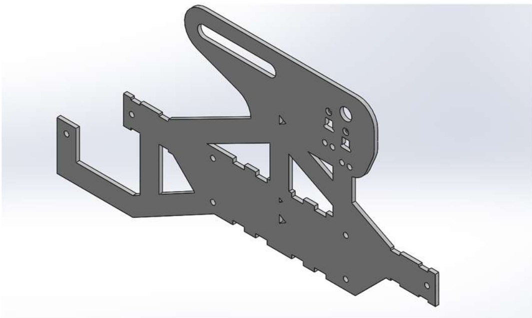


Figure 7.1 - Former Elevation

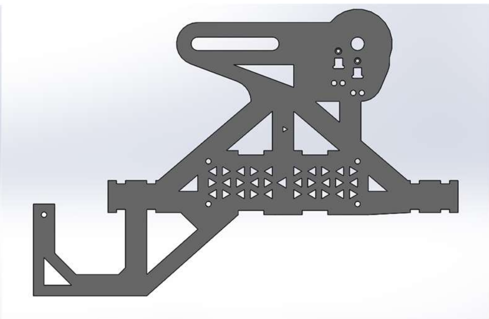


Figure 7.2 - Current Elevation

Description of Second Team AEV Design and Ruler Module

It was originally envisioned for Team P's AEV to have a aerodynamic outer shell made out of halved Fanta bottles and caps with sawed-off holes for motors. However, commercial Fanta bottles proved to be too tough to be reconfigured easily, even with coping saw and box cutters. On the other hand, though it was technically possible for the team to redesign and 3D-print a custom-made shell, the idea was ultimately scrapped due to time constraints. Therefore, by the end of Performance Test 2, it had been decided that the original AEV design shall be implemented without the Fanta bottle shell, as shown in Figure B.13 below:

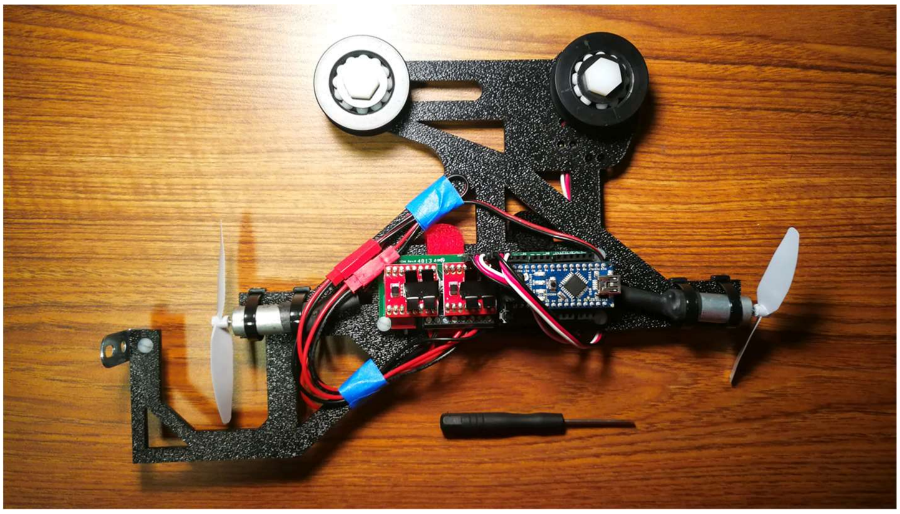


Figure 8.0 - Team P AEV Design Used in Performance Tests

This AEV model allowed easy access to the Arduino nano's uploading port, as well as the AEV start button; moreover, it saved more than 20g weight compared to the bottled design. By the end of Performance Test 2, an real-time AEV position display module (AEV Ruler) had been introduced to obtain more accurate AEV positioning data when it's moving along the test track. The Ruler module had been designed to be detachable and easy to operate. Its program was based off of the pre-existing reflectanceSensorTest() function, as shown in Appendix C.8. Team members would push the AEV module along the tracks with the modded reflectanceSensorTest() running, and take readings of the position of each check point. The attached AEV Ruler module is shown in Figure B.14 below:

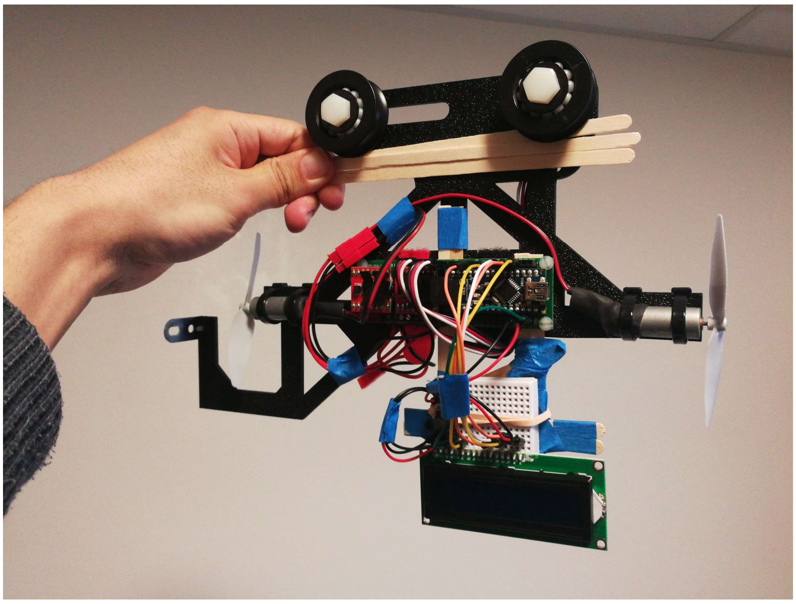


Figure 9.0 - AEV with Ruler Module (Real-time Mark Display)

Performance Test 2 Results

Performance test 2 was completed in approximately 22.5 seconds while using 170.967 Joules of energy. Again, the time and energy used were not ideal for optimal performance. However, they simply did not matter at this point. Also, the AEV did not wait five seconds after attaching to the caboose. This was due to an issue in the code that could not be detected. The observations made during the first two performance tests allowed the team to develop methods to minimize energy usage, while decreasing time taken to complete the run. These ideas were an increase in motor speed and a simplification of the code. The increase of motor speed was necessary because it allows the AEV to move much faster while also decreasing the time that the motor must be running. Also, the simplification of code was needed as the code used for performance test 2 was unnecessarily overcomplicated. This led to aR&D lab 3: simple code usage and motor speed testing. This was viewed as the best way to use less energy.

Advanced Research and Development Lab 3 Results

aR&D 3 began with using increasing motor speeds for performance test 2. Analyzing this data led to the knowledge that higher motor speed led to less energy used and less time taken to complete the run. This was possible at the cost of consistency. As the motor speeds grew higher, the accuracy and consistency decreased. This led to the decision on which motor speed offered the greatest results while also being the most consistent. The initial conclusion was that 75% motor speed provided this goal. Therefore, a code that used 75% motor speed was developed to complete the final performance test (C.13). The final performance test criteria was completed using this code and data was extracted to observe the time and energy used. This run used 109.747 Joules and was completed in approximately 40 seconds. However, upon observation of the AEV carrying the caboose past the gate and to the final destination, it was clear that braking was necessary to slow down the AEV due to the momentum while carrying the caboose. Therefore, braking was implemented at that portion of the run and the test was completed again. This run used approximately 5 more joules of energy but was necessary to improve accuracy. After completing the test at a constant 75% power, another observation was made. It was hypothesized that the AEV could use many different motor speeds depending on which portion of the run it was at. This is referring to the four different portions of the run: AEV to gate, AEV to caboose, AEV and caboose to gate, and AEV and caboose to final destination. It was thought that different motor speeds could be used since different portions of the run required more accuracy than others. For instance, the initial AEV to the gate requires much more accuracy than AEV to the caboose. Therefore, additional testing using different motor speeds will be implemented. A table highlighting the data from different motor speeds completing performance test 2 from aR&D 3 is shown below.

Table 10.0 - aR&D Lab03 Result

Motor speed	Energy used (J)	Time (seconds)
50%	49.521	15.80

65%	41.754	13.77
75%	38.718	13.15
90%	35.302	12.39

Final Performance Test Results

Three runs were performed for the final performance test, with the best two tests being scored. The three tests received an accuracy score of 32,38, and 38 respectively, with the third run producing the most efficient energy usage and time (B.15). The results analyzed from the final performance test only include the second and third run. The average time used for the last two runs was 51 seconds. Additionally, the average energy used in the last two runs was 120.9 joules. In comparison to the class average of 55 seconds and 224 joules, team P's AEV proved to perform relatively well. However, the only major downfall was the fact that the total cost was $534,014.04. In comparison to the allotted budget of $500,000, the team's total cost ended up being over-budget. A table of the total cost from the second and third runs is shown below.

Table 11.0 - Final Performance Test Result and Cost Analysis

	Best 2 of 3 Runs	**RUN 2**	**RUN 3**
Capital Costs	$ 148,540	$ 148,540	$ 148,540
Energy Costs	$ 185,450	$ 186,000	$ 184,900
Time Costs	$ 166,500	$ 168,000	$ 165,000
Accuracy Penalty	1.052631579	1.052631579	1.052631579
R&D Costs	$ -	$ -	$ -
Safety Violations	$ 15,000	$ 15,000	$ 15,000
TOTAL COST	**$ 534,014.04**	**$ 536,171.94**	**$ 531,856.15**

Discussion

Discussion of Preliminary Research and Development Lab 1-5 Results

The whole focus of the PR&D labs was to create and find improvements for the design of the AEV. Based on the results of testing the smaller propellers and the failure of the AEV to move, the larger propellers were the next test. It was hypothesized after research that larger propellers would provide more force which would potentially cause the AEV to move. This hypothesis was proven true through the testing which enabled the AEV to move. By PR&D lab 4, each group member was asked to create an individual AEV model sketch. Later, these were screened and scored (B.3, B.4). Based off the screening and scoring tables, a group model was made (B.5) that focused on three main factors: aerodynamics, lightweight, and pulling. After further research for the AEV, it was hypothesized that the teardrop shape of the shell for the group model would drop the drag of the vehicle. A test was made to test this theory, but it was found to have no effect on the efficient of the vehicle, therefore it was removed.

