Abstract

Recent studies on animals, insects, and mammals have resulted in numerous bio inspired robotic designs to solve modern day technical problems. Nature's insight can sometimes provide more efficient solutions in fact, such robots have aided in military defense applications saving the cost of human casualties. Currently, few robots have the capability to address the problem of inclined or vertical surface terrain. Enervate has studies the looping gait mechanism of an inch worm combined with the adhesive nature of a gecko to develop a robot with the ability to scale inclined surfaces addressing this issue. Enervate achieved the desired result through Dynamixel actuators, adhesive grips, and an unhinging method to mimic the inchworms natural gait. The inch worm robot was tested on flat and inclined angles ranging from (0-55) degrees where it was determined the robot was able to achieve a velocity of 1 inch per second for both surface environments. Further implementation beyond the scope of our design will incorporate a video feedback camera and wireless Bluetooth controller further enhancing the capability of the robot. This project was inspired by Dr. Bhounsule as a preliminary prototype illustration in a DOD proposal, which will lead to further development in disaster management reconnaissance.

Table of Acronyms

- τ = Torque
- τ_{stall} = Torque required to stall a motor
- I = Applied Current
- I_{free} = The current being drawn into the motor while performing no action
- I_{stall} = Current required to stall a motor
- ω = Angular Velocity
- ω_{free} = The angular velocity of the motor when no load is applied
- r = Radius of object being rotated
- W_p = Weight parallel to the surface
- W_v = Weight perpendicular to the surface
- PLA = Polylatic Acid
- f_F = The force of friction.
- UTSA = The University of Texas at San Antonio
- RAM = Robotics and Motion

Table of Contents

List of Figures

List of Tables

Acknowledgments

The engineers of Enervate would like to acknowledge the following, as without the leadership and mentorship this project would not be possible:

- Christian Emil Wahrmund
- Dr. Pranav Bhounsule
- Dr. John Simmons
- Dr. James Johnson
- Dr. Gold Hood

1. Introduction and Background

Inchworms, named for their size usually being an inch, are worms who lack appendages in their middle body. This absence has made this species devise a creative way for propelling itself forward. To do so, the worm hinges its middle portion upward to draw in its backside. Once this has been accomplished the front side will then propel itself forward, and then the process is repeated. Alongside its unique movement, the inchworm also possesses the ability to scale a variety of inclined surfaces. The combination of the two has drawn Dr. Bhounsule's, of the Robotic and Motions Laboratory, attention.

2. Purpose

Dr. Bhounsule is devising new ways to tackle problems being faced by our armed forces through robotics. His focus is particularly in indoor search and rescue missions, in which sending in humans can be dangerous due to the presence of criminals. Since most buildings these days hold air ducts, he intends on utilizing these as the means of searching. To do this, a robot must be small enough to fit inside these ducts as well as contain the ability to scale the various inclines.

3. Objectives

The first objective of this project is to design, analyze, build, and test an inchworm robot to be delivered to RAM Labs. This robot overall must function and operate as an inchworm does. This includes its abilities to scale various inclinations, and in the case of this project an inclination of at least 45 degrees. The robot must also be able to move at a speed of .4 inches per second. This has since been increased to one inch per second to reach rescues quicker. The robot must also not have a hinge greater than six inches, this is to keep it small enough to move in various sized ducts. Finally, the robot must be able to move to at least three ft.

4. Specifications

4.1 Performance Specifications

- Highest angle of incline: 45 degrees
- Minimum speed: 0.4 in/sec
- Cover a minimum distance of 3 feet

- Robot must be capable of contracting with a load of 2 lbs.

4.2 Physical Specifications

- Max Segment Height: 5 inches
- Max Segment Length: 5 inches
- Max Segment Width: 4 inches
- Max Total Length: 3 ft.
- Maximum weight (For entire robot): 8 lbs.
- Hinged Height of Robot: 6 inches

5. Concept Designs

5.1 Concept 1: Smart Memory Alloy

Shape memories alloys have just begun to show potential progress in the field of robotics. This robot makes use of the transformation process from the SMA material properties as it turns from martensite to austenite with change in temperature. Flexinol will be used for this specific concept design in the actuation process of our inchworm robot. The material, when heated above 90 degrees Celsius, reverts back to its original shape. The body will be made of 3 mm thick carbon fiber sheets. Flexinol ribbon will be used to actuate the robot to take the desired omega motion. Three flexure ribbons at the middle segments of the robot will be used to attach both front and back pieces together. The Flexinol material will be Copper Laminated Kapton Film. Two separate 1750 mAH, 3.7 V battery power sources will be placed at the front and back. An Arduino microcontroller will be utilized to send current to the SMA initializing the actuation process of the Flexinol. The entirety of the concept is illustrated in fig. 1 below.

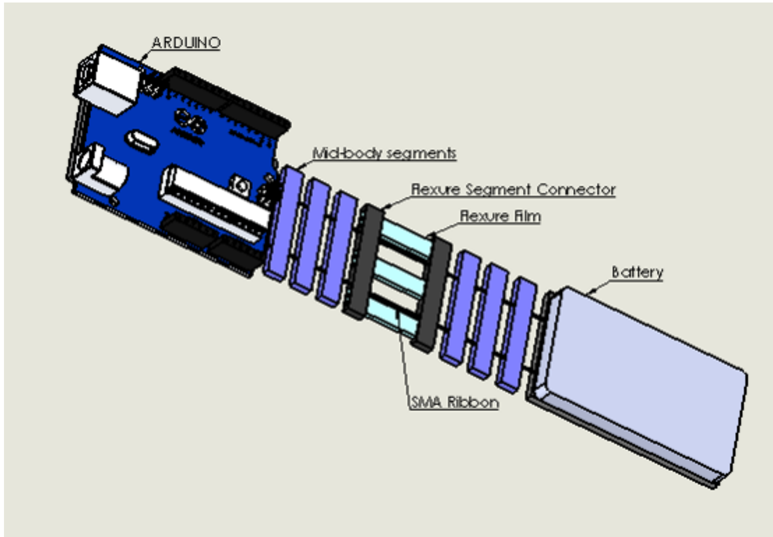


Figure 1: Concept 1, SMA Robot

Based on battery life specifications, the robot should be able to perform 800 cycles until a new battery will be needed for replacement. The adhesive will consist of a rubber silicon pad that will allow the robot to grip and when motion is taking place. The robot will be small and lightweight to maneuver between tight spaces and throughout different pipe systems.

