Critical Design Review Report

Submitted to:
Inst. Richard Busick
GTA Rahel Beyene

Created by:
Team P
Timothy Kalmar
Seth Moore
Aaron Wood
Peida Han

Engineering 1182
The Ohio State University
Columbus, OH
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Executive summary:

Team P of Koffolt Properties is dedicated to the design and development of an AEV, or Alternative Energy Vehicle, to act as a tran-esque form of public transportation in the city of Columbus, Ohio. A greener form of public transportation is a must for the city of Columbus in order to minimize emissions and give commuters more cost efficient transportation options. As the public becomes more and more travel oriented, designing a means of transportation which will minimize natural resource consumption and optimize speed and safety should be a priority for this generation and many generations to come. Today's vehicles focus on compact, sleek design which decrease weight allowing for increased speeds and decreased energy consumption. Team P believes they have replicated this trend with the following AEV. Equipment used during the research and analysis process are commonly used in engineering and should be used as good practice for all engineers.

This report is designed to showcase the process of researching and refining the design for the AEV in order to optimize its consistency, energy and timed efficiency, and general performance. Our design highlights each of these areas to the best of our abilities. This process is showcased below, and how the team decided on the final design is described. From design, research, and analyzation, it was found a two motor design which is a pull for the first leg of the run, with the eight cm propeller, and a servo to act as a braking mechanism served to be the most optimal set-up.

With a compact, lightweight design, Team P produced an AEV with a weight of .1665 kg and consuming 187J per run. The vehicle completed all tasks listed in the Mission Concept Review with minimal accuracy penalties for a successful final product.

It was discovered that the servo motor used much less energy than the reverse command. Therefore, the servo motor was incorporated into the final design not only for its minimal energy usage but also its braking efficiency. It was found that running the engines for the entire journey was not necessary due to basic properties of physics that an object in motion will stay in motion. Therefore, coasting down declines and as the AEV approached the gate or docks was utilized in the final design to save energy.

In creating an Advanced Energy Vehicle with maximum efficiency and consistency, it is encouraged to minimize weight and optimize balance. The lighter and more balanced the AEV is, the more consistent each run on the track will be and the less energy will be consumed. It is also highly recommended that the ServoMotor be utilized as a brake because it enables the AEV to stop quicker and more precisely. The code should ulize mark commands as they are more consistent and accurate when compared to timing methods.

Table of Contents

Introduction:

The objective of the Advanced Energy Vehicle project focused on the creation and evaluation of an efficient battery powered vehicle prototype that could consistently retrieve the caboose and return to the starting point. Designing and assembling the parts as well as maintaining consistency were primarily closely focused on. The laboratory process of all of this was kept well-recorded on a consistent, weekly basis. Team-oriented exercises with various testing in the Arduino coding program and the tools provided in the AEV kit created an atmosphere of learning, familiarity, and effectively teaching the group how to improve the design.

This report will highlight the design process, experimental methodology, and analysis of the overall AEV performance over multiple tests.

Experimental Methodology:

The goal for this project is Initially, have basic understanding of components from the AEV and coding software Arduino. Furthermore, by evaluating the sample AEV given by this project, group started brainstorm every possible creative design with the advantage behind from the design. While designing the AEV and software codes for the performance tests, group P collect quite amount data to improve the efficiency and stability of AEV. The AEV prototype was evaluated through a series of three different performance tests.

The purpose of performance test 1 was to develop two different protocols for the AEV to pass the sensor gate checkpoint located halfway through the track provided. To do this, the AEV must first reach the IR sensors and brake without touching the gate and wait 7 seconds for the gate to open. Only after the gate has moved can the AEV activate its motors and move past the checkpoint, completing the performance test.

Group P accomplished performance Test 1 successfully. Two major issues were decided with several minor adjustments within group. First, for Performance Test 1, the goToAbsolutePosition() function was treated as an independent variable that was adjusted and compared with other runs to find an ideal mark for the AEV to reach the gate checkpoint. Taking into account the inclined rail factor, the group approximated the distance and had several test trials to find the optimal function value 206 marks to the gate. Second, for the braking system itself, the group implemented the reverse motors command at high power to stop the AEV immediately. The braking system was very stable and reliable even though it consumed a large amount of energy. The energy consumption for reverse function braking is shown below in figure 3. From the data, even though group implemented reverse braking system, group also took servo braking system in consideration. Because servo might be a alternative way to cut off many unnecessary energy waste instead of using reverse function in Arduino. For some minor adjustment, group set up relatively high power supply in order to increase the efficiency and save time.

Stepping in to Performance test 2, Group P implemented a more energy efficient braking system in order to complete the second test; a friction based servo. The servo provided more efficient braking than using a reverse motors function compared with the reverse braking seeing above in figure 3 and figure 5. The group fitted the servo with rubber bands and brackets to ensure the arms contact with the wheel wouldn't move the servo body. Furthermore, the group used a rubber band to make the servo arm better at breaking by increasing the coefficient of friction between the arm and wheel. In order to find the proper function to take the AEV from the gate to the loading dock, many test trials were ran with an educated guess and check system. The group ultimately decided on a distance of 484 marks after the gate, following a command to cut off the power supply, and after coasting down the decline, the servo was used to stop the AEV at 546 marks. This long slow down was done in order to ensure that the AEV wouldn't contact the cargo too hard. The initial trials were not optimistic as Group P tried to find an exact distance for several test trials under which the AEV was functioning inconsistently. However, the last trial was successful and caused the group to pass the performance test 2.

For the Final Performance test, the ultimate goal was to run AEV through the gate to loading dock and sent AEV back to the initial position. With the success of performance test 1 and performance test 2, the Arduino codes kept the same. The only challenge was to estimate the distance from the loading dock back to the gate, which was performed via a limit approximation of repeated overestimating and underestimating the correct distance, with each iteration decreasing the differential value between the marks.

Results:

The first task which faced Team P was constructing and designing an AEV which optimized each of the criteria for a successful product. In Figure 1 below, Team P used screening and scoring matrices to decide on the general body for each AEV design. Although Tim's design had a better net score, Han's design was chosen to be combined with Aaron's with the ideal of creating a lighter prototype.

Concept Screening Matrix					
Criteria	Prototype	Han's	Tim's	Seth's	Aaron's
Stability	0	0	-	0	0
Aerodynamics	0	+	+	0	+
Weight	0	+	+	+	-
Durability	0	-	+	0	+
Safety	0	+	0	-	+
Sum +	0	3	3	1	3
Sum -	0	1	1	1	1
Sum 0	5	1	1	3	1
Net Score	0	2	2	0	2
Continue?	N/A	Combine	Revise	No	Combine

Concept Scoring Matrix											
		Prototype		Han's		Tim's		Seth's		Aaron's	
Criteria	Weight	Rate	Score	Rate	Score	Rate	Score	Rate	Score	Rate	Score
Stability	0.25	2	0.5	2	0.5	2	0.5	2	0.5	3	0.75
Aerodynamics	0.1	2	0.2	4	0.4	5	0.5	1	0.1	5	0.5
Weight	0.25	2	0.5	4	1	3	0.75	4	1	1	0.25
Durability	0.2	3	0.6	1	0.2	3	0.6	1	0.2	5	1
Safety	0.2	3	0.6	3	0.6	3	0.6	2	0.4	4	0.8
Total Score			2.4		2.7		2.95		2.2		3.3
Continue?		No		Develop		No*		No		Develop	

Figure 1: Concept Screening and Scoring Matrices

After conducting this screening and scoring analysis, Group P created two different AEV designs with different braking mechanisms. For the first one in Appendix B-Solidworks, AEV Model A: Reverse Function Braking, group P designed a braking system with reverse function written in Arduino Nano. The way to use reverse is to set up 60% power for 1.1 second in reverse direction to force the AEV vehicle stop at the gate.