Discussion of Advanced Research and Development Lab 1 Results

The whole focus of the aR&D labs was to find ways to improve the energy efficient of the AEV. One of the topics of focus was to find the efficiency of the motor configurations. It was hypothesized after research that the pulling method was the most efficient method. After testing (B.6, B.7, B.8), it was found to be true and even better, it was the most consistent in terms of energy and also went the farthest distance, therefore pulling motors would be used. These test took longer than expected due to issues with compiling to the Arduino and the reflectance sensors which ultimately led to switching reflectance sensors.

Discussion of Advanced Research and Development Lab 2 Results

After the aR&D 1 tests, it was found on the energy vs. time graph that the energy initially spiked up before it decreased and then remained relatively consistent. It was hypothesized that an addition of an acceleration would cause the energy spike to be removed if acceleration was used. For aR&D 2, different lengths of acceleration were tested (B.9, B.10, B.11). The results showed that the one second acceleration was the most efficient time length for the acceleration, but when compared to the pulling tests, the energy efficient was better with a constant motor speed rather than the acceleration.

Discussion of Performance Test 1 Results

For the Performance Test 1, the group was asked to make the AEV go up an inclined ramp and stop for seven seconds in between two sensors and then move forward passed the stop. The group's original approach was to allow the AEV to coast to a stop to minimize the energy used, but after testing and an failed attempt, it was clear that the results were not consistent enough. In order to fix this ordeal, power braking was implemented. After further testing, this method proved to be efficient. The ineffectiveness of the coasting method was due to a lack of knowledge on the accurate measurements of each mark on the track, therefore guessing was used to estimate the length of the track. Another potential error was most likely due to slipping with the wheels on the AEV track, causing the coasting to be inconsistent. To eliminate these errors, consistent overshooting was used to make sure the AEV would get to the desired mark on the track in which the power braking could be used to enable the vehicle to come to a complete stop. The current model proved to be much better than the former model due to extra clearance of weight and the addition of the large propellers.

Discussion of Performance Test 2 Results

For the Performance Test 2, the group was now asked to make the AEV do the same thing as last time but at the end, make it connect to a caboose then take it and exit the loading zone. The group's approach was to connect a mark reader in order to have accurate measurements. The group used the information and created a code for the Performance Test 2. The group tested the code and expected accurate results, but instead received no stop at five seconds when connected to the caboose. The group's code had something wrong with the loop in the code so it was re-made and ready to be tested.

Discussion of Advanced Research and Development Lab 3 Results

In focus on the energy of the runs, the group hypothesized that higher motor speeds would provide a more energy efficient and time efficient run. As a result of this theory, different motor speeds were tested. Although the hypothesis was found to be true, the consistency of the run was not precise. This also may be due to the inconsistency of the charge in the batteries. It was noted that as the battery gets lower, the runs become noticeably inconsistent. The motor speed of 75% was found to be the best because it was in between the efficiency of time and power and consistency.

Discussion of Final Performance Test Results

In preparation for the Final Performance Test, the group had successfully created a code that ran the performance test. It was hypothesized by the group that this code would continue to work as it had before. Unlike the expected results, the code was significantly inconsistent. The inconsistency was directly related to the charge of the battery as the professor notified the class that the batteries were not completely charged. The group had ran the first run of the Final Performance Test fully knowing that the results would most likely not be successful. The group then adjusted the code to work around the non-fully charged batteries and was able to create relatively consistent runs.

Defense of Final AEV Model

Over the course of the PR&D labs, aR&D labs, and Performance Tests, changes in the AEV design were made. Originally, the group compared each individual model and decided on a model with a outer shell that was lightweight, which would be aerodynamic reducing drag, and applied a propeller on each side of the design. When tested, the AEV did not initially move, so large propellers were implemented and worked successfully. The shell proved to have little to no impact on the efficiency of the AEV, therefore it was ultimately removed as it only was etra weight. Then, a support arm was created through 3D printing and removed lots of necessary weight such as a base. This lightweight AEV with large propellers on each side proved very efficient with time and energy, but the consistency relied on the battery which was the only difficulty when preparing for the Final Performance Test.

Conclusion and Recommendations

Conclusion and Recommendations of Pre-R&D Lab 1-5

The main takeaways from the preliminary research and development led the way to the team’s current AEV design. It was concluded that larger propeller size was an important factor. Additionally, it was hypothesized that pulling was more efficient than pushing. This hypothesis led to further testing in advanced research and development. The main takeaways that impacted our current design came from the scoring and screening tables (B.3,B.4). These tables explicitly stated the group’s order of importance for different factors of the AEV. The three most important factors were weight, propeller, and aerodynamics. Since aerodynamics was concluded as an important factor, it would be further tested in advanced R&D. It is important to note that the next most important factor was concluded to be cost efficiency. In retrospect, this could have been the most important factor. A recommendation going forward would be to make cost minimization the most important factor when designing an AEV.

Conclusion and Recommendations of aR&D Lab 1-2

The two Advanced Research and Development labs were the most helpful for the refinement of the efficiency of the AEV. The first test was to see whether a pushing or pulling motor configuration would be more power efficient. After testing, it was obvious that the motors needed to be pulling to save the most power. The second test was to see if the initial power spike was able to be decreased. The cause of this spike was because the AEV had to overcome the static friction when at rest. The durations of accelerations tested were 0.5, 1, and 2 seconds. The results that were found were that adding acceleration added unnecessary time and was also less efficient. The conclusions from these two AR&D tests were used to create the most effective code for future Performance Tests.

Conclusion and Recommendations of aR&D Lab 3

The last Advanced Research and Development was continuing the focus of energy efficiency. The test was to see if different motor speeds would make the runs more energy efficient with time in consideration as well. Due to the inconsistency of the actual runs, 75% motor speed was found to be the best for time, energy, and accuracy of the run. The results from this performance test were implemented into the Final Performance test.

Conclusion and Recommendations of Performance Test 1-2

The Performance Test 1 and 2 had many takeaways. From the Performance Test 1, it was learned that power braking was an effective and efficient method of having consistent results. The original method was to coast to a stop, but after further testing and gathering research, it was found to be very inaccurate. The power braking gave consistent results needed for an accurate stop therefore it will be used in further tests. The Performance Test 2 had inaccurate results due to inaccurate readings from the mark reader. The code also didn’t have a loop working, but was re-made and ready to be tested. All takeaways were put in consideration for the Final Performance Test.

Conclusion and Recommendations of Final Performance Test

The Final Performance Test had a fair share of issues, but overall was successful. A proper code was created, but do to the inconsistency of the batteries, it was forced to be changed. Different powers and markings for coasting and braking were implemented. In the future, it would be preferable to have a fully charged battery to have consistent results.

AEV Project Final Conclusion and Recommendations

As the project finished up, the results were analyzed for the Smart City Columbus. It would be recommended to invest in the design for the large propellers on both sides as well as using high speeds and power braking for energy and time efficiency. During the testing, the battery's charge level resulted in inconsistent results, which was accounted for by additional testing and adjusting for the level of charge. In the future, it would be important to have fully charged battery for consistent results at will successfully run with the same code every time. Although the budget was over the limit, the design overall was very successful with energy efficiency and accuracy.

Appendices

Appendix A: Team Roles and Project Timeline

Table A.1 Team Information of Contact and Roles

Name and Email	Cell Phone	Team Role and Description
Jon Kim.7238	(614) 753-2464	Human Resource Manager: Facilitate and record meetings using memos
Keming He.1537	(614) 558-6658	Research and Development Manager: Lead AEV hardware and software design
Nick Cron.39	(513) 510-7359	Business Manager: Evaluate and manage AEV design and cost
Zach Milicia.3	(440) 742-1154	Marketing Manager: Update and manage team website

Table A.2 Team P aR&D Lab Schedule 1

Dates and Lab No.	AEV Objectives	Expected Result
02/20 Committee Meeting	• Assign team roles	• Nick - Business; • Zach - Marketing; • Keming - R&D; • Jon - HR;
02/27 aR&D Lab01 Pt.1	• Assemble test AEV model; • Fix AEV wiring; • Perform pull vs. push propeller test;	• Test AEV model fully fixed and assembled; • 3 sets of aR&D lab01 code verified, uploaded, and run correctly;
03/01 aR&D Lab01 Pt.2	• Complete pull vs. push propeller test; • Organize test data, generate Power vs. Time graphs for analysis;	• 3 test runs for each propelling method - push, pull, and hybrid, completed • Conclusion drawn for the most effective propelling

		method
03/05 aR&D Lab02 Pt.1	● Assemble test AEV model; ● Perform aerodynamic shell test;	● Test AEV model with detachable aerodynamic shell completed ● One set of aR&D lab02 code verified, uploaded and run correctly
03/06 aR&D Lab02 Pt.2	● Complete aerodynamic shell test; ● Organize test data, generate Power vs. Time graphs for analysis; ● Assemble Performance Test 1 AEV model;	● 3 test runs for with and without aerodynamic shell runs are completed; ● Conclusion drawn for whether the aerodynamic shell is cost-effective enough to be included as part of design ● Final Performance Test 01 AEV model designed
03/08 Performance Test 1	● Create algorithm and arduino code for Performance Test 1 based on results from aR&D lab 01 and 02; ● Perform test runs on tracks;	● Performance Test 01 AEV model completed and test code verified, uploaded, and running correctly ● Changes are made on the test code to enhance percision