5.2 Concept 2: Three Segment Robot

This concept is a 3-segment robot manufactured from Polylactic Acid (PLA) through the work of a 3D printer shown in Fig. 2.

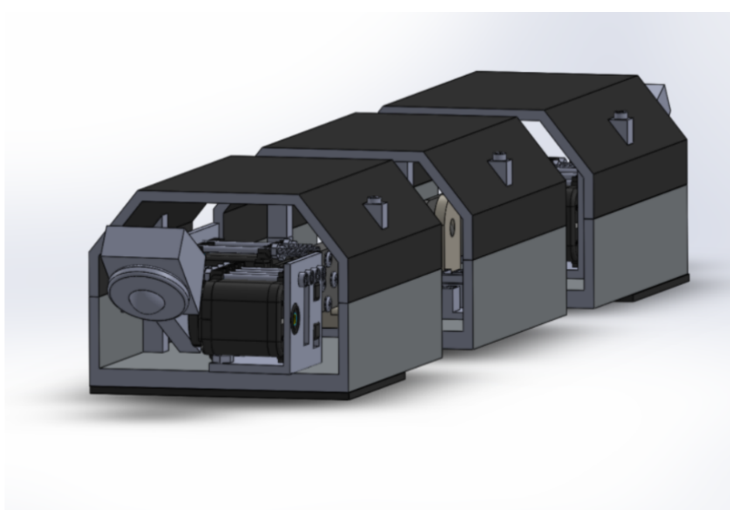


Figure 2: Concept 2, Three-Segment Robot

The robot will be tethered to an external AC/DC power source converter supplying approximately 11.1 Volts rather than battery powered. The tether will be connected to an OpenCM9.04 Robotics Microcontroller which will be coded to achieve the inchworm gait motion. Four Dynamixel Ax-12A servo motors will be daisy chained together and ultimately connected to the microcontroller to complete the electrical circuit. An exploded view of the three-body segment and all of the parts included are shown below in Fig. 3.

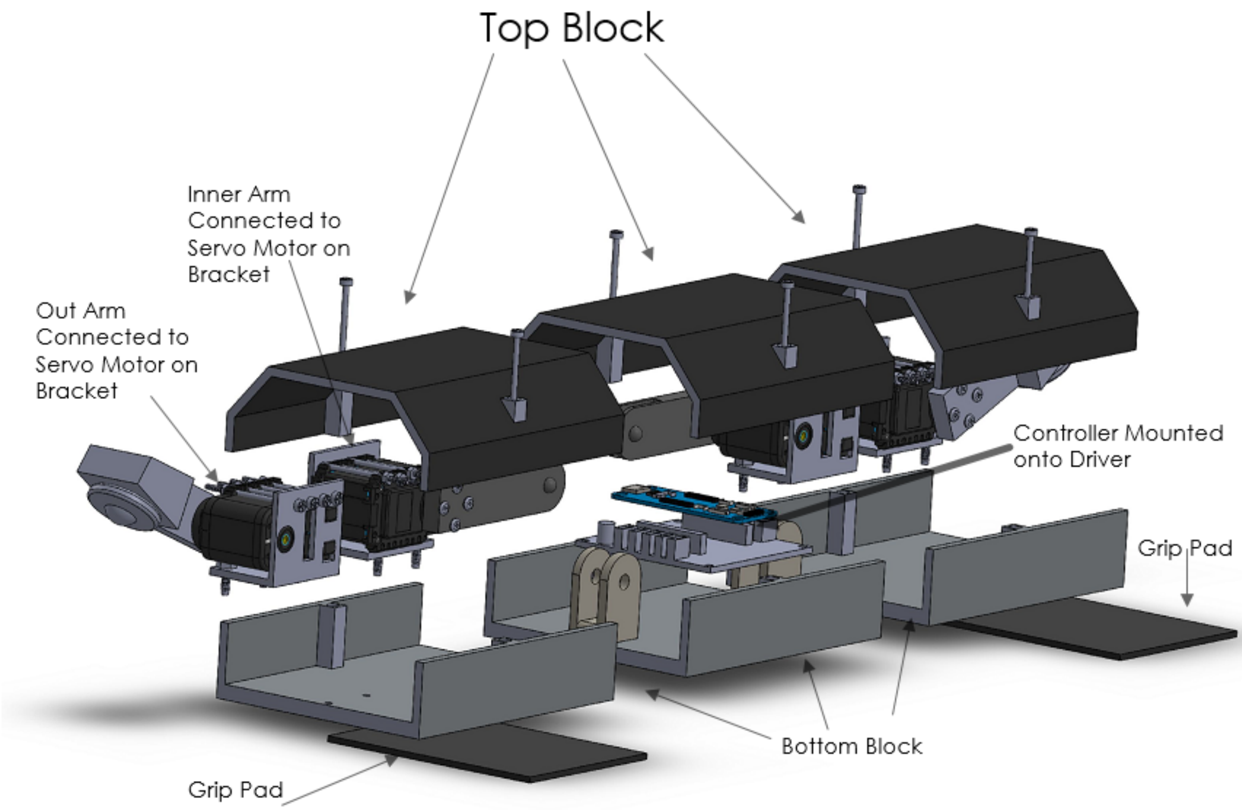


Figure 3: Concept 3, Exploded View

The servos will be able to interpret signals given from the microcontroller through I2C processing. Each motor has its own PID control to ensure that there is a steady motion with no overshooting or errors. The servos will be attached to servo arms shown in fig. 3. The middle segment of the robot will house not only the microcontroller but two hinge mechanisms attached to the inner servo arms. To start the actuation process of lifting the middle segment, the Dynamixel motors will work together with the servo arms attached to the body of the robot to achieve the gait of the inchworm.