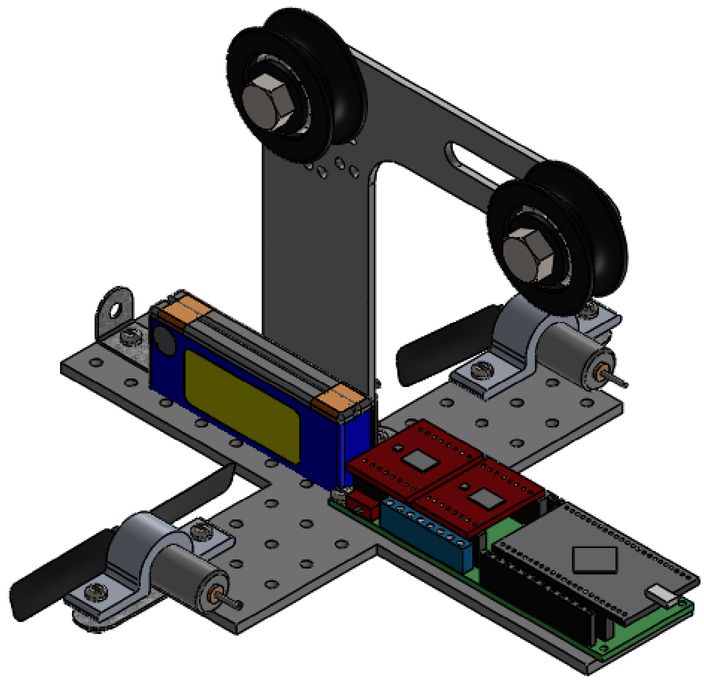


Figure 2: AEV Model A

This design was found to consume large amounts of energy during this reverse-function braking design as evident in the large spike found on the energy-time graph in Figure 3 as the brake was engaged.

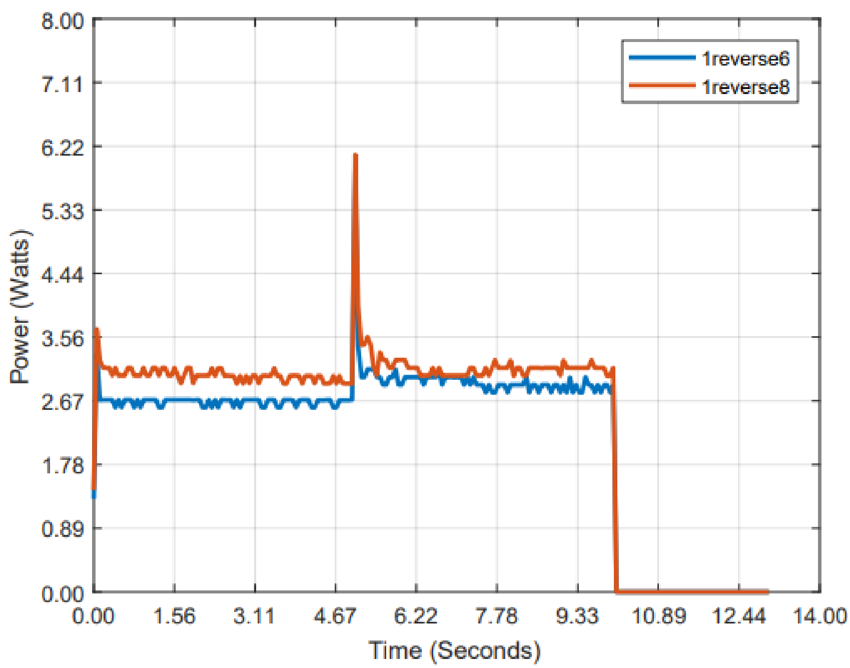


Figure 3: Energy Consumption for Reverse Function Braking

For the second design in Appendix B-Solidworks, AEV Model B: Servo Braking, Group P intended to set up a servo attached on the arm in order to rotate the servo and theoretically stop the wheel immediately. This was done to prove the servo was far more energy efficient for braking, and to maximize this effect tape was put around the servo in order to increase the friction on the brake arm.

However, a problem arose as the servo did not stop the wheel immediately by resisting the wheel, due to the inertia of AEV and the limited friction between the duct tape brake arm and the wheel. Therefore, Group P found a way to offset this problem by shortening the original distance used in the first AEV design by 5 marks. Therefore, the AEV design could slide to the exact location in front of the gate after servo resists the front wheel.

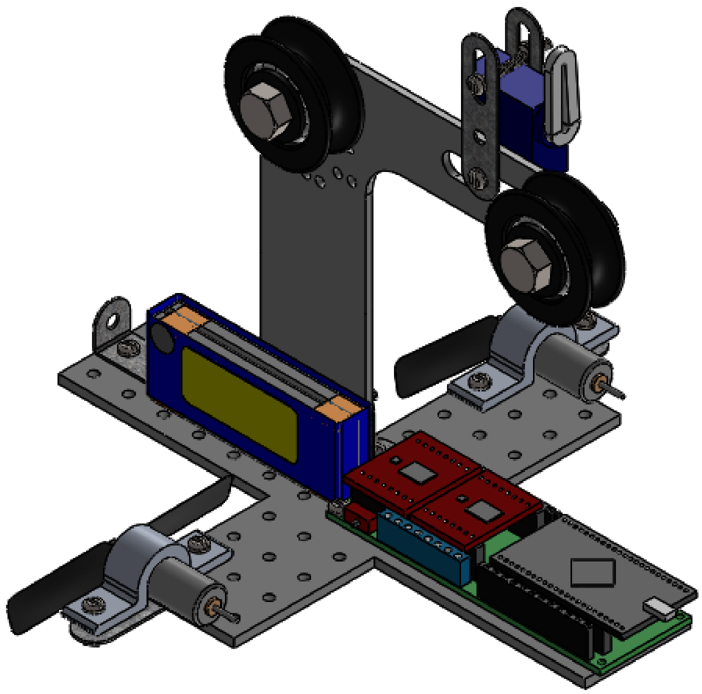


Figure 4: AEV Model B

This second AEV design decreases the energy consumption significantly because it does not use nearly as much power to stop the AEV since braking with the servo takes almost a 7th of the energy as reversing to stop does (see Figure 5). As Group P expected, the second trial, or the servo trial, proved a more efficient and reliable braking system than the first AEV design, the reversed motor brakes trial and therefore resulted in it’s continuation for the rest of the project.

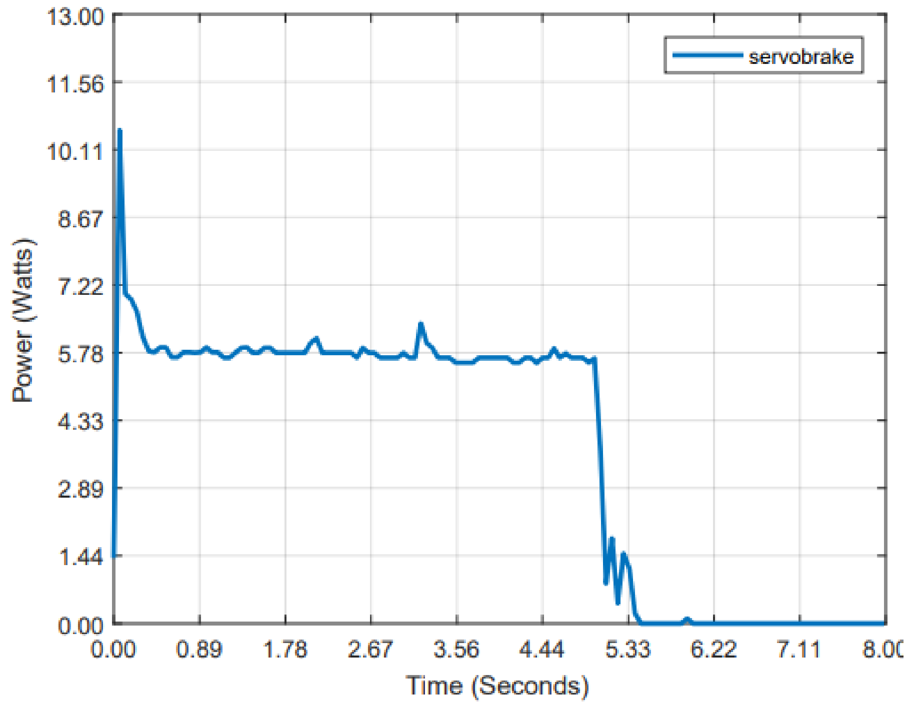


Figure 5: Energy Consumption for Servo Braking

After determining the optimal AEV design and braking mechanism, Team P further researched variables of energy optimization via propellor size and quantity. Variables to test were using either 1 motor or 2, and either a 6cm or 8cm propellor. Both Figures 6 and 7 argue that the six inch propellers are barely functional compared to the eight inch, and in the one motor setup the six inch propeller couldn't even move the AEV.