Table A.3 Team P aR&D Lab Schedule 2

Dates and Lab No.	AEV Objectives	Expected Result
3/19 Lab12	● Create the proper code for the Performance Test 1 ● Prepare for R&D Oral Presentation ● Work on Critical Design Review (CDR) Draft	● Do and pass the Performance Test 1
3/20 Lab13	● Present R&D Oral Presentation ● Work on Critical Design Review (CDR) Draft ● Prepare for Performance Test 2	● Share group's findings with other groups
3/22 Lab14	● Prepare for Performance Test 2 ● Prepare for Committee Meeting 2 ● Work on Critical Design Review (CDR) Draft	● Create the proper code for the Performance Test 2

3/26 Lab15	• Perform the Performance Test 2	• Pass the Performance Test 2
3/27 Lab16	• Select and submit topics • Complete Committee Meeting 2	• Gain feedback from the meetings
3/29 Lab17	• Work on Progress Report 3 • Work on Final Oral Presentation Draft	• Have topics helpful to AEV design • Create systematic methodologies
4/2 Lab18	• Work on Progress Report 3 • Work on Final Oral Presentation Draft • Conduct new research to improve AEV	• Collect valid data and interpret the findings

Table A.4 Team P aR&D Lab Schedule 3

Dates and Lab No.	AEV Objectives	Expected Result
4/9/19 Lab 21	• Continue testing for Final Performance Test • Work on Critical Design Review and Final Website • Prepare for Final Oral Presentation	• Create a proper code with accurate markings and power with braking
4/10/19 Lab 22	• Continue testing for Final Performance Test • Work on Critical Design Review and Final Website • Prepare for Final Oral Presentation	• Complete Final Performance Test
4/12/19 Lab 23	• Dissemble AEV and make sure all pieces are inside the kit • Work on Critical Design Review and Final Website • Prepare for Final Oral Presentation	• Return the AEV kit
4/16/19 Lab 24	• Work on Critical Design Review and Final Website • Prepare for Final Presentation	• Present Final Oral Presentation
4/17/19 Lab 25	• Work on Critical Design Review and Final Website • Listen to other group's Final	• Complete Critical Design Review and Final Website

	Presentation	

Appendix B: Tables, Figures, and Graphs

Table B.1 AEV Project Cost Analysis

Total Budget ($)	=	(	Energy Costs ($)	+	Time Costs ($)	)	*	Accuracy Penalty	+	Capital Cost ($)	+	R & D costs ($)	+	Safety Violations ($)

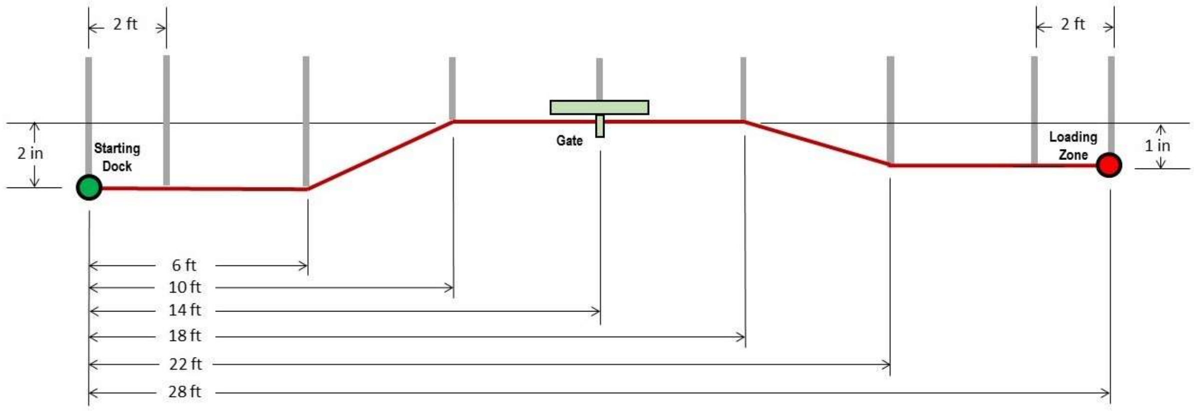


Figure B.2 Dimensions of the AEV Test Track

Table B.3 - Scoring Table

		Reference (Sample AEV)		Keming Design		Jon Design		Zach Design		Nick Design	
Success Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Weight	25%	3	0.75	4	1	2	0.5	4	1	4	1
Propeller	25%	3	0.75	2	0.5	3	0.6	2	0.5	2	0.5
Aerodynamic	20%	3	0.6	3	0.6	2	0.5	4	0.8	3	0.6
Cost	20%	3	0.6	4	0.8	2	0.5	3	0.6	2	0.4
Aesthetic	10%	3	0.3	3	0.3	2	0.5	1	0.1	2	0.2
Total Score			3		3.2		2.6		3		2.7

Continue?					Yes		No		No		No

Table B.4 - Screening Table

Success Criteria	Reference	Keming Design	Jon Design	Zach Design	Nick Design
Propeller	0	"-"	"+"	0	"-"
Weight	0	"+"	"-"	"+"	"+"
Aerodynamic	0	0	"0"	"+"	“+”
Cost	0	"-"	"-"	0	0
Aesthetic	0	"+"	0	"-"	“-“
Sum +’s	0	2	1	2	2
Sum 0’s	5	1	2	2	1
Sum -‘s	0	2	2	1	2
Net Score	0	0	-1	1	0
Continue?	Combine	Yes	No	Yes	No