Fig. 4 shows the flowchart of the logic process that will enable the forward movement of the robot and the process each servo will perform to achieve forward motion.

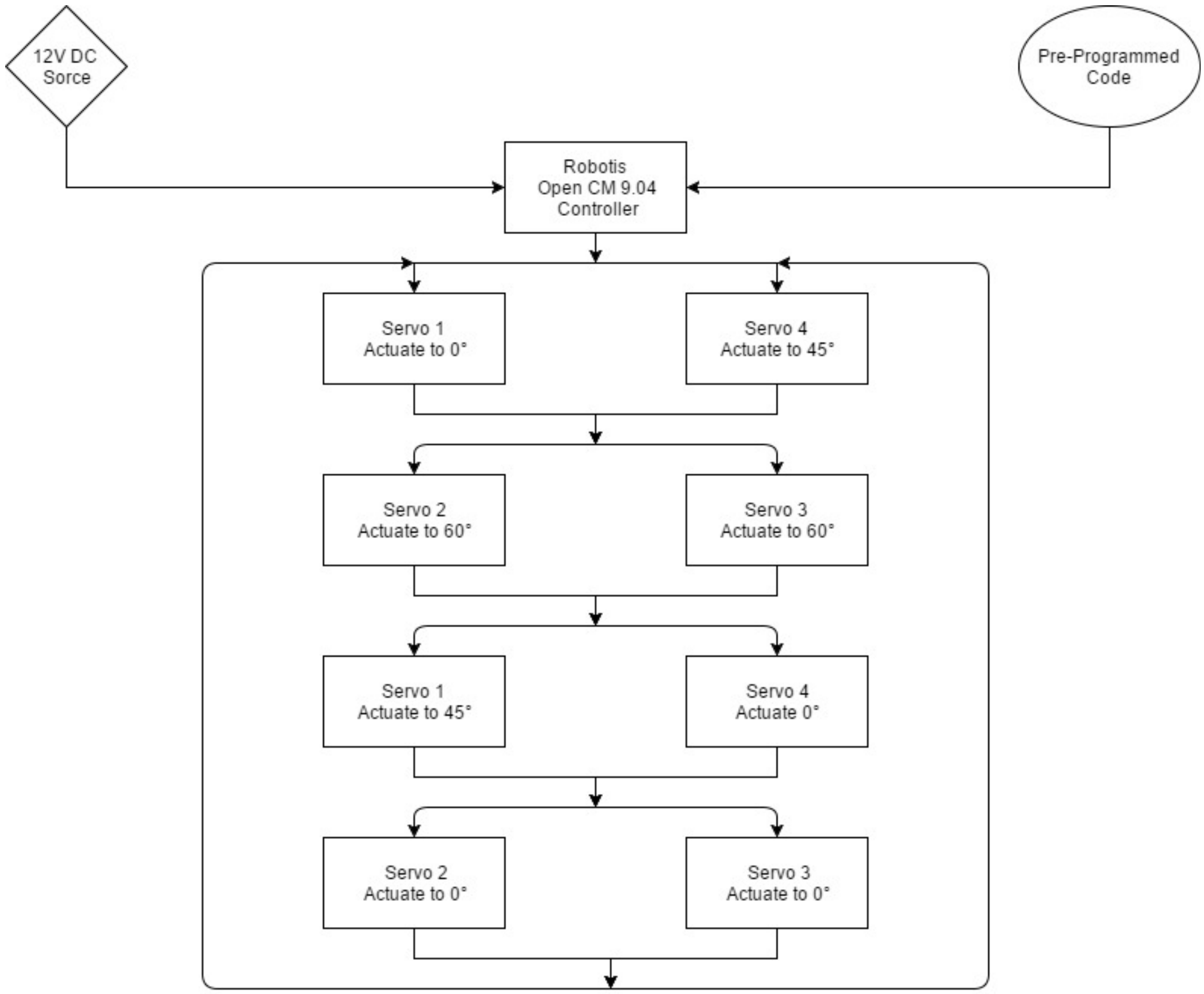


Figure 4: Flowchart of the Movement

A ball bearing attached to the front and rear servo arms will allow for the desired break of the grip from the adhesion pads on the anchoring segments. The adhesive pads will be micro-fabricated silicon pads that resemble the natural mechanics of a gecko's feet, otherwise known as gecko style adhesive.

5.3 Concept 3: Suction Cup Robot

This two-segment robot concept design allows for operations on both horizontal and vertical planes. The robot is made from PLA similar to concept 2. It accomplishes grip with the use suction cups of diameter 0.787 inches which can provide enough force to hold the total weight of the robot on both a level and inverted surface. The length was set in each segment to accommodate the five-inch 50 ml syringe that would be housed inside. The 50 ml syringe was chosen as it can consume enough air to provide effective suction force provided by the plungers to the suction cups to hold the robot. To actuate the syringes, small DC motors capable of operating between 3 – 6 Volts with 16500 RPM were chosen. Servo motors attached to rods would provide the actual motion of the robot. Three-inch rods were implemented in the design to allow a little over an inch in displacement with an angle change of 60 degrees from the servo motor. Finally, an Arduino Microcontroller would be programmed and tethered to an AC/DC converter to control the servos and dc motors in order to achieve the desired motion. A SolidWorks rendering of the third concept is illustrated below in fig. 5.