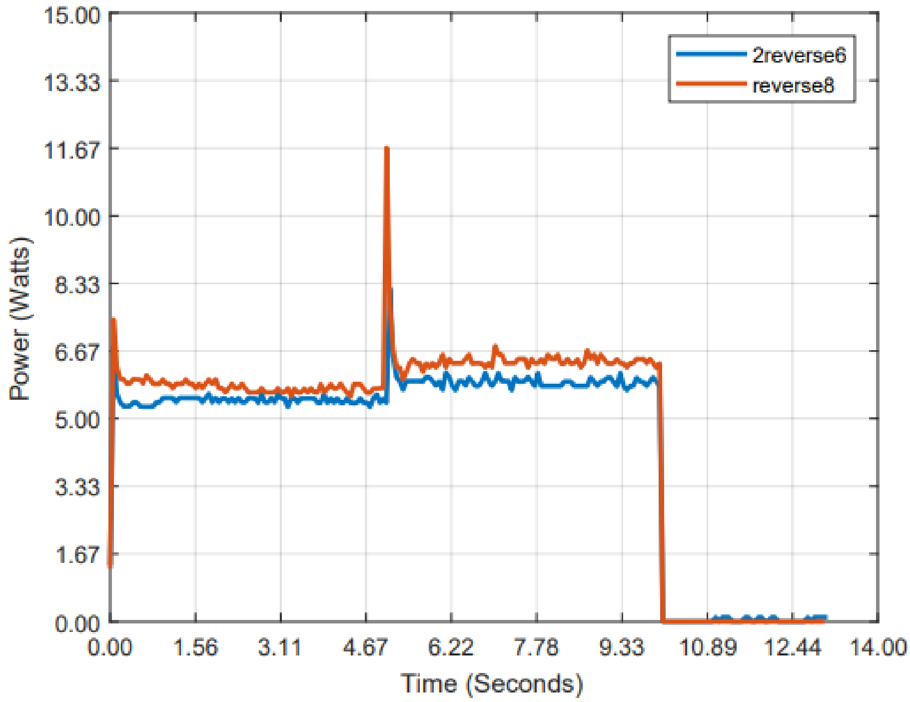


Figure 6: Time vs Power for 6cm vs 8cm Propellor

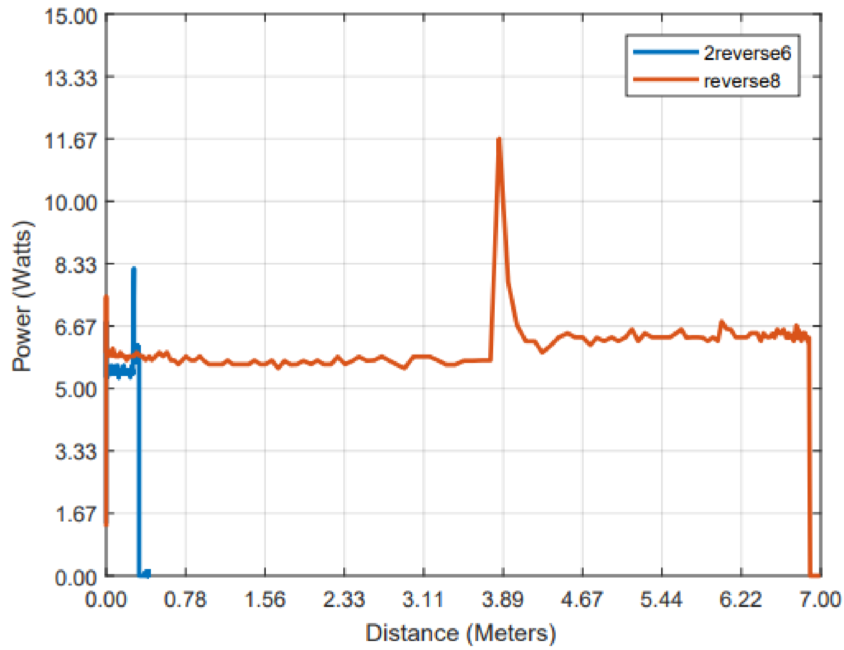


Figure 7: Distance vs Power for 6cm vs 8cm Propellor

For motor quantity, the one motor only setup moved the AEV less than a fourth the distance that two motors did, for only half the power consumption. The one motor running on an eight inch prop went under a fourth of the distance two motor setup traveled, and consumed about half the power. So for a similar energy consumption, the two motors should theoretically still go twice the distance one motor can. So if budgeted properly, the two motor setup is more efficient. The graphs below (Figures 8 and 9) demonstrate the difference in propellor size using a 1 motor configuration, the blue being the 8cm while the red being the 6cm.