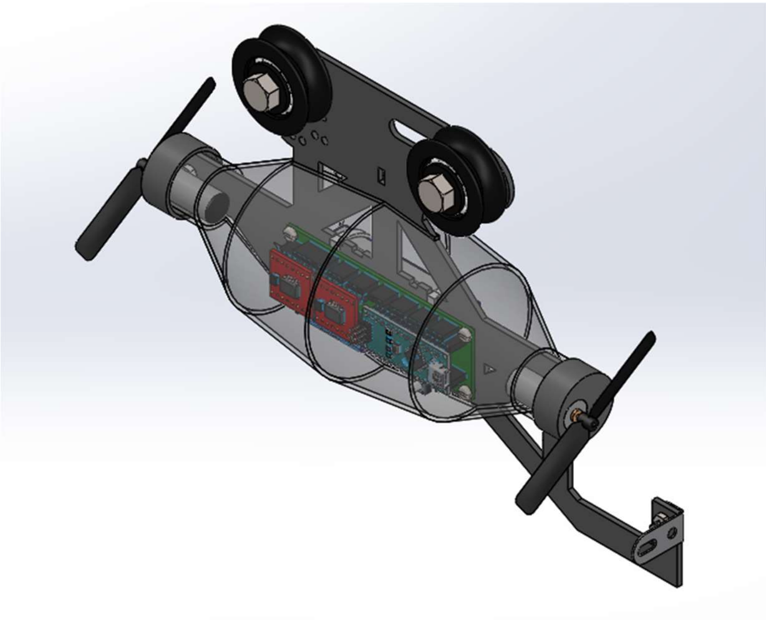


Figure B.5 - Initial AEV design

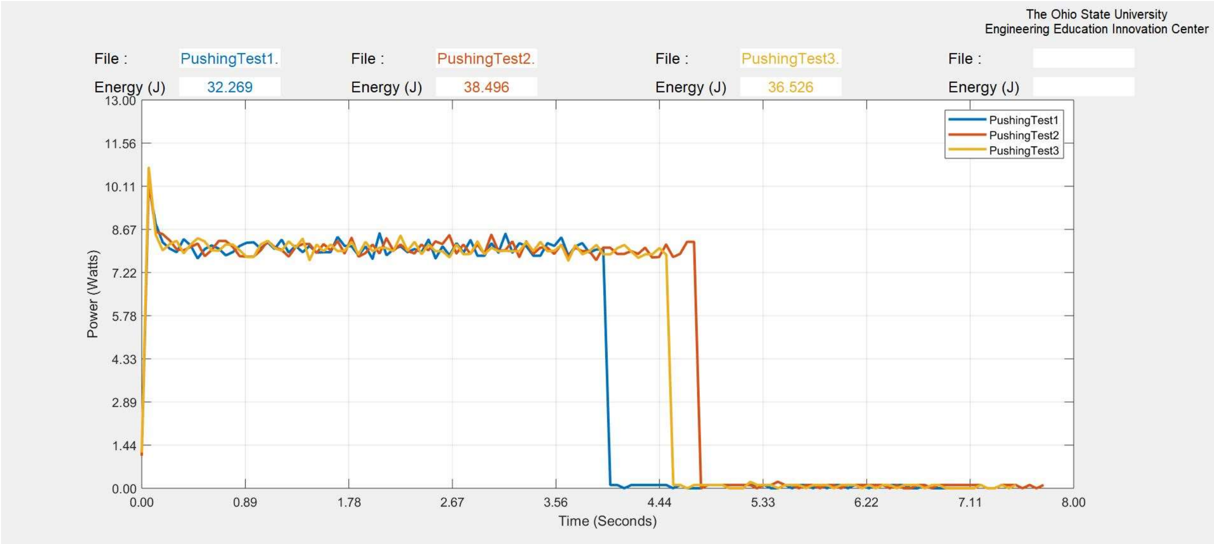


Figure B.6 - Pushing test combined graph

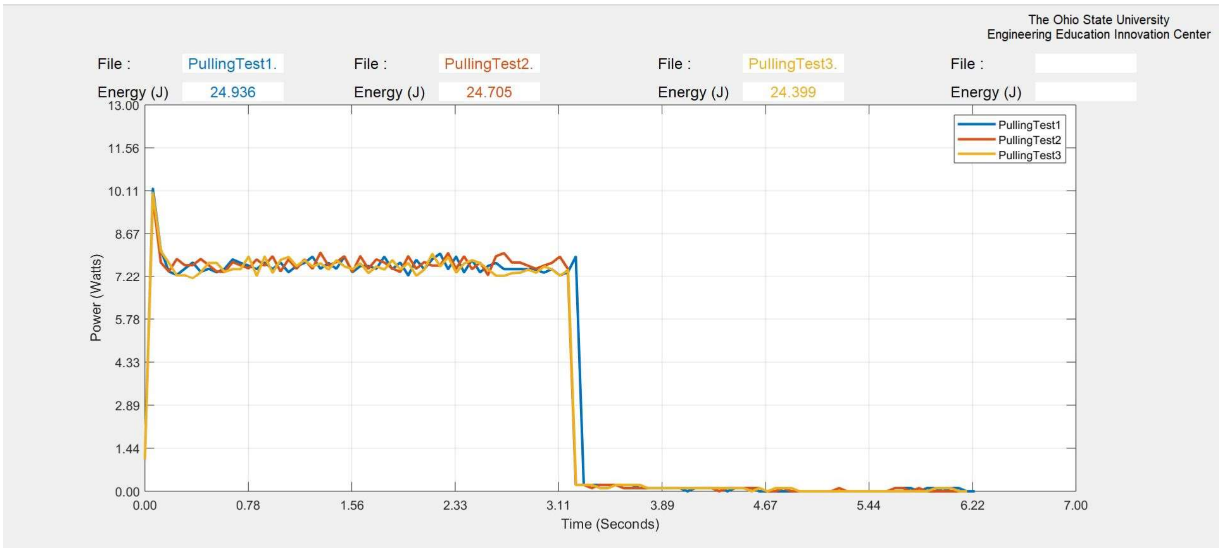


Figure B.7 - Pulling Test combined

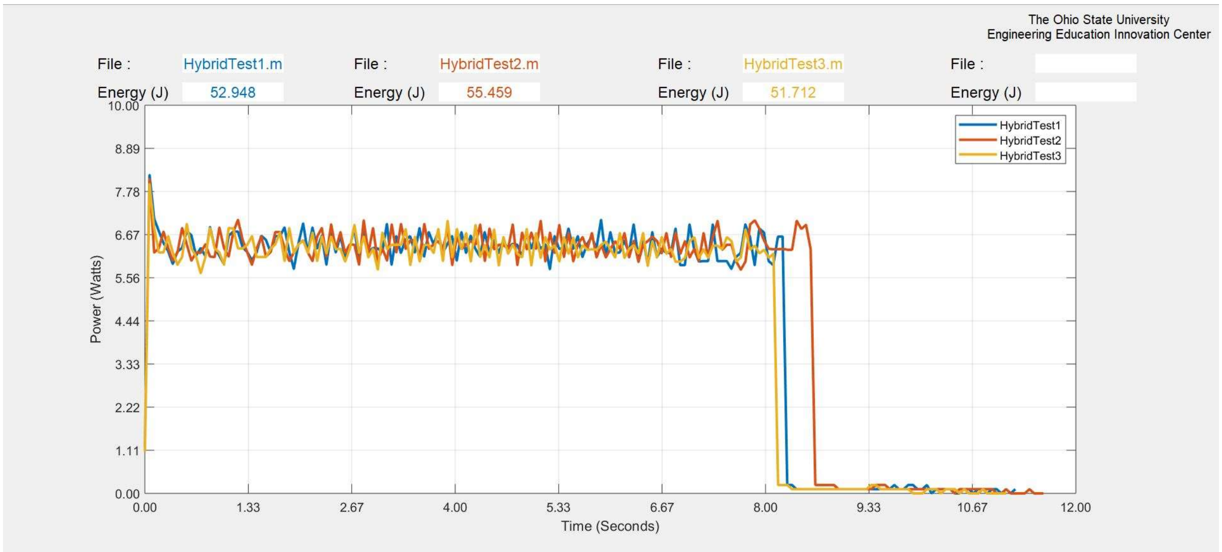


Figure B.8 - Hybrid combined

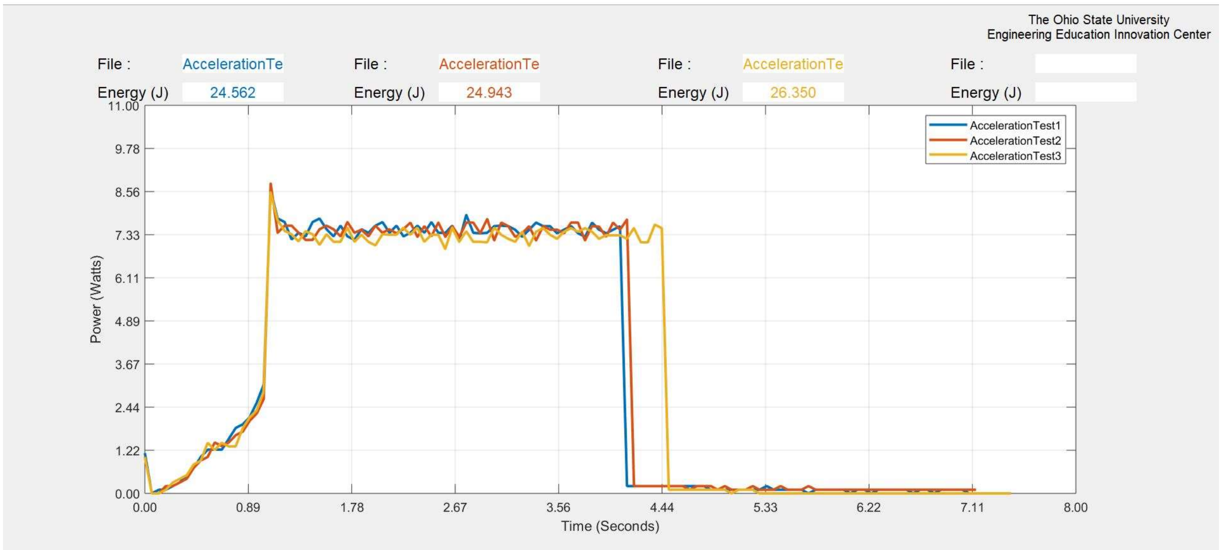


Figure B.9 - Acceleration graphs

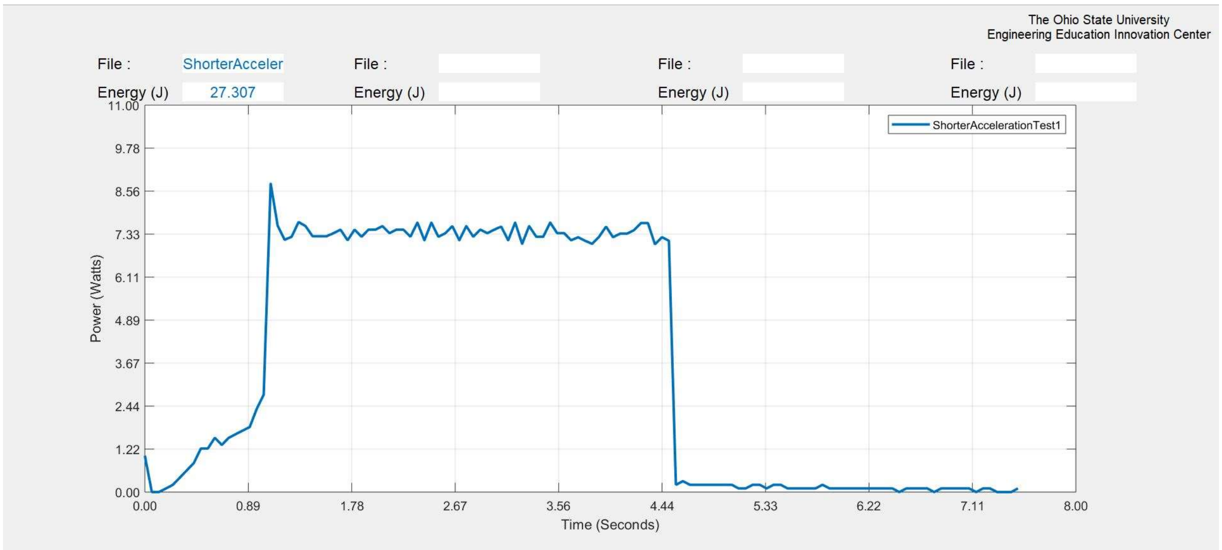