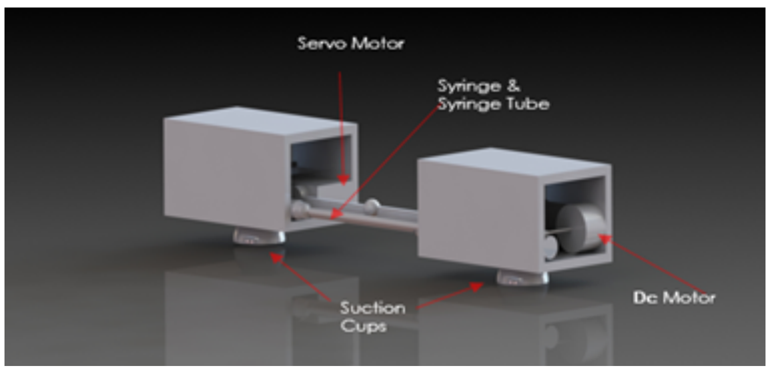


Figure 5: Concept 3, Suction Cup Robot

5.4 Selection Process

In selecting the final concept, different aspects needed to be considered. To do this, a table was created to compare each concept with essential requirements demanded from the client. In table 1 the requirements can be seen which include categories such as speed, length, weight, etc. As seen in this table, below each category lies a value that corresponds to a predetermined numbering system to rank these concepts fairly.

Table 1: Comparison Matrix

	Weight	Speed	Length	Cost	Durability	Modifiability	Total:
Concept 1	9	2	6	8	9	2	36
Concept 2	7	10	2	5	8	8	40
Concept 3	6	2	3	6	9	2	28

The numbering system was created to be fair for all concept designs and to help decide which would be the best decision. An example of this can be seen in table 2 which depicts speed. The left side possess values of speed that correlate to the right side of the table which holds values. The faster the speed, the higher the number. Each concept had its speed calculated and then was assigned the corresponding number to which the speed was determined to be. This was done for each category and finally each concept was tallied to find the total of points generated.

Table 2: Speed Rating System

Speed [in/sec]	Rating
.4	1
.8	2
1.2	3
1.6	4
2	5
2.4	6
2.8	7
3.2	8
3.6	9
4	10

6. Prototype Design

6.1 Analytical Methods

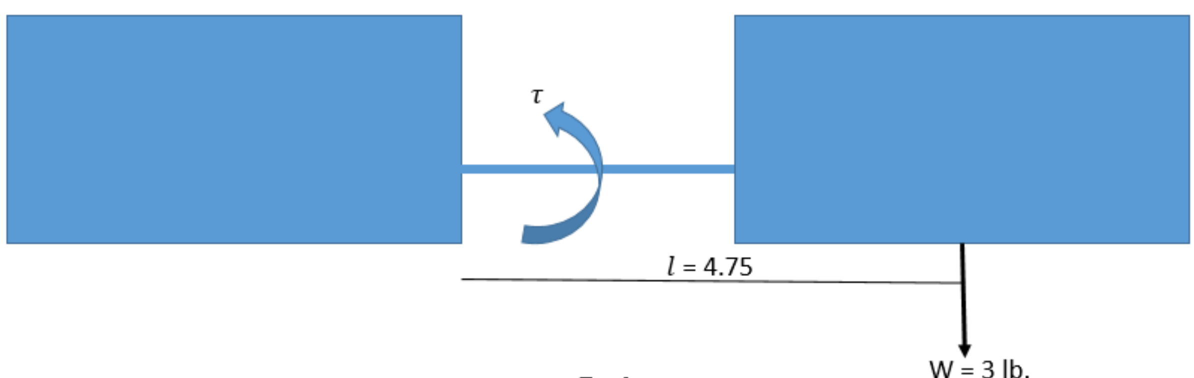
Servo motors are the muscles of this design, so it was important to ensure proper sizing of the motors. To do this, small calculations pertaining to what was expected from the servo motors were conducted. This involved lifting various loads, as well as the speed that could be emitted from these motors.

6.1.1 Lifting

In regards to lifting, the motors would have to be capable of lifting at least 2 lbs. That means that the team needed to find the torque that would be produced from this. Torque is found by multiplying force and the perpendicular lever arm to the rotation, the equation can be seen below:

$$\tau = F * l$$

The team decided that these servo motors would be attached to servo arms measuring about two and three-quarter inches, this will be added to the location of the center of mass two inches away from the end. The team then added one pound to the two pounds needing to be lifted to take account for the mass of the block. The resulting torque came to be 14.25 lb.*in, seen in fig. 6, so the servo motor had to possess a stall torque greater than this value. This led the team to choose a motor possessing a stall torque of roughly 16 lb.*in.



$$\tau = F * l$$

$$\tau = 3lb.* 4.75in$$

$$\tau = 14.25\ lb.* in$$

Figure 6: Torque Evaluation

6.1.2 Speed

The team decided that the robot should be capable of moving a minimum speed of .4 inches per second. Since the robot does not move via wheels, finding speed meant finding how fast the servo motors could displace one block. This meant the team first needed to solve for a minimum angular velocity to then find the corresponding linear velocity. Since this angular velocity will be affected by torque, the equation below was used.

$$\omega(\tau) = -\frac{\omega_{free}}{\tau_{stall}} * \tau + \omega_{free}$$

Previously, a minimum torque of 14.25 lb.*in was found, so this value will take the place of τ. From the motors selected based off the calculations done in the section prior, τ_{stall} was given to be 16 lb.*in, and ω_{free} to be 10.16 rad/sec [2]. After plugging in these values, an angular velocity of 1.11 rad/sec was found. To be safe other calculations were performed for a variety of loads, and can be seen in table 3. With this newly found value, a linear velocity can be found with the equation seen below.

$$v = \omega * r$$

The final result was shown to be 3.05 inches per second, meaning the team selected a motor not only capable of producing the torque needed but also capable of producing a speed greater than the goal.

Table 3: Analytical Calculations for Velocity

Load [lb.*in]	Angular Velocity	Linear Velocity [in/sec]
1.375	9.3	25.5
2.75	8.4	23.1
4.125	7.5	20.7
5.5	6.7	18.3
6.875	5.8	15.9
8.25	4.9	13.5
9.625	4.0	11.1
11	3.1	8.6
12.375	2.3	6.2
13.75	1.4	3.8

6.2 Product Safety/Failure Analysis

Product safety is very important, as the team does not what the robot to stop working due to malfunctions. Since servo motors are the main attribute in this design, they were evaluated to determine what could stop them from working. The team also decided to analyze when the slipping point of the robot to prevent falling and breaking.