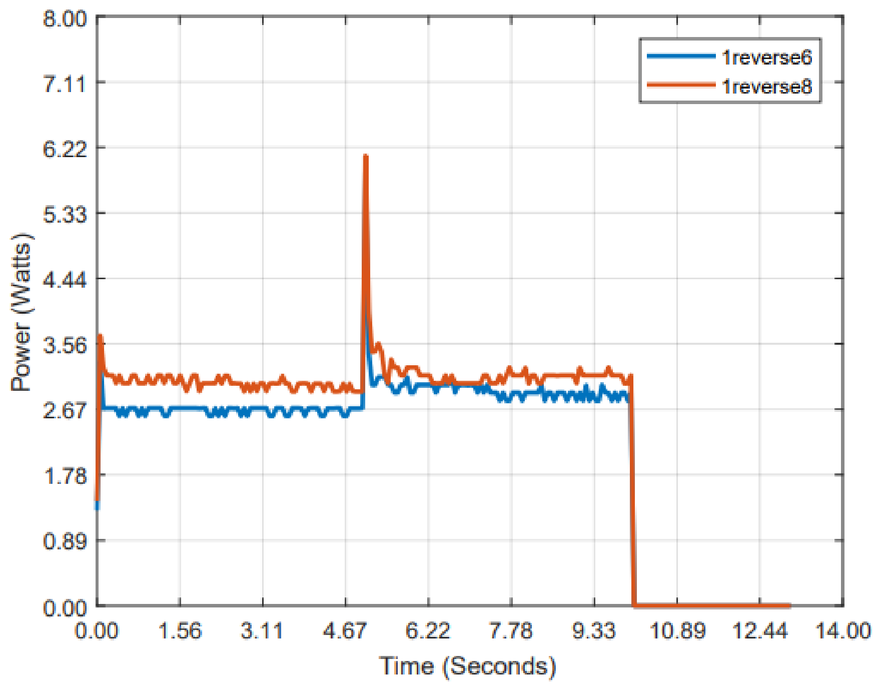


Figure 8: One Propellor Configuration Power vs Time

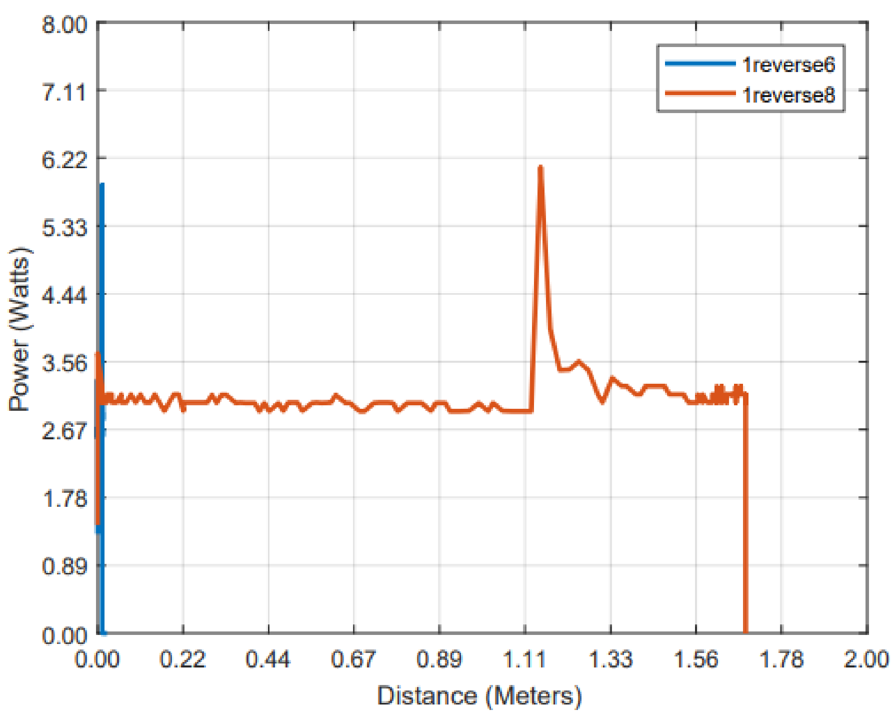


Figure 9: One Propellor Configuration Power vs Distance

For motor configuration, the results from testing determined that the pull setup using our design used slightly less energy (approx. 0.3 volts) but went a similar distance according to the graphs 10 and 11.

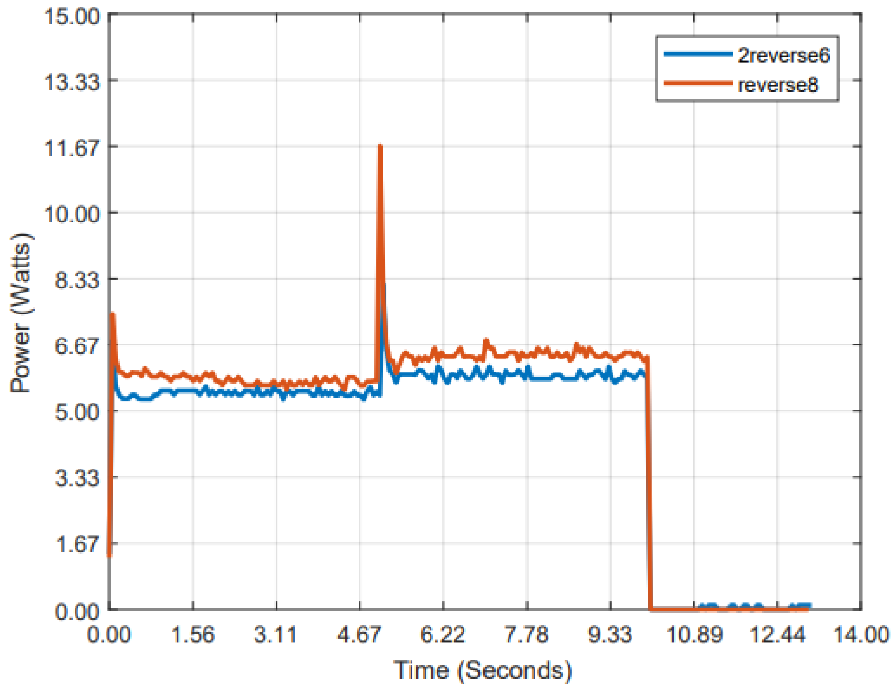


Figure 10: Pull (before spike) vs Push (After Spike)

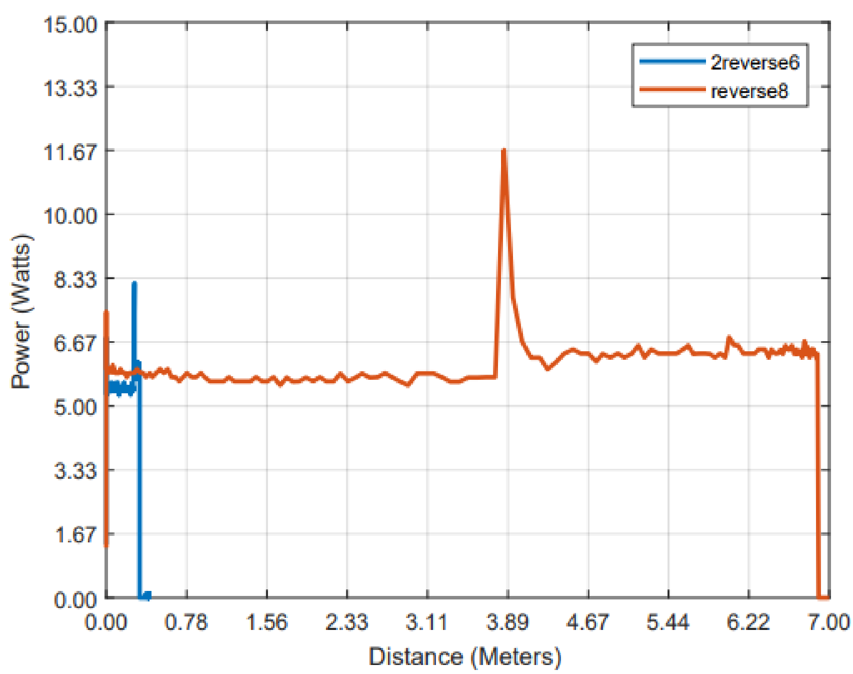


Figure 11: Pull (before spike) vs Push (after spike)

Having determined an optimal setup of a dual motor configuration with 8cm propellers while first engaging in a pull configuration and then a push configuration after picking up the load, the last task for Team P was to complete the Performance Test. Figures 12 and 13 analyze the power usage and time taken to complete the Final Performance Test.