Figure B.10 - short acceleration graph

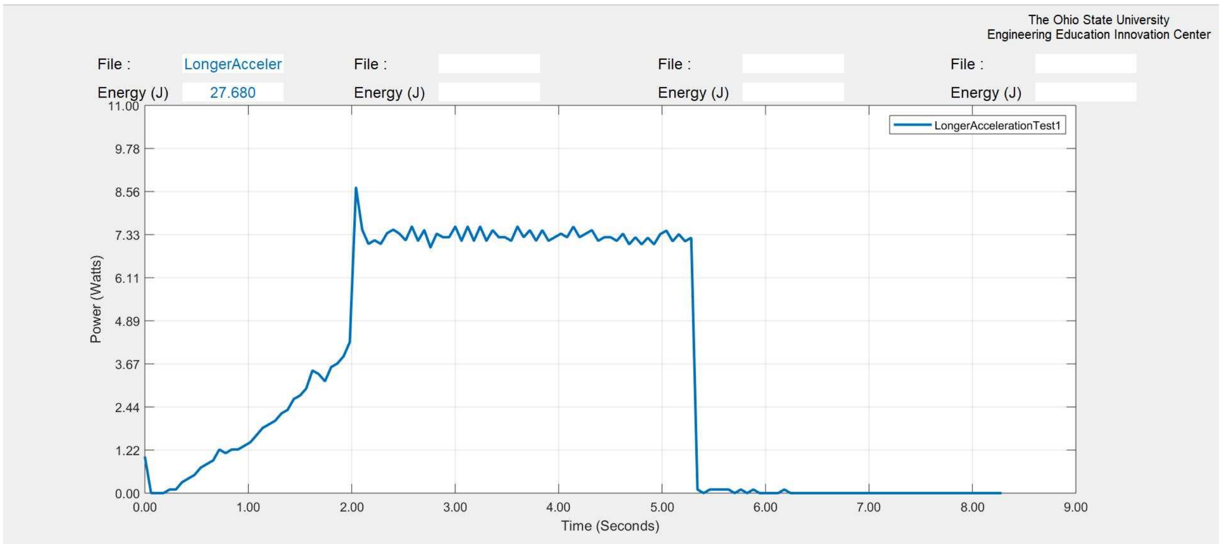


Figure B.11 - long acceleration graph

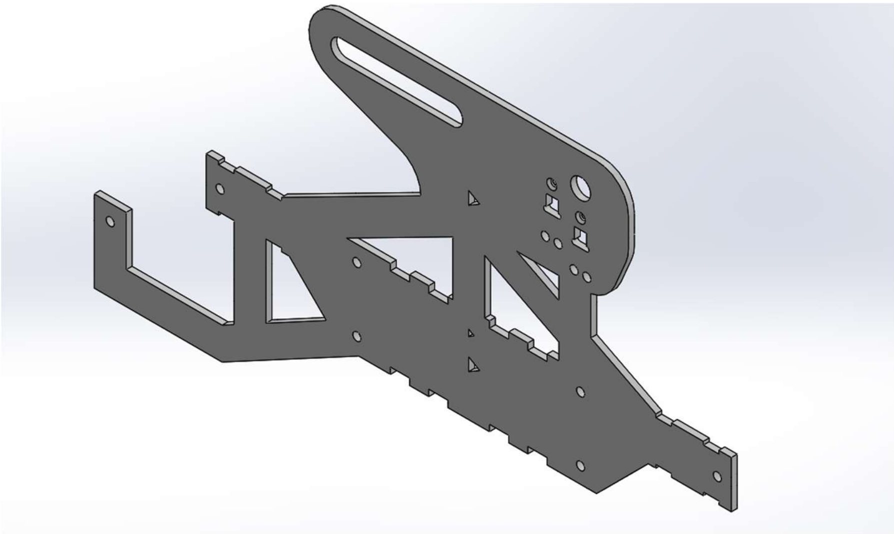


Figure B.12.1 - AEV Support Arm Former Elevation

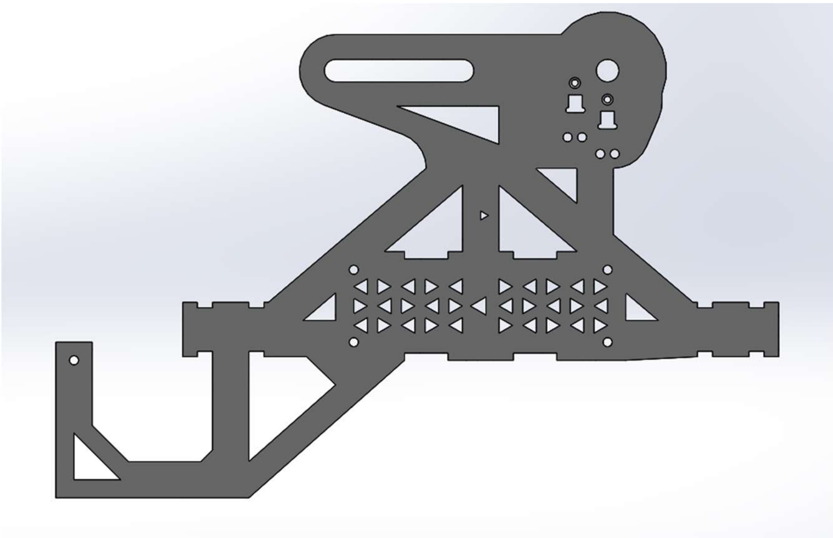
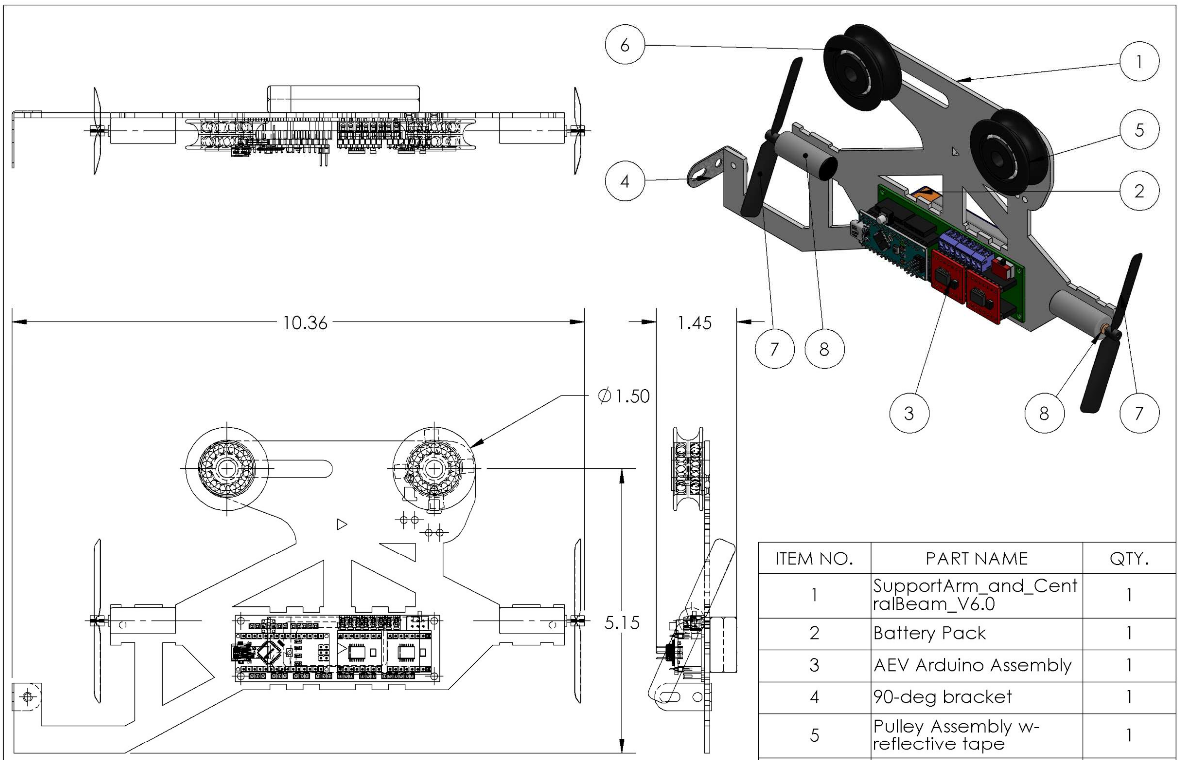


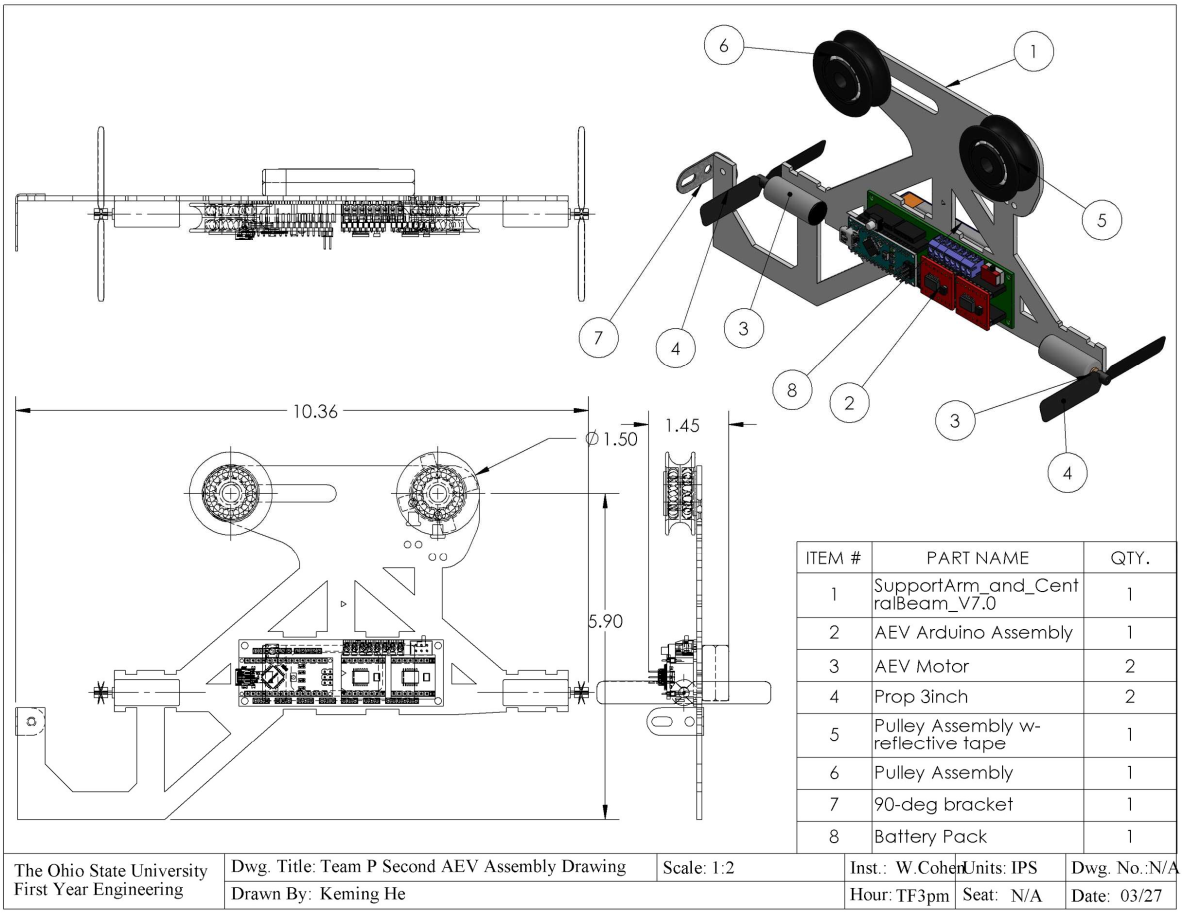
Figure B.12.2 - AEV Support Arm Current Elevation