6.2.1 Stall Torque

Stall torque is the torque required to stall the motor. This means any torque greater than the motors rated stall torque will result in failure. The motors rated stall torque is roughly 16 lb.*in, and since the lever arms value is fixed, we can solve for what weight would cause this occurrence. Performing this calculation gives a weight of four pounds. To prevent failure, the team will ensure the motors do not exceed lifting this weight. This calculation was also conducted for a variety of weights to determine torques being experienced, this can be seen in the table below.

Table 4: Weight vs Torque

Weight [lb.]	Torque [lb.*in]
0.5	1.375
1	2.75
1.5	4.125
2	5.5
2.5	6.875
3	8.25
3.5	9.625
4	11
4.5	12.375
5	13.75

6.2.2 Stall Current

Stall current is the current that would cause failure of the motor. The rated stall current for the chosen motor is 2.2 amperages. Since the motors will lifting various loads, current must be found in terms of torque. The following equation below was used for all calculations.

$$I(\tau) = \frac{I_{stall} - I_{free}}{\tau_{stall}} * \tau + I_{free}$$

The team decided to do calculations for a variety of loads that could be experienced to determine when this stall current would be reached. The table below depicts the results of these calculations.

Table 5: Load vs Current

Load [lb.*in]	Current [Amps]
1.375	0.24
2.75	0.42
4.125	0.61
5.5	0.79
6.875	0.98
8.25	1.16
9.625	1.35
11	1.53
12.375	1.72

The values above relate an experienced torque to the resulting current. The final load measured is a result of having to lift a 4.5 pound weight, which is above the motors capabilities. From this data, the team is confident that the motors will not stall as the current value never reaches 2.2 amperages.

6.2.3 Inclination Safety

Since the robot is to scale inclined surfaces, calculations needed to be done to protect the robot from attempting an inclination that would result in slipping and potentially breaking of materials. To do this, first a grip pad needed to be selected. The first choice grip pad proved to be too difficult to obtain so the backup pad was purchased through eGrips. Unfortunately, the manufacture did not include the coefficient of static friction, so tests were used to find this value. After finding the angle in which the grip pad begin slipping, the tangent was taken and determined the friction value to be roughly 1.3.

The next step was to analyze the robot at an inclination. A free body diagram of this can be seen in fig. 7. The diagram is simplified showing the parallel and vertical weight summed for all three blocks.

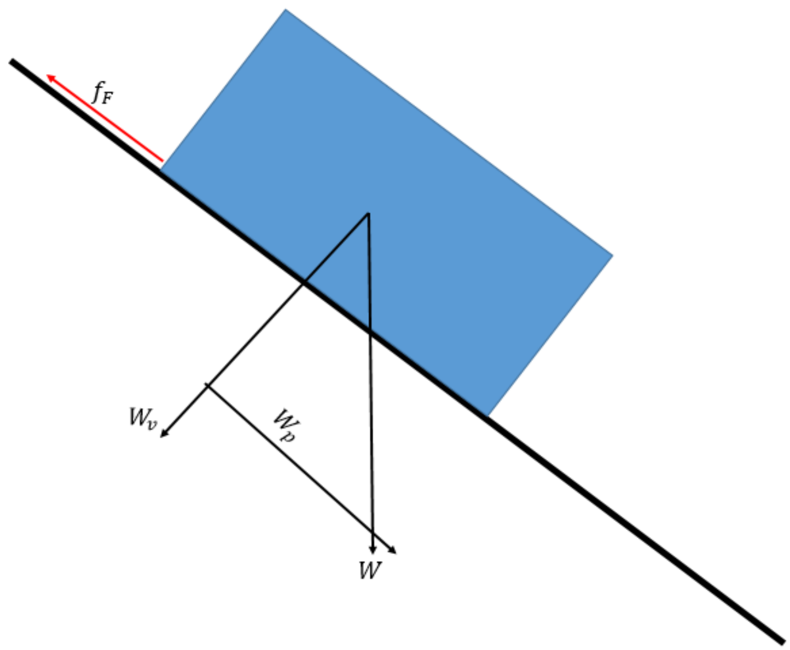


Figure 7: Inclination Analysis

It was determined that the force of friction would have to be greater than the parallel weight in order to keep the block from slipping. The team decided to analyze a variety of angles to determine when this would occur, and can be seen in table 6.

Table 6: Friction Force vs Parallel Weight

Angle	f_F [lb.]	W_p [lb.]
40	4.4	3.1
41	4.3	3.1
42	4.2	3.2
43	4.2	3.2
44	4.1	3.3
45	4.0	3.4
46	3.9	3.4
47	3.9	3.5
48	3.8	3.5
49	3.7	3.6
50	3.6	3.7
51	3.6	3.7

52	3.5	3.8
53	3.4	3.8
54	3.3	3.9
55	3.2	3.9

As seen in this table, the parallel weight becomes greater than the friction force at roughly 50 degrees. This is when we can expect slippage, so the team will avoid having the robot climb an inclination equal to or greater than this value.

6.3 Design Refinements for Optimization

6.3.1 Overall Dimensions

In the beginning of this project the team decided each block would have the dimensions of 4” x 4” x 3”. After choosing the motors the team realized that the width of the outer blocks would have to be extended an inch to have enough room to house the servo motors as well has a place to hold a load. The team also realized that the length of the middle block would have to be extended an inch due to the dimensions of the expansion board. Since all blocks were to be equal in overall dimensions they all underwent these changes. This left the overall dimensions of each block to be 5” x 5” x 3”.

6.3.2 Bottom and Top Block Connection

Connecting the top and bottom blocks was first designed to be a snap fitting. This was later changed to a screw design to prevent the snap fittings from breaking when putting on and taking off the top block. The screw design also underwent some changes as far as how many screws would be used to connect the blocks. It was first drawn out to hold four screws, one for each corner, but was then realized that having screws placements on the corners would interfere with the servo motors center position. To avoid this, the team decided to have two screw locations at the center of the block on the inside of the walls.