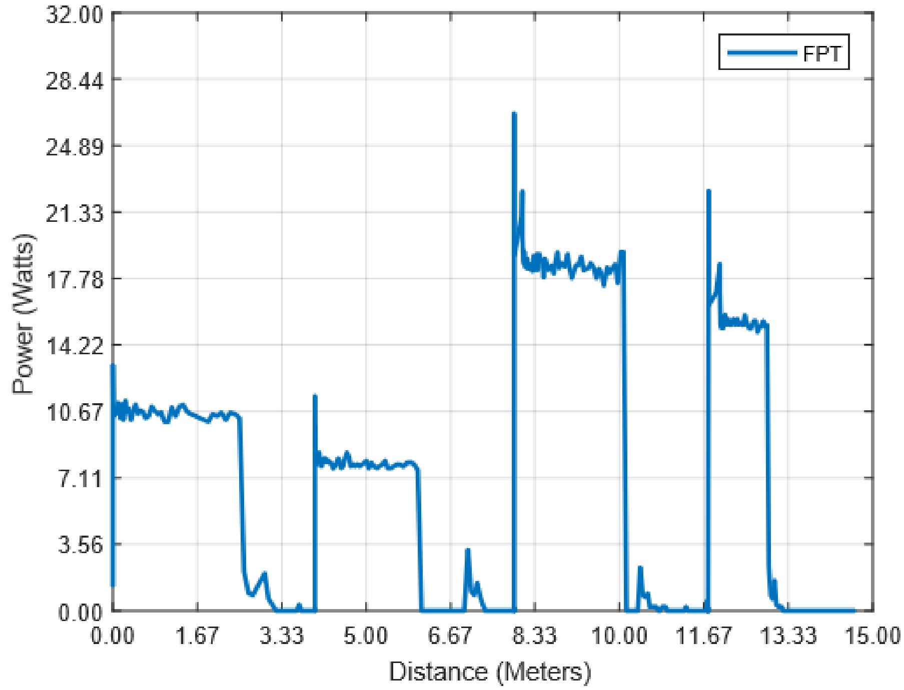


Figure 12: Power vs Distance

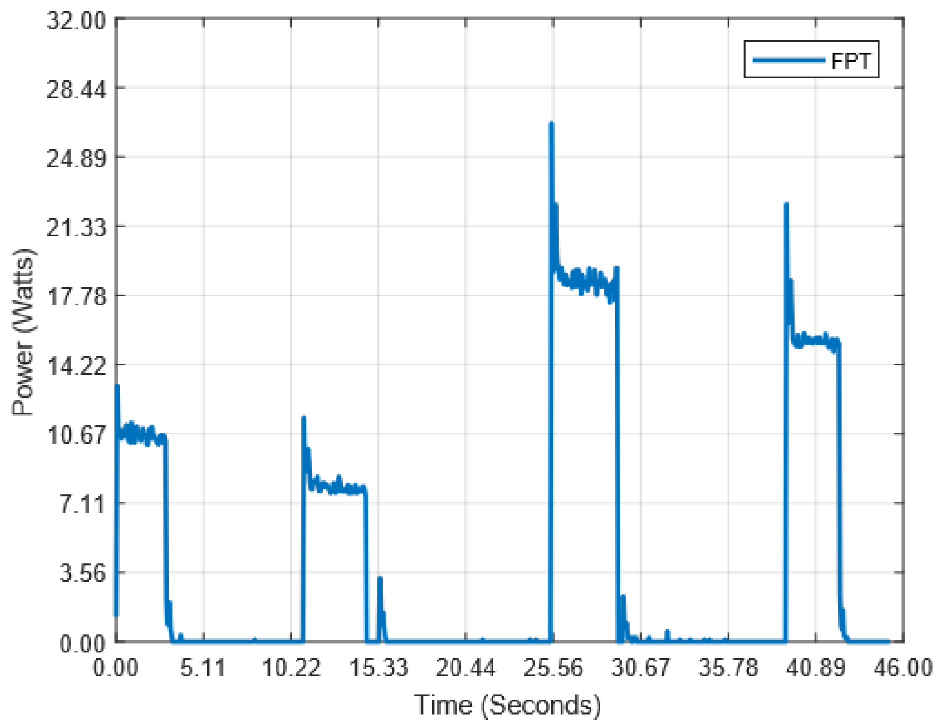


Figure 13: Power vs Time

As seen in Figures 11 and 12, the run took approximately 42 seconds while consuming 187J of energy. After performing the Final Performance test, the total cost of our AEV consisting of materials, time, energy, resources, etc. is described by the equation in Figure 14.

$$\text{Total Budget (\$)} = \underbrace{\left(\text{Energy Costs (\$)} + \text{Time Costs (\$)} \right)}_{\text{THESE WILL BE TOTALLED FOR BEST TWO RUNS}} * \text{Accuracy Penalty} + \text{Capital Cost (\$)} + \text{R \& D costs (\$)} + \text{Safety Violations (\$)}$$

Figure 14: Equation for total cost of AEV

Given a total budget of $500k, the following costs are described: Energy Cost consists of $500 per Joule used; Time Cost consists of $1.5k per second consumed; Accuracy Penalty is the inverse of score given out of 40pts; Capital Cost is cost of AEV (See Figure 3B in Appendix B); R&D Cost are $25k for every 60min outside of class; and Safety Violation include $50k for fire and $15k for falling off the track.

Figure 15 shows the calculations for the Total Cost of the AEV and the excess budget after all was said and done.

Total Cost=([(187J x $500)+(42sec x $1.5k)] x (30/40)^-1 + $162,550 + $25k + $15,000)
Total Cost= $411,216.67
Under Budget= $500,000-$411,216.67=**$88,783.33**

Figure 15: Final Cost and Excess Budget of AEV

Discussion:

Unlike the reverse motor testing, the servo performance test was initially unable to be completed due to the unknown limitation of servo. The AEV would assign motorspeed and run correctly to the gate and brake with the servo as programmed; then when rotating the servo back to initial position the motors slightly burst and then cease, not adequately moving the Arduino past the gate. This error was resolved by assigning motorspeed to one motor at a time, but it also poses the puzzling question of *why?* The answer to the question may lie within the function definition for rotateServo(). Group P proposes that because the motor function seems to occur simultaneously as the servo is rotating, a communication error occurs when the servo reaches its final position, causing the motors to stop.

Although the reverse protocol did complete the test faster, Group P continued onward with the servo braking prototype because of its room for improvement with the external servo arm material and its more efficient power usage. The servo test was a point of contention for the group research. When run, it obviously used less energy than reversing, as comparable in Figures 3 and 5 with the power consumption differential (Figure 3 showing a more than double increase in power whereas figure 5 shows approximately a 1 Joule increase) [Results, page 9-11, Figure 3 and 5].

With an emphasis on a sleek and compact design, group P produced an AEV which efficiently traversed the rail in a safe and timely manner. Although, the Servo braking introduced a margin of error in regards to braking distance that became evident during the Final Performance Test. When adjusting the absolute position for the arduino to rotateServo at the docking station, instances of inverse correlation occurred (ex: reducing absolute position by 5 marks to see the AEV go further than the previous attempt). Although Group P cannot provide a finite reasoning for this experimental error, it is hypothesized that shifting of the external surface of the servo arm and battery power may be variables to take into account. Given more time to investigate and analyze these bugs, group P believes the Final Performance test could have been completed without error.

Conclusions and Recommendations:

The purpose of this experiment was to create an advanced energy vehicle that could complete a predetermined mission using as little energy as possible. The first part of the mission entailed the AEV progressing along the track unl reaching the gate. The AEV stopped at the gate for seven seconds unl the gate opened. Then, the AEV traveled to the end of the track to pick up the cargo. After the cargo was picked up, the reverse command was initiated and the vehicle and cargo traversed back to the gate. After another seven seconds, the gate opened and the AEV went back to the starting point . The code used for the final testing can be found in Figure 4B of the Appendix.

Through a series of tests of which analyzed energy consumption, power output, braking methods, and motor quantity, Team P has found that a dual motor configuration on an x-shape base utilizing an L-shape arm with motor in an initial pull configuration will provide a superior product. The aforementioned results and experimental analysis have led Team P to conclude that AEV Model B, utilizing the servo motor as a braking function, will maximize consistency and efficiency while minimizing energy cost. Team P will carry this design forward for not only the previously mentioned reasons, but this design also maximizes aerodynamics (e.g. tied down wires, minimal surface area), minimizes weight, and minimizes total cost. Although Model B does cost approximately $7,000 more, as seen in Appendix A Figures 3A and Appendix B Figure 3B, the use of the servo minimizes energy costs which will far outweigh the difference in initial unit price of the Models when taking into consideration the energy cost of Model A. Team P believes Model B aligns precisely with the Mission Concept Review and therefore should be further developed in an attempt to further improve the product.

Overall, this lab has given the group the opportunity to coordinate an organized effort toward creating an efficient design. The team was able to narrow down designs, complete preliminary testing, alter the design based on testing, and complete the assigned task. This design process is necessary in all engineering disciplines, so this project gives a structured introduction for how to efficiently complete such an assignment. The general techniques used to design the AEV was a more important takeaway than the specifics of completing the project. In addition, basic professional skills such as communication and time management were developed as a result of this project.