ITEM NO.	PART NAME	QTY.
1	SupportArm_and_CentralBeam_V6.0	1
2	Battery Pack	1
3	AEV Arduino Assembly	1
4	90-deg bracket	1
5	Pulley Assembly w-reflective tape	1
6	Pulley Assembly	1
7	Prop 3inch	2
8	AEV Motor	2

The Ohio State University First Year Engineering	Dwg. Title: First Team P AEV Assembly Drawing	Scale: 1:2	Inst.: W.Cohen	Units: IPS	Dwg. No.:N/A
	Drawn By: Keming He		Hour: TF3pm	Seat: N/A	Date: 03/27

Figure B.12.3 - Team P First AEV Assembly: $149,310 (including $770 grant)



ITEM #	PART NAME	QTY.
1	SupportArm_and_CentralBeam_V7.0	1
2	AEV Arduino Assembly	1
3	AEV Motor	2
4	Prop 3inch	2
5	Pulley Assembly w-reflective tape	1
6	Pulley Assembly	1
7	90-deg bracket	1
8	Battery Pack	1

Figure B.12.4 - Team P Second AEV Assembly: $149,288 (including $748 grant)

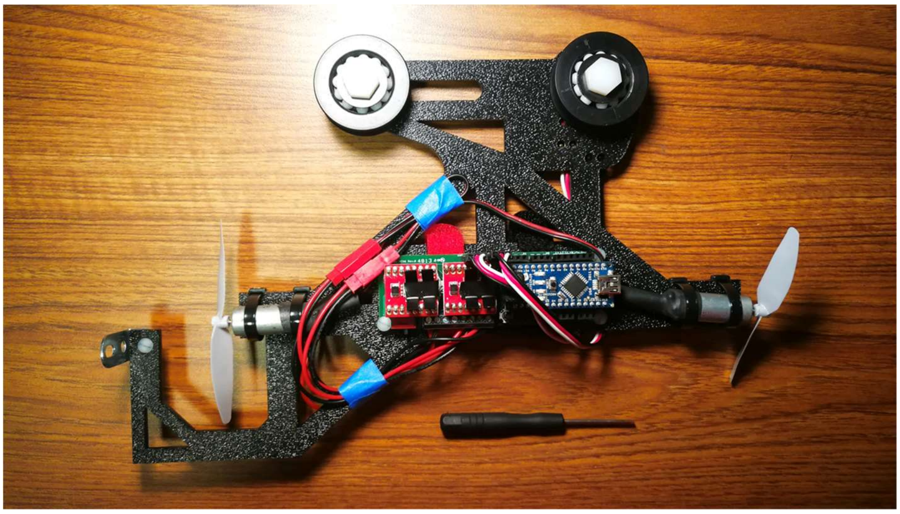


Figure B.13 - AEV Design Used in Performance Test 01 and 02

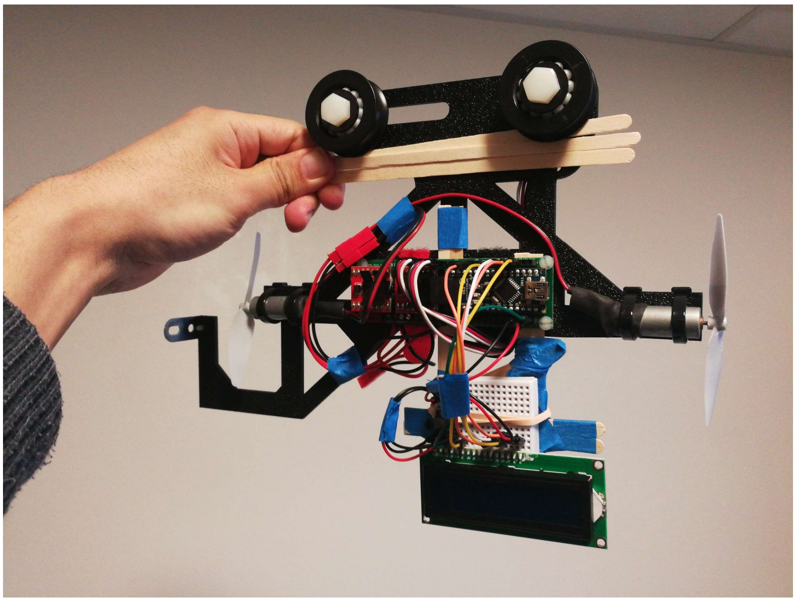


Figure B.14 - AEV with Ruler Module (Real-time LCD Display)

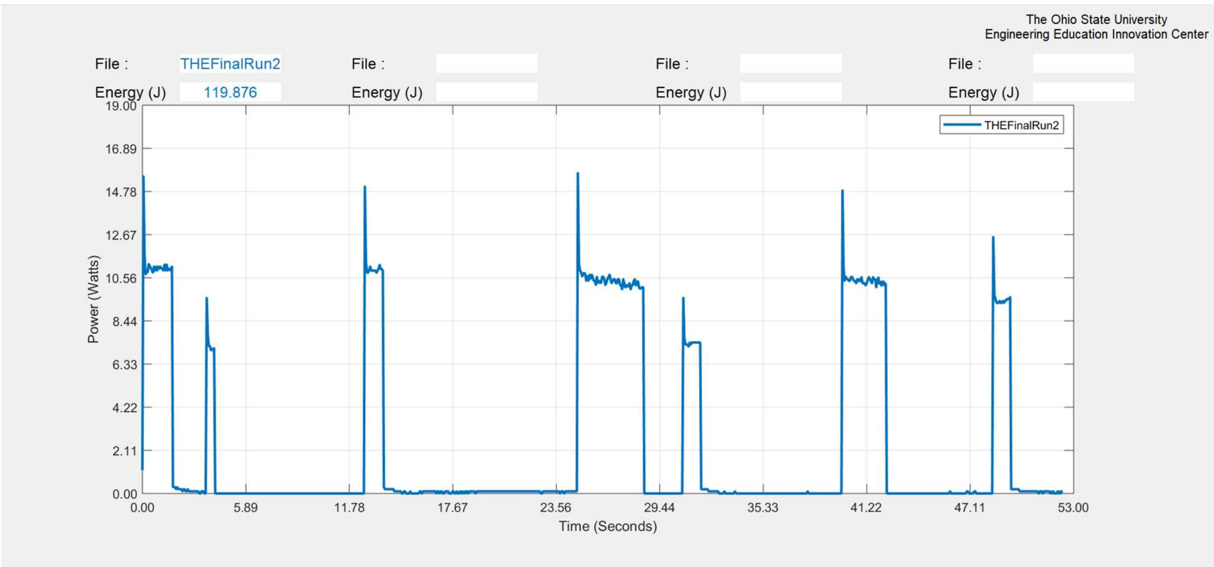


Figure B.15 Final Performance Test (Best 1 of 3)