7. Prototype Fabrications

7.1 Fabrication Method

Many of the parts implemented in this design were 3D printed out of PLA and were printed via an Ultimaker 3D printer. The printing of these parts depended on size and took anywhere from 2 to 15 hours for completion. Roughly 20% of these parts needed to be filed down with sandpaper to meet tolerances and specifications. This is due to a set feature within the 3D printer that prints braces to help stabilize the desired part.

The only parts not fabricated were the servo motors, microcontroller, expansion board, Bluetooth receiver, grip pads, and ball transfer units. The servo motors, microcontroller, Bluetooth receiver, and expansion board were all purchased through Robotis. The ball transfer unit was purchased and manufactured by a company called Omnitrack. Finally, the grip pads were purchased through the cell phone parts manufacturing company eGrips.

7.2 Assembly method

All three lower block segments had to be tapped to ensure a quality bind when screwing into the block. The figure below demonstrates how this process was done.

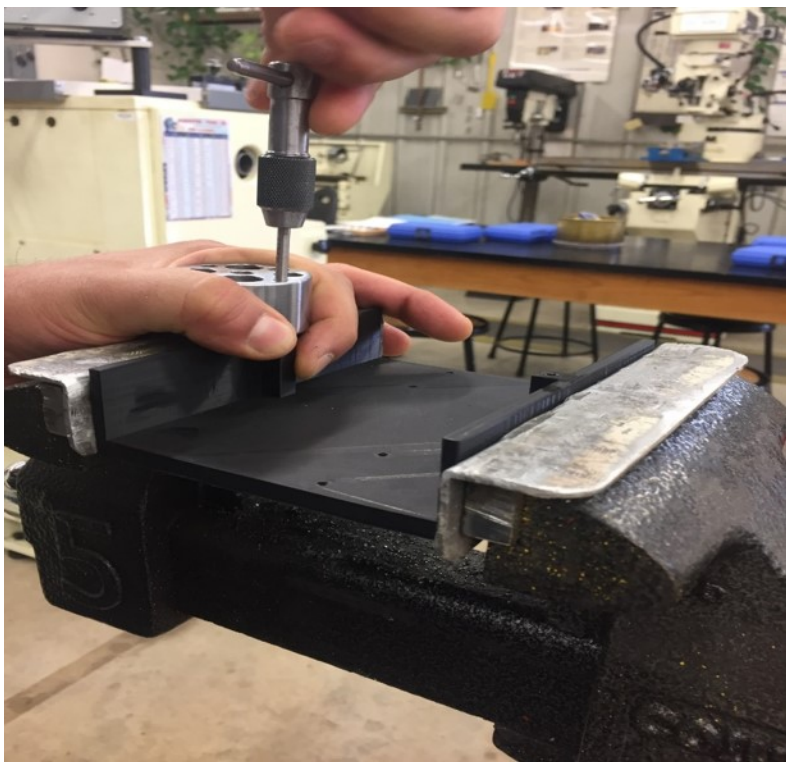


Figure 8: Tapping Holes on Bottom Block

With the holes tapped, the top and bottom block can now be connected when need be. Other assembly involved screwing in the servo brackets into bottom blocks. Once this was accomplished the servo motors could then be attached to the brackets to prevent movement during operation. Connecting the servo arms to the servo motors was done by screwing in screws through the arm to connect to the holes on the servo motor. Finally, the servo arms could be connected to the hinges of the middle block by press fits. A detailed outline of how assembly is accomplished can be read in Appendix A.

7.3 Drawings

A detailed drawing package can be seen in Appendix D. This appendix displays the overall assembled robot, subassemblies, and each manufactured part. Each manufactured part located in this appendix gives detailed instructions on how each part is to be created. This also contains tolerances that need to be met to ensure proper movement of the robot. The subassembly section presents two subassemblies, one for the lifting of the robot and the other for disengaging of the grip pads. In these subassemblies detailed instructions are given on what parts are needed as well as how to assemble each assembly.

7.4 Bill of Materials

Table 7: Bill of Materials

Part	Cost
Dynamixel Servo Motors	$379.6
Motor Shield	$29.90
Roller Bearings	$7.00
OpenCm9.04 Microcontroller	$19.90
Grip Pads	$13.95
3D Printed Parts	$15
BT-210 Bluetooth Receiver	$32.90
Test Apparatus	$20.00
Total:	$418.25

8. Prototype Testing

8.1 Test Plan Summary

All testing took place in the RAM Laboratory, located on the main campus of UTSA. Various tests were performed to determine if the prototype was capable of delivering all set goals made prior to building. This included testing on both leveled and inclined surfaces as well as motor performance.

These tests were performed over a two week interval and a detail overview of all test results can be seen in Appendix C. Meanwhile Appendix B describes why these tests were conducted and how the team had intended on performing these tests.

8.2 Test Setup

8.2.1 Motor Tests

The Dynamixel AX-18A's was mainly evaluated on lifting a load of 2lbs or more. To test this parameter, the engineers wrote a script on the Robotis IDE to rotate the bar hinge up and down, and example can be seen in fig. 9. The engineers began testing the motor load capacity at a fairly light load up to fail state, where the Dynamixel servos could not perform the written task under a higher load.

```
void setup() {
  Dxl.begin(3);
  Dxl.jointMode(1); //Allows motor one to move to positions

}

void loop() {
  Dxl.setPosition(1,512, 100); //motor, position, speed
  delay(1000);                 //wait one second
  Dxl.setPosition(1,700, 100);
  delay(1000);

}
```

Figure 9: Code to Lift

To test this load, a container was utilized so that additional weight could be added periodically. A string was then attached from the bucket to the servo motor through a hole on the servo arm. Once the desired weight was added, the motor was turned on to determine if the motor was strong enough carry that set load. This set up can be observed in the figure below.