A few minor problems faced during the research process involved the servo arm not creating enough friction between itself and the wheel in order to stop it quickly. This was temporarily combated by adding an adhesive tape to the servo arm as more methods are being researched and developed. There were also other minor technical difficulties utilizing the servo, involving the motors not functioning after the servo was called to function. This was solved by changing the code to call each motor separately rather than both simultaneously.

This AEV design is more consistent and uses less power than others in the class. The servo motor, which pressed against the wheel to brake it, combined with the use of the reflective wheel sensors, provided an accurate and consistent braking mechanism. This design had a much lower energy usage than if reverse function method of braking had been utilized. The AEV did not have any parts that were unnecessary for its performance, so it required less power to accelerate and less force by the servo arm to brake. The final design also had a sustainable wire (i.e. floss) that was used to tie down wires and create an overall compact and sleek design. All of these factors made the AEV as efficient as possible.

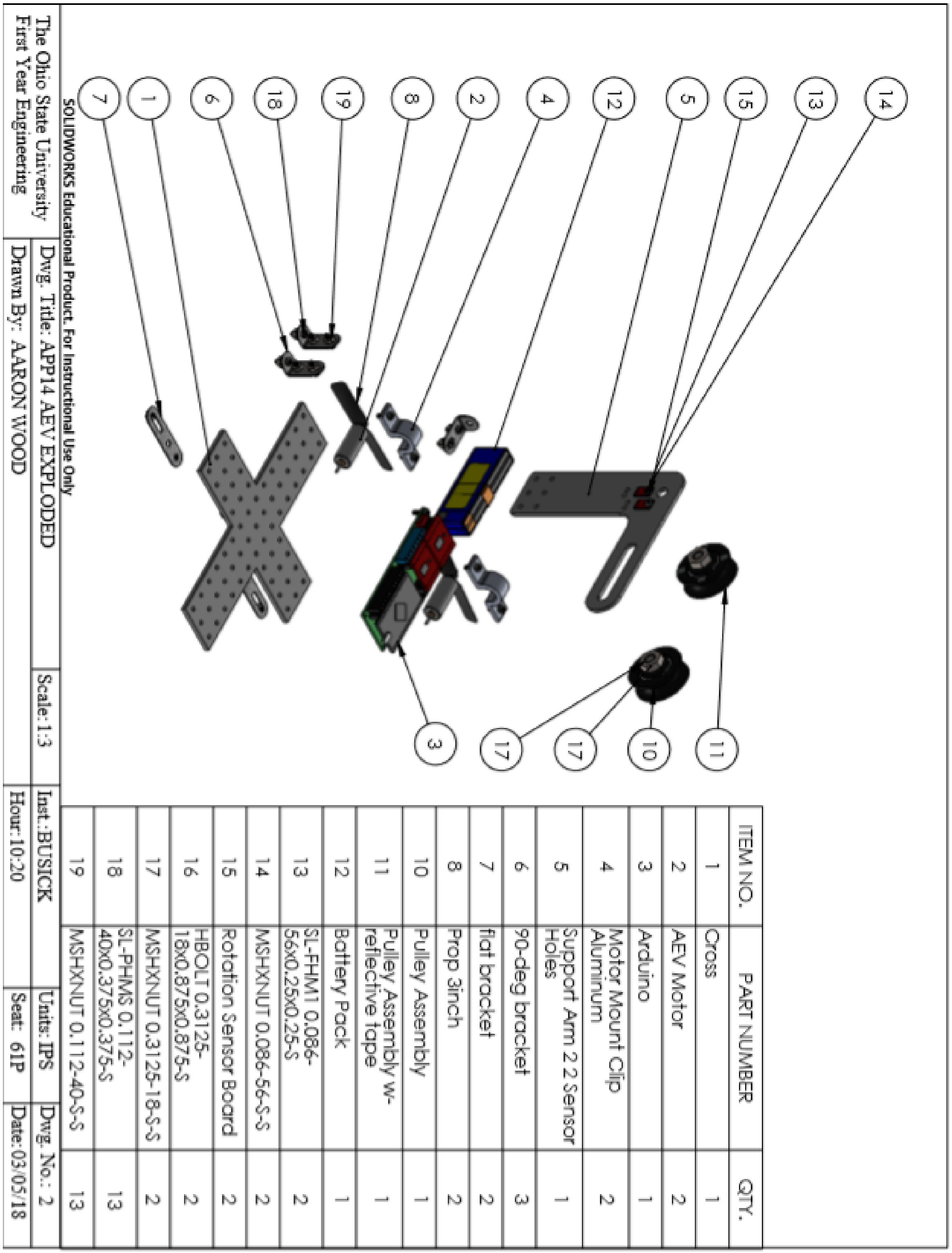
Appendix A-Schedule

Task	**Start Date**	**Due Date**	**Time**	**Han**	**Tim**	**Aaron**	**Seth**	**% Done**
Website Update 1	1/16	1/18	2hr	0	0	2	0	100
Team Meeting Minutes	1/15	1/18	1hr	1	0	0	0	100
Website Update 2	1/30	2/1	1.5hr	0	0	1.5	0	100
Grant Proposal	2/13	2/14	2hr	0	1	1	0	100
Committee Meeting 1	2/14	2/15	1.5hr	.5	0	.5	.5	100
R&D Presentation	2/26	2/28	1hr	0	1	0	0	100
Website Update 3	2/28	3/1	1.5hr	0	0	1.5	0	100
Progress Report 2	3/6	3/8	5hr	.75	2	1.5	.75	100
Performance Test 1	3/14	3/21	2hr	1	.5	0	.5	100
CDR Draft	3/23	3/24	16hr	4	3	6	3	100
Progress Report 3	3/26	4/4	4hr	0	3	1	0	100
Performance Test 2	3/13	3/28	2.25hr	1.05	.3	.35	.55	100
Website Update 4	3/26	4/4	1.5hr	0	0	1.5	0	100
Committee Meeting 2	3/27	3/29	2hr	.75	.75	0	.5	100
Oral Presentation	4/5	4/9	3hr	0	2	.5	.5	100
Final Performance Test	3/13	4/12	3hr	1	.75	.75	.5	100
Final Oral Presentation	4/12	4/17	2hr	0	1.5	0	.5	100
Final Website	4/15	4/19	3hr	0	0	3	0	100
CDR	3/23	4/22	10hr	3	0	4	3	100

Appendix B-Solidworks

AEV Model A: Reverse Function Braking

Figure 1A: Model A Exploded Drawing with Bill of Materials



ITEM NO.	PART NUMBER	QTY.
1	Cross	1
2	AEV Motor	2
3	Arduino	1
4	Motor Mount Clip Aluminum	2
5	Support Arm 2 2 Sensor Holes	1
6	90-deg bracket	3
7	flat bracket	2
8	Prop 3inch	2
10	Pulley Assembly	1
11	Pulley Assembly w-reflective tape	1
12	Battery Pack	1
13	SL-FHM1 0.086-56x0.25x0.25-S	2
14	MSHXNUT 0.086-56-S-S	2
15	Rotation Sensor Board	2
16	HBOLT 0.3125-18x0.875x0.875-S	2
17	MSHXNUT 0.3125-18-S-S	2
18	SL-PHMS 0.112-40x0.375x0.375-S	13
19	MSHXNUT 0.112-40-S-S	13