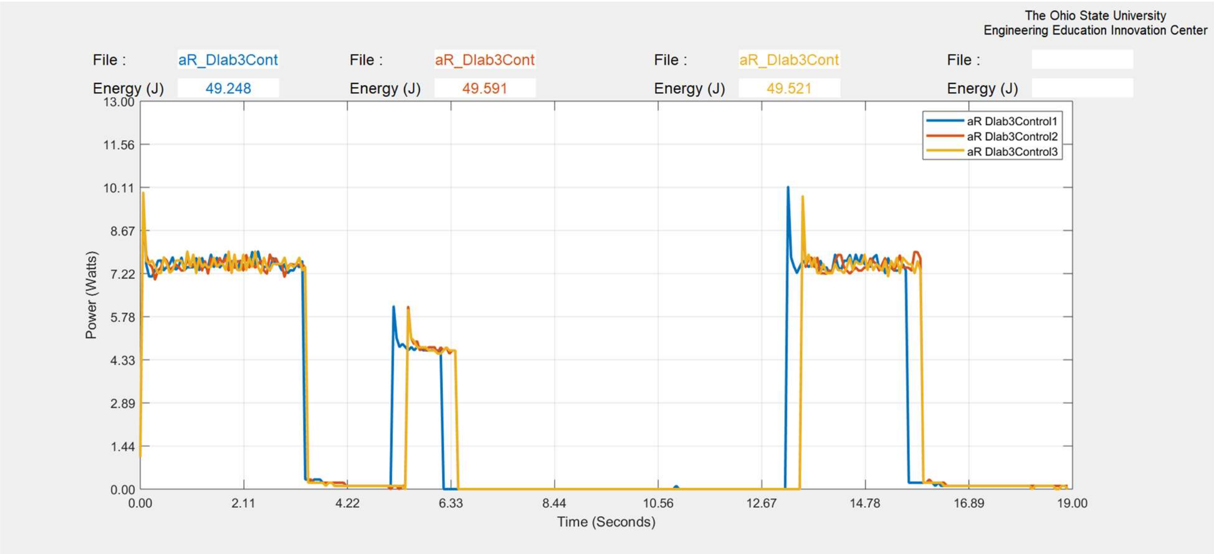


Figure B.16 Performance Test 2 Under 50% Forward Power and 35% braking Power

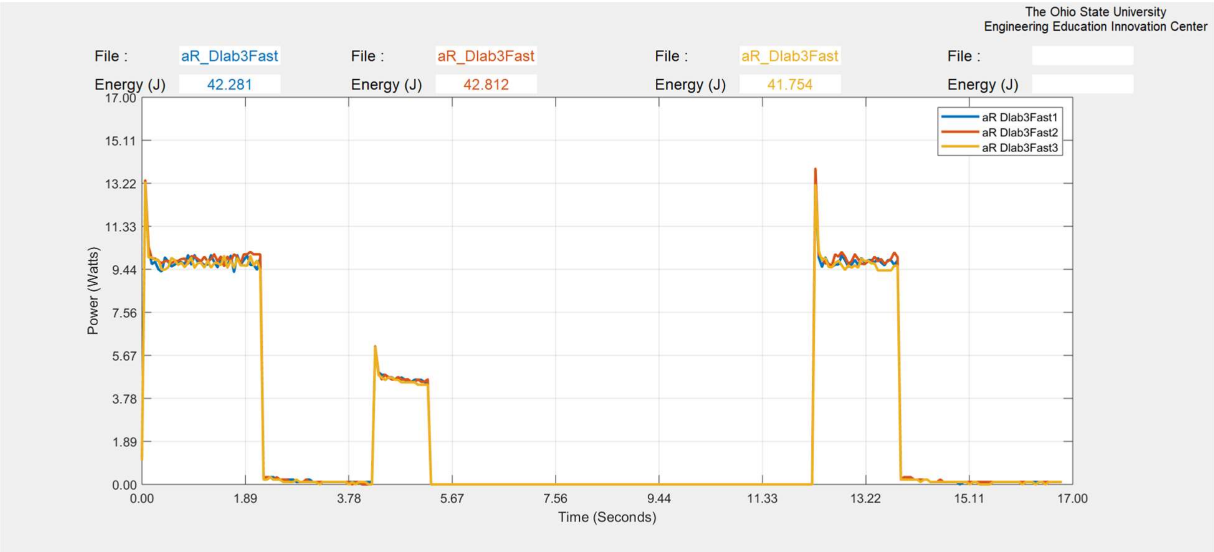


Figure B.17 Performance Test 2 Under 65% Forward Power and 35% braking Power

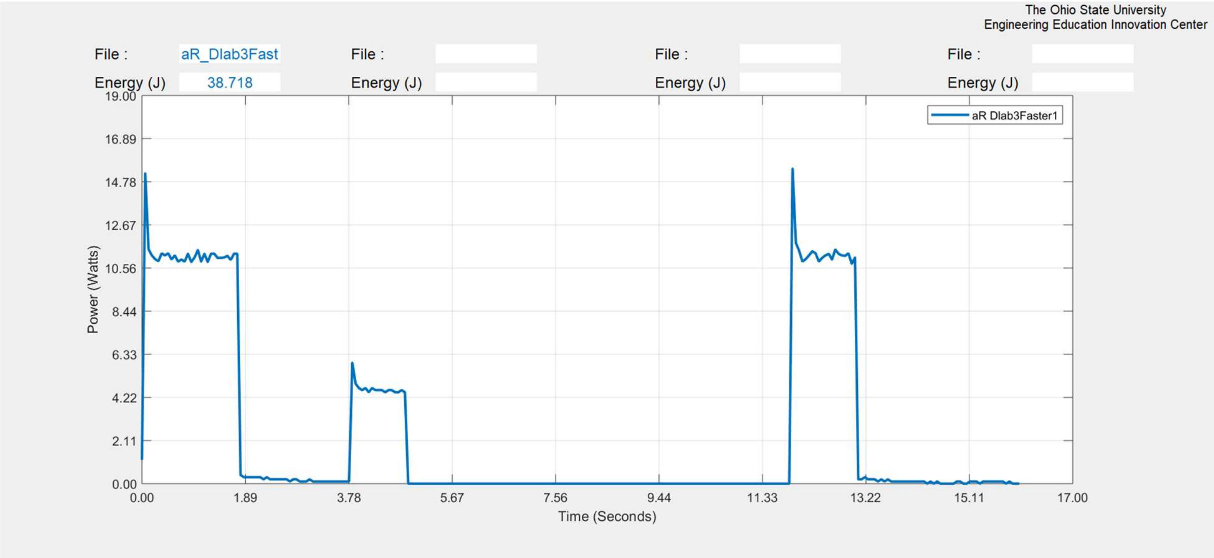


Figure B.18 Performance Test 2 Under 75% Forward Power and 35% braking Power

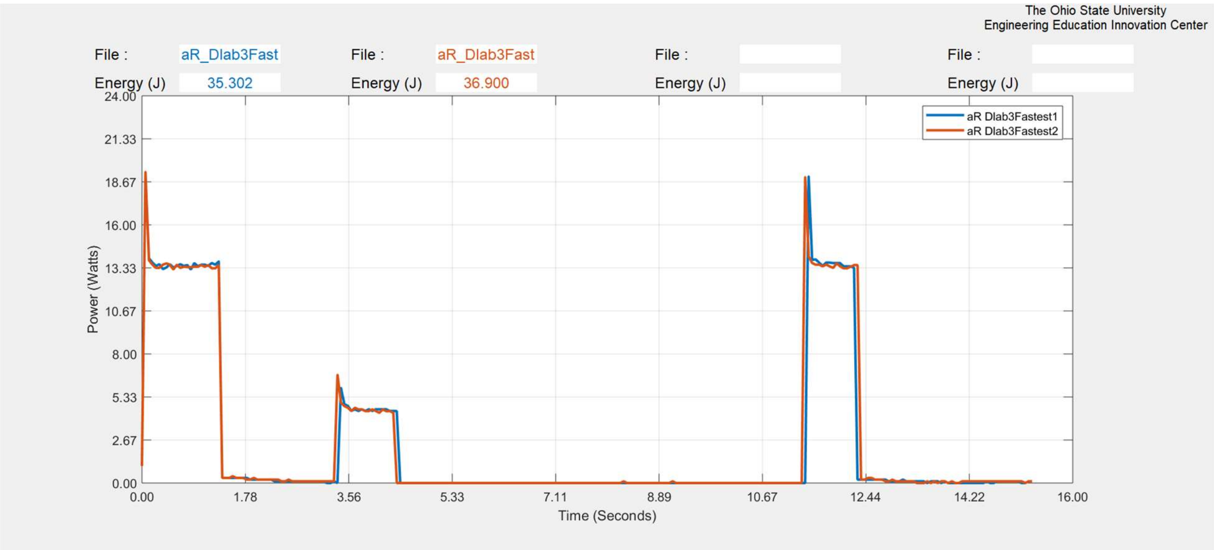


Figure B.19 Performance Test 2 Under 90% Forward Power and 35% braking Power

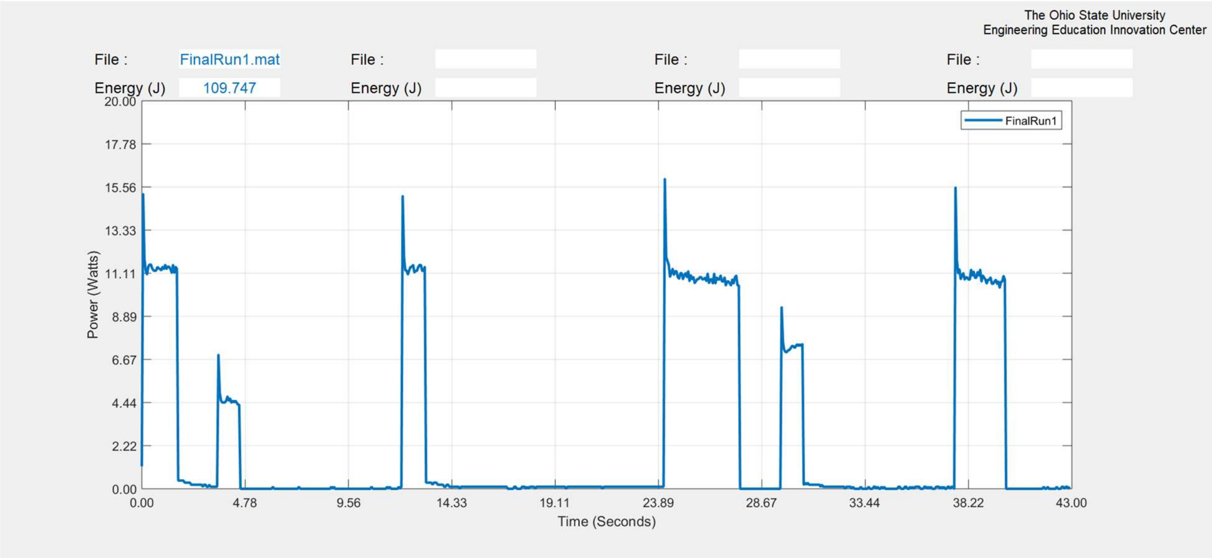


Figure B.20.1 Final Performance Test Under 75% Forward Power (Run #1 no final braking)