Figure 10: Motor Testing

8.2.2 Leveled Testing

To ensure that the forward movement of the robot met the required velocity, the engineers of Enervate tested the robot's speed on a leveled table using a timer and a labeled surface. To test the speed, a code that can be seen in fig. 11, was utilized.

```
void loop()  {

  Dxl.setPosition(1, cent, 1023);
  Dxl.setPosition(2, cent, 1023);
  Dxl.setPosition(3, cent, 1023);
  Dxl.setPosition(4, cent, 1023);

  // motor, position, speed
  Dxl.setPosition(1, down, 500); //lifts front block
  delay(500);

  Dxl.setPosition(2, 660,500); //lifts middle seg
  Dxl.setPosition(3, 368,500); //lifts middle seg
  delay(500);

  Dxl.setPosition(1, cent,500); //returns outer arm back up
  delay(500);

  Dxl.setPosition(4, down,500); //lifts back block
  delay(500);

  Dxl.setPosition(2, cent,500); // puts down middle
  Dxl.setPosition(3, cent,500); //puts down middle
  delay(500);

  Dxl.setPosition(4, cent,500); //puts down bottom block
  delay(1000);
}
```

Figure 11: Full Cycle Code

The surface that was used to test the linear velocity is labeled by increments of one inch up to 12 inches as shown in fig. 12. The end block of the robot was placed on the starting side of the labeled table and was ran until the same end block crossed the one-foot indicator. As the inchworm robot crossed the first indicator till the last indicator, a timer was recording the time to calculate the velocity. These procedures were repeated ten more times to obtain the average linear velocity.

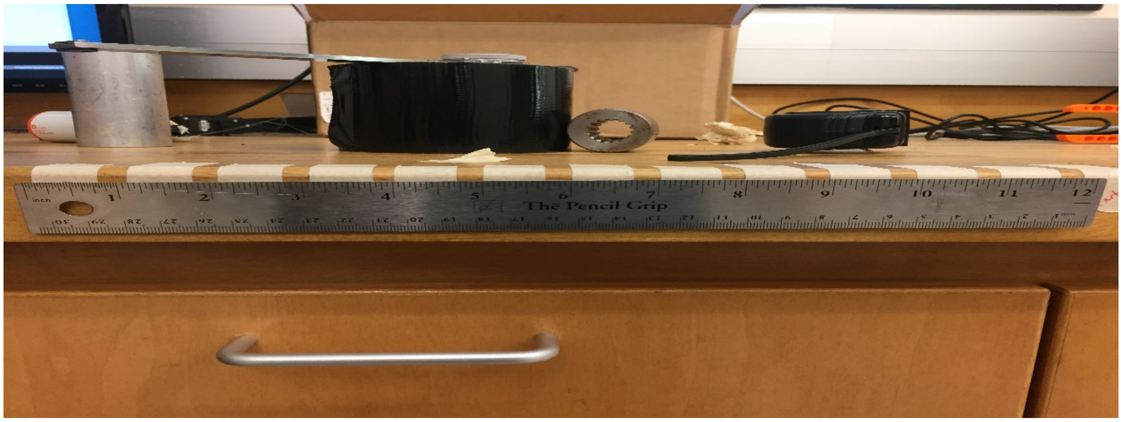


Figure 12: Inch Increments for Linear Speed Tests

8.2.3 Inclination Testing

The robot's capabilities of scaling incline was also evaluated along with the examinations done on a level surface. Following the same procedures for testing linear velocity and range, the inchworm robot went under a series trials on an incline apparatus, shown in fig. 13, to test the robot's speed, range and capability on an incline surface.

Figure 13: Incline Testing Apparatus

Before tests were started, the apparatus was marked on one-foot, seen in fig. 13. Then, the robot was placed on the incline surface and controlled to move forward to the edge of the apparatus. This process was done over steps of inclination until the robot was not capable of scaling any further. The apparatus possessed foot marks to help determine the overall speed and can be seen on fig. 14.

Figure 14: Inclined Foot Marks

8.3 Test Results

Observed in table 8, it can be seen that Enervate passed all testing except for one, inclination testing. Table 9 shows the recorded values for each test and if this was an acceptable outcome. A detailed table of all other tests that were conducted can be seen in Appendix C.

Table 8: Overall Test Results

Item No.	**Feature to be Tested**	**Specification Ref. in Appendix A**	**Testing or Verification Procedure**	**Pass or Fail**
1	Segment Length	1	Ruler (Pass or Fail)	Pass
2	Overall Length	4	Ruler (Pass or Fail)	Pass
3	Segment Width	2	Ruler (Pass or Fail)	Pass
4	Segment Height	3	Ruler (Pass or Fail)	Pass
5	Lifted Height	6	Ruler (Pass or Fail)	Pass
6	Overall Weight	5	Scale (Pass or Fail)	Pass

7	Inclination	7	Incline Apparatus (Pass or Fail)	Fail
8	Minimum speed	8	Speed Apparatus (Pass or Fail)	Pass
9	Distance	9	Ruler (Pass or Fail)	Pass

Table 9: Physical and Functional Test Matrix

Parameters	Recorded Value	Required Value	Pass/Fail
Overall Length		3 feet	pass
Segment Width	4 inches	4 Inches	pass
Segment Height	5 inches	5 Inches	pass
Segment Length	5 inches	5 Inches	pass
Lift Power	4 lbs.	2 lbs.	pass
Range	10 feet	3 Feet	pass
Min. Inclination	20 Degrees	45 Degrees	fail
Min. Speed	4 inches per Sec	0.4 Inches per Sec	pass
Max. Weight	1 lb. 9 oz.	8 lbs.	pass

9. Program Management

9.1 Personnel

- **Anthony Abundis** – *Design Engineer*

Anthony was in charge of overseeing the design of this project. He ensured all designs made or changed did not affect the robot's ability to perform.

- **Flavio Moreira –** *Project Engineer*

Flavio was in charge of the overall project. This meant assigning duties to each member as well holding them labial to completion. Although the team may vote on a particular subject, his vote can over throw a tie.