Figure 2A: Model A Drawing with Basic Dimensions and Estimated Weight

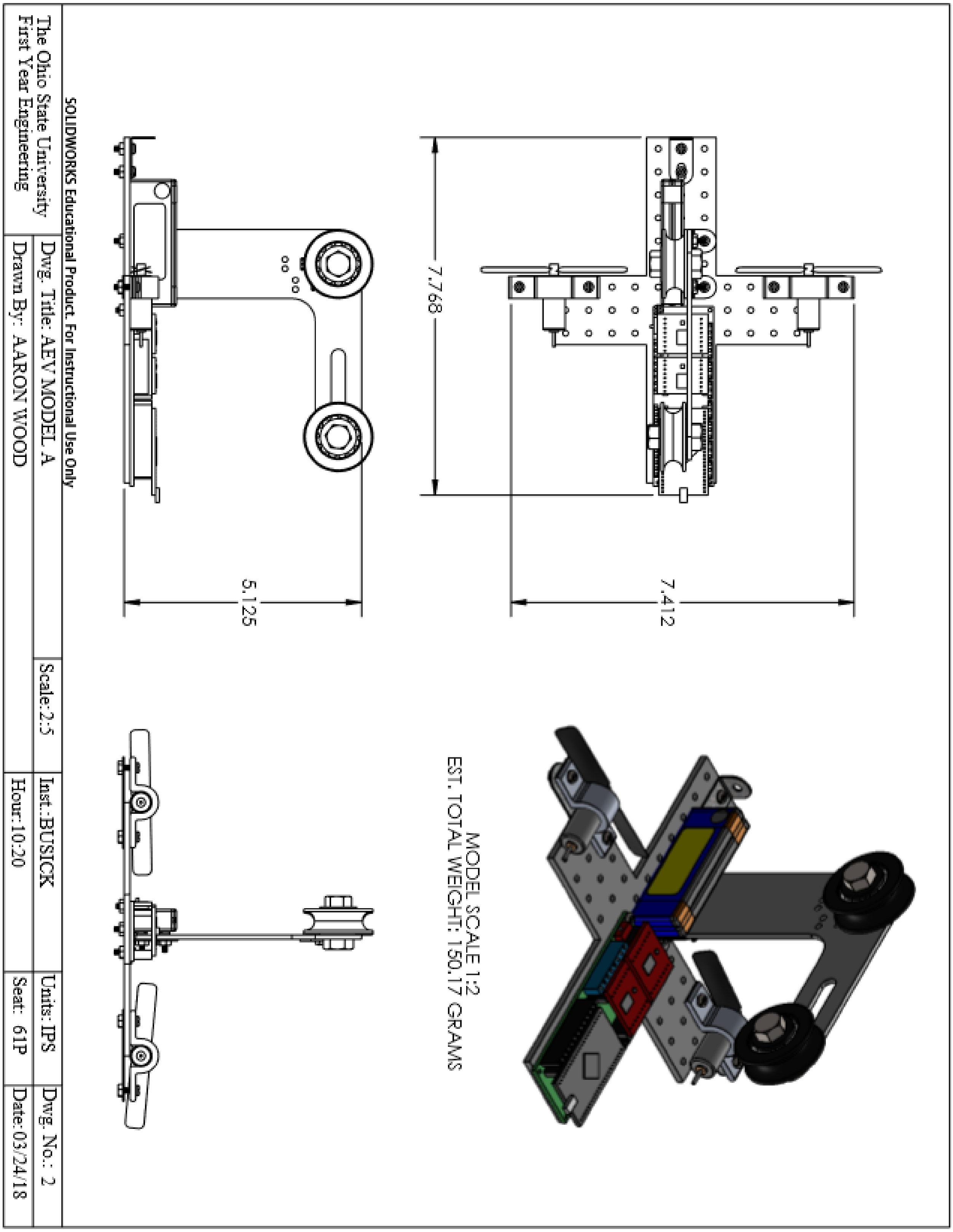


Figure 3A: Estimated Cost of Model A:

Part	Quantity	Unit Cost ($)	Total Cost ($)
Arduino	1	100,000	100,000
Motors	2	9,900	19,800
Reflectance Sensors	2	2,000	4,000
Sensor Connector	2	2,000	4,000
Propellers	2	450	900
X-Shape Base	1	2,000	2,000
Wheels	2	7,500	15,000
L-Shape Arm	1	3,000	3,000
Motor Clamps	2	590	1,180
Brackets	6	840	5,040
		Total Cost:	**$154,920**

Figure 4A: Code for Performance Test 1

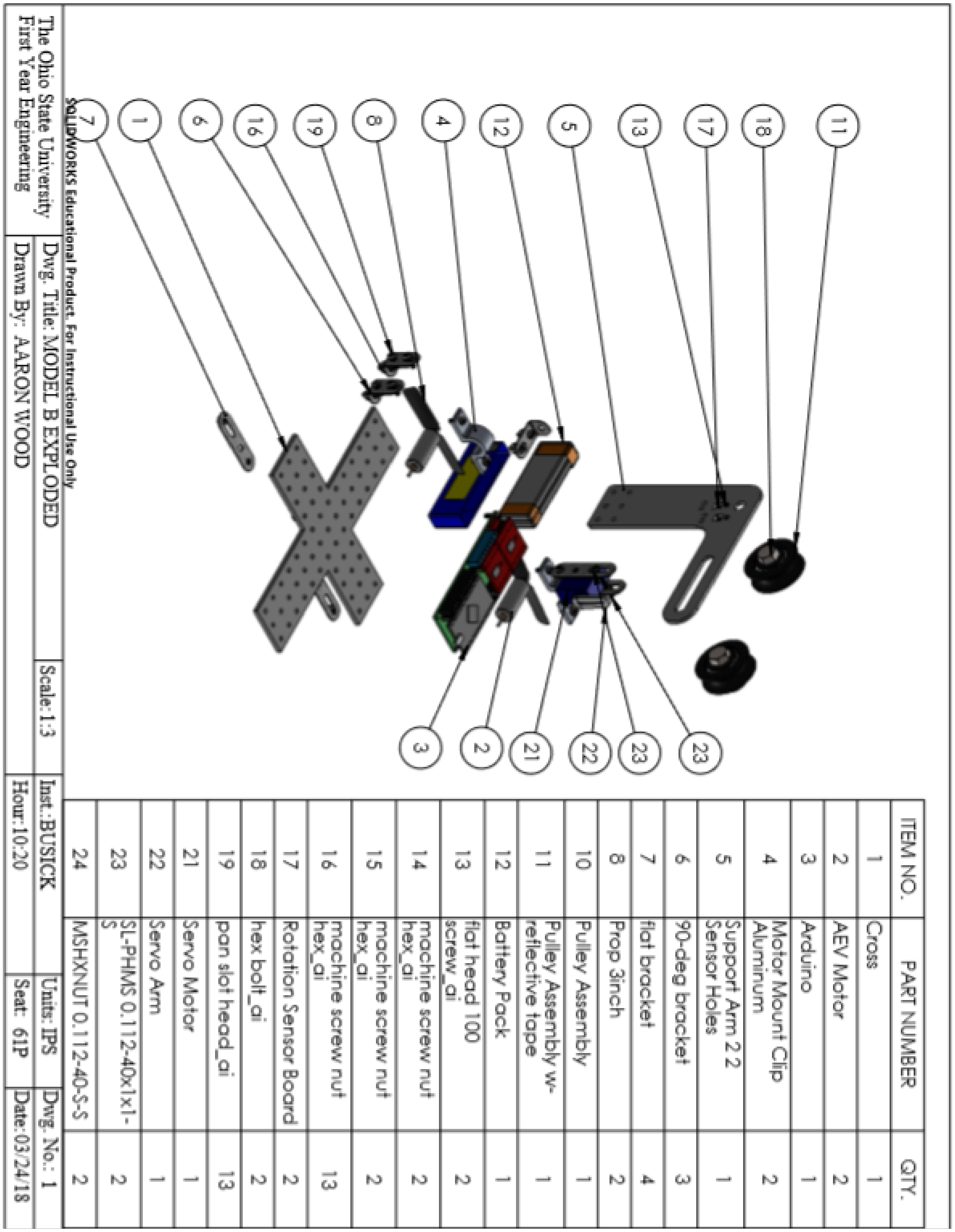
```
//Starting Dock
motorSpeed(4,40);  //set all motors to 40% power
goToAbsolutePosition(206);  //travel 206 marks to gate
brake(4); //cut power to all motors


//Gate
reverse(4); //reverse all motors
motorSpeed(4,60); //set all motors to 60% power to brake at gate
goFor(1.1); //run previous function for 1.1 seconds
brake(4); //cut power to all motors
goFor(7); //wait in gate for 7 seconds
```

```
//Toward Loading Dock
reverse(4); //reverse motors in order to travel forward out of gate
motorSpeed(4,40); //set all motors to 40% power
goFor(2); //run previous task for 2 seconds
brake(4); //cut power to all motors
reverse(4); //reverse all motors to brake
motorSpeed(4,60); //set all motors to 60% power to brake
goFor(1.1); //run previous task for 1.1 seconds
brake(4); //cut power to all motors
```