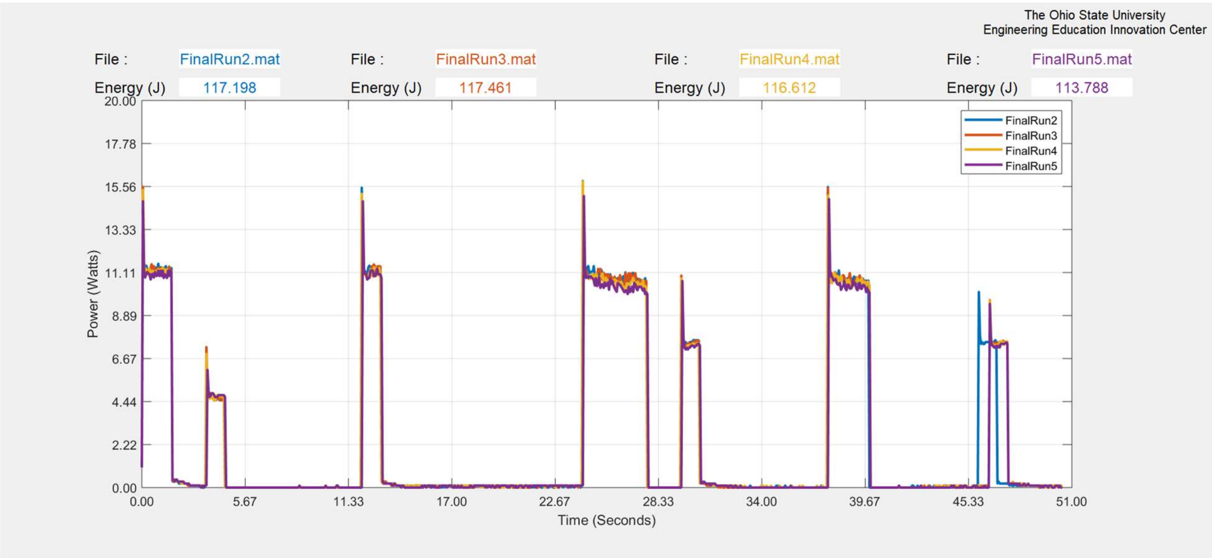


Figure B.20.2 Final Performance Test Under 75% Forward Power (Run #2-5 with final braking)

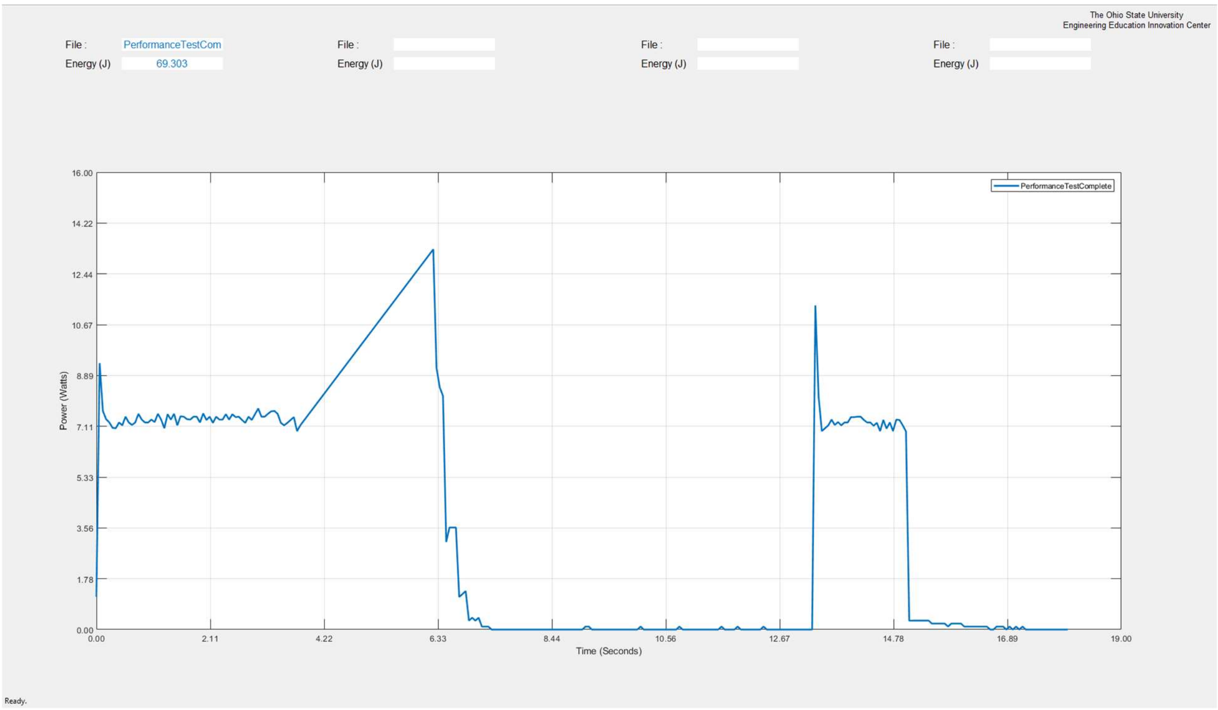


Figure B.21 Performance Test 1 - Graded

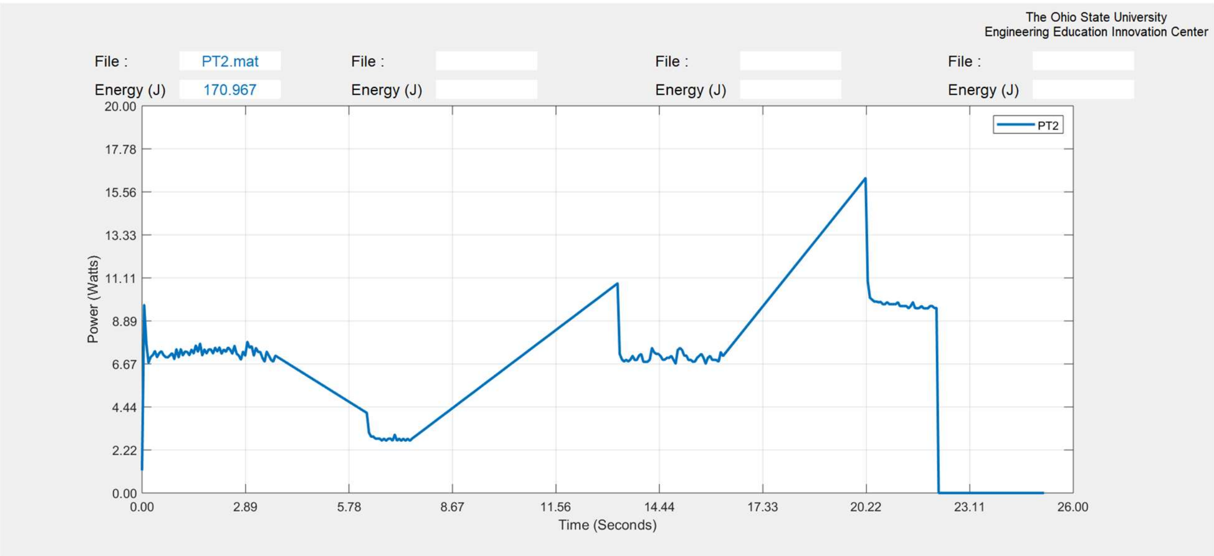


Figure B.22 Performance Test 2 - Graded

Appendix C: Arduino Code

C.1 - Initial pR&D 35% code

(Code removed for purpose of academic integrity.)

C.2 - aR&D Lab01 - Pushing code

(Code removed for purpose of academic integrity.)

C.3 - aR&D Lab01 - Pulling code

(Code removed for purpose of academic integrity.)

C.4 - aR&D Lab01 - Hybrid code

(Code removed for purpose of academic integrity.)

C.5 - aR&D Lab02 - 1s Acceleration code

(Code removed for purpose of academic integrity.)

C.6 - aR&D Lab02 - 0.5s ShortAcceleration code

(Code removed for purpose of academic integrity.)

C.7 - aR&D Lab02 - 2s Long acceleration code

(Code removed for purpose of academic integrity.)

C.8 - AEV Ruler Code

(Code removed for purpose of academic integrity.)

C.9 Performance Test 01 Code (used after Performance Test 1)

(Code removed for purpose of academic integrity.)

C.10 Performance Test 02 Code (used during Performance Test 2)

(Code removed for purpose of academic integrity.)

C.11 New Performance Tests Code (used before aR&D Lab03)

(Code removed for purpose of academic integrity.)

C.12.1 aR&D Lab03 Code (under consistent 50% power)

(Code removed for purpose of academic integrity.)

C.12.2 aR&D Lab03 Code (under consistent 65% power)

(Code removed for purpose of academic integrity.)

C.12.3 aR&D Lab03 Code (under consistent 75% power)

(Code removed for purpose of academic integrity.)

C.12.4 aR&D Lab03 Code (under consistent 90% power)

(Code removed for purpose of academic integrity.)

C.13 Final Performance Test Code (under consistent 75% power) (Un-Modified)

(Code removed for purpose of academic integrity.)

C.14 Final Performance Test Code (Modified for 4/10 testing)

(Code removed for purpose of academic integrity.)

Appendix D: Work Cited

- Mission Concept Review, https://osu.box.com/s/3mal1rsekfbvd5oflbhmbuahawq9oc8p, Accessed Mar. 27, 2019