AEV Model B: Servo Braking

Figure 1B: Model A Exploded Drawing with Bill of Materials



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6	90-deg bracket	3
7	flat bracket	4
8	Prop 3inch	2
10	Pulley Assembly	1
11	Pulley Assembly w-reflective tape	1
12	Battery Pack	1
13	flat head 100 screw_ai	2
14	machine screw nut hex_ai	2
15	machine screw nut hex_ai	2
16	machine screw nut hex_ai	13
17	Rotation Sensor Board	2
18	hex bolt_ai	2
19	pan slot head_ai	13
21	Servo Motor	1
22	Servo Arm	1
23	SL-PHMS 0.112-40x1x1-S	2
24	MSHXNUT 0.112-40-S-S	2

Figure 2B: Model B Drawing with Basic Dimensions and Estimated Weight

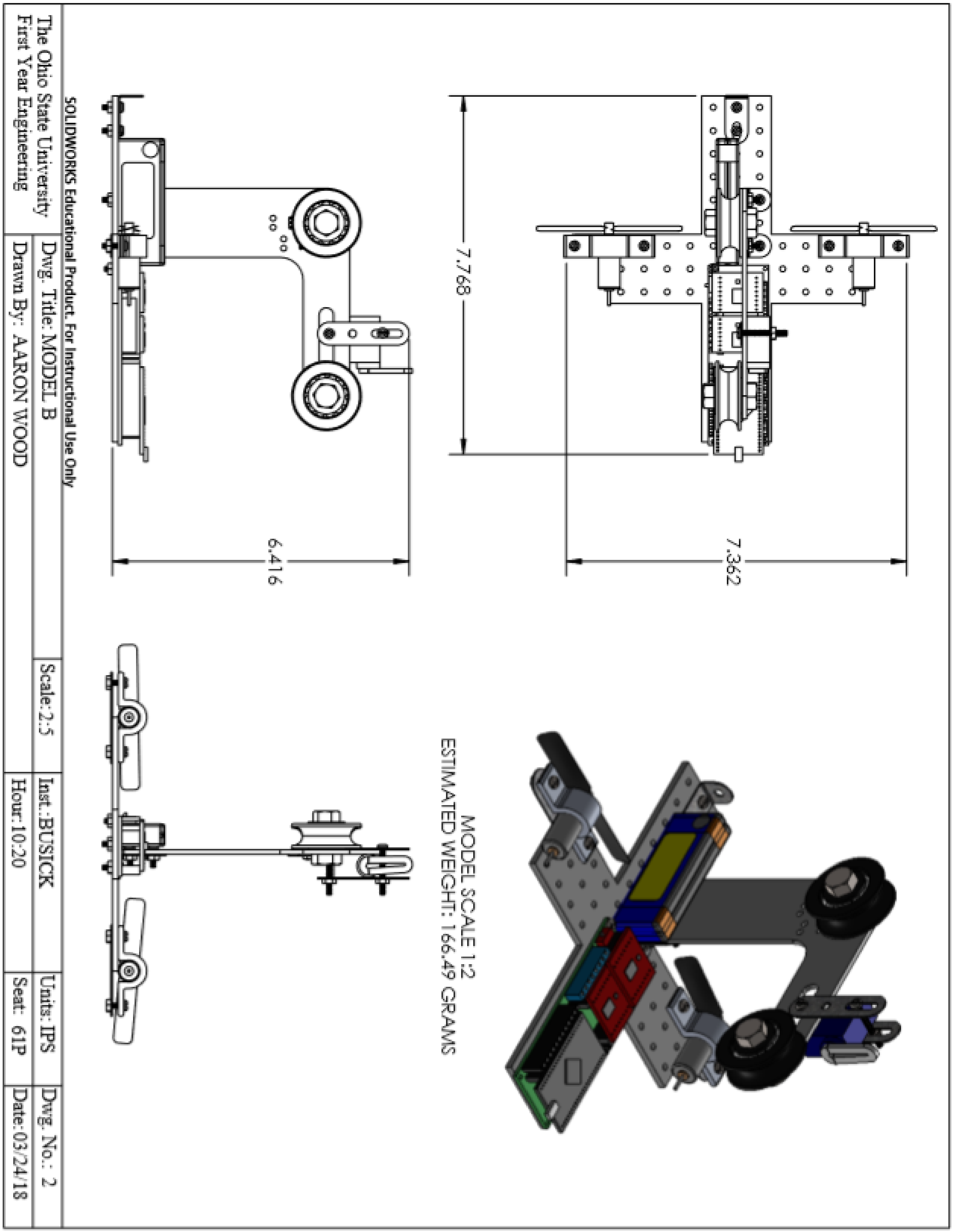

Figure 3B: Estimated Cost of Model B

Part	Quantity	Unit Cost ($)	Total Cost ($)
Arduino	1	100,000	100,000
Motors	2	9,900	19,800
Reflectance Sensors	2	2,000	4,000
Sensor Connector	2	2,000	4,000
Propellers	2	450	900
X-Shape Base	1	2,000	2,000
Wheels	2	7,500	15,000
L-Shape Arm	1	3,000	3,000
Motor Clamps	2	590	1,180
Brackets	8	840	6,720
Servo	1	5,950	5,950
		Total Cost:	**$162,550**

Figure 4B: Final Performance Test Code

```
//Starting Dock
motorSpeed(4,40); //set motors to 40% power
goToAbsolutePosition(195); //enter gate

//Gate
rotateServo(99);// rotate servo as manual brake system
brake(4); //cut all power to motors
goFor(8); //sit in gate for 7 seconds for gate to open, 1 sec allows for braking time
rotateServo(5); //release manual brake

//Toward Loading Dock
motorSpeed(4,35); //resume slightly slower speed toward loading dock due to decline
goToAbsolutePosition(484); //runs motors until defined distance
brake(4); //cuts power to engines, starts coast down incline
goToAbsolutePosition(546); //coast until gate

//Enter Loading Dock
rotateServo(99); //engage brake
goFor(7); //sit in loading dock for 7 seconds, allowing time for braking
rotateServo(5); //release brake
reverse(4); //reverse motor direction

//Depart Loading Dock with Load
motorSpeed(4,65); //resume increased speed in reverse to account for weight of load

//Enter Gate
goToAbsolutePosition(491); //continue last command until determined distance
brake(4); //Cut power to motors begin coast into gate
```

```
goToAbsolutePosition(469); //Continue coast until determined distance
rotateServo(90); //Engage servo brake
goFor(9.5); //Sit in gate for 7 sec
rotateServo(5); //release brake

//Depart Gate for Starting Dock
motorSpeed(4,55); //Resume slightly slower speed due to weight of load
goToAbsolutePosition(260); //Continue until 260 marks out from gate
brake(4); //Cut power to motors
rotateServo(90); //Engage servo brake
brake(4); //Cut all power
```

References:

Advance Energy Vehicle Design Project: Mission Concept Review and Deliverables. The Ohio State University College of Engineering, 18 Aug. 2017.