- **Justin Castillo –** *Analyst Engineer*

Justin is in charge of all analysis for the project. His job is to analytically determine how the robot will perform based off various parameters. He also took charge of the scheduling and is the reason the team stayed on schedule.

- **Michael Aguirre –** *Production Engineer*

Michael is in charge of all production dealing with the project. He was dealt with the fabrication and assembly of the robot to make certain the robot functions as a whole unit.

9.2 Overall Schedule (including ME 4812 and ME 4813)

9.2.1 Assigned Tasks

Below is a complete view of our Gantt chart for senior design 1 & 2. Critical deliverables are shown with the percent complete for each task. Important key resources for the success of our project can be seen below. Each resource was allocated depending on the task and had a corresponding cost per unit time.

- Engineer
- Engineer A
- Engineer F
- Engineer J
- Engineer M
- Laborer
- Machine Shop
- Polylactic Acid
- Secretary
- Senior Project Manager
- Technician
- Senior Engineer

The Engineer was a general resource used for the purpose of completing analysis, research, and design for the project. Engineer (A, F, J, M) correspond to the different engineers working on the project. Engineer A-Anthony Abundis, F-Flavio Moreira, J-Justin Castillo, M-Michael Aguirre. During the course of senior design 1, the Engineer resource was used on allocated tasks where the success was driven by all team members. During senior design 2, at the bottom of the Gantt chart, we see individual representation of engineer assigned to different tasks. The laborer was responsible for purchasing and transporting materials where needed. The UTSA Machine shop resource was used when professional help or tools were needed for our project. Polylactic Acid was the primary material used for our projects body shell. The secretary was used to provide support on timesheets, reports, and scheduling. The technician was used to provide help during the assembly and mock drawings for concept designs. The senior engineer (Dr. Bhounsule) was used to tackle the responsibility of providing support and feedback for our project when needed. The final resource was the senior project manager (Dr. James Johnson). Also, this resource was used to provide lecture support and guidance on our project, feedback on progress, major key deliverables grading, presentation feedback, and meeting updates, which were all key elements to the success of our project.

GANTT CHART

	Task Name	Total Cost	Qtr 1, 2017 – Qtr 4, 2017 (Jan–Nov)
0	**Project1ganttchart**	**$461,163.27**	
1	Team Enervate (Inchworm Robot)	$0.00	
2	**Senior Design 1**	**$135,668.27**	Senior Design 1
3	**Senior Design 1 Tasks**	**$135,668.27**	
4	**Meetings**	**$2,250.00**	Meetings
5	Meeting 1 : Discuss Three Potential Project Ideas	$187.50	1/31
6	Meeging 2: Discuss Choosen Project	$187.50	2/7
7	Meeting 3: Discuss Work Packet 2 + Review over Work Packet 1	$187.50	2/13
8	Meeing 4: Discuss 2 Alternative Design Solutions	$187.50	2/21
9	Meeting 5: Discussed Preliminary Design Concept	$187.50	2/28
10	Meeting 6: Reviewed PowerPoint for Midterm Presentation	$187.50	3/6
11	Meeting 7: Discuss Plan for Fabrication	$187.50	3/20
12	Meeting 8: Discuss Test Plans	$187.50	3/27
13	Meeting 9: Review and Assesment of Poster for TechSymposium	$187.50	4/3

GANTT CHART

	Task Name	Total Cost	Qtr 1, 2017 – Qtr 4, 2017 (Jan–Nov)
14	Meeting 10: Discussed Work Packet 7/ Gantt Chart	$187.50	4/10
15	Meeting 11: Discuss Final Presentaion Advice	$187.50	4/17
16	Meeting 12: Discuss Setup for TechSymposium	$187.50	4/24
17	**Assignments(100%)**	**$5,180.00**	Assignments(100%)
18	Assignment 1: 25 Unique Senior Design Projects	$1,620.00	Secretary
19	Assignment 2: Compressed Air Powered Rocket	$3,200.00	Engineer
20	Assignment 3: Project Schedual Gantt Chart	$360.00	Secretary
21	**Work Packets-(100%)**	**$60,755.00**	Work Packets-(100%)
22	**Work Packet 1: Team Formation**	**$1,980.00**	
23	Identify Each Team Member	$180.00	Secretary
24	Criteria for Member Selection	$180.00	Secretary
25	Team Goals	$270.00	Secretary
26	Team Name	$630.00	Secretary
27	Team Logo	$630.00	Secretary
28	Formal Signed Statme	$90.00	Secretary
29	**Work Packet 2: Identification of The Design Problem**	**$7,055.00**	
30	Identify the design problem	$800.00	Engineer
31	Identify Functional Requirments	$3,200.00	Engineer

GANTT CHART

Qtr 1, 2017 (Jan, Feb, Mar) · Qtr 2, 2017 (Apr, May, Jun) · Qtr 3, 2017 (Jul, Aug, Sep) · Qtr 4, 2017 (Oct, Nov)

	Task Name	Total Cost	Resource
32	Develop Prelimanry Specifications	$1,400.00	Engineer
33	Identify Supporting Faculty	$800.00	Engineer
34	Discuss Team Strengths to Solve	$180.00	Secretary
35	Discuss Team Weaknesses	$45.00	Secretary
36	Summarize 25 Patents related to	$630.00	Secretary
37	**Work Packet 3: Performance Specifications**	**$17,400.00**	
38	Define Functional Requirments for	$1,400.00	Engineer
39	Define Specification for Project	$2,000.00	Engineer
40	Present Min of 3 Soln to Project	$14,000.00	Engineer
41	**Work Packet 4: Fabrication Plan of Selected Concept**	**$5,040.00**	
42	Develop Fabrication Plan of Selected Concept for Project	$3,600.00	Secretary
43	Write Report for WP4	$1,440.00	Secretary
44	**Work Packet 5: Detailed Analysis of Selected Concept**	**$17,440.00**	
45	Detailed Analysis of Selected Concept	$16,000.00	Engineer
46	Report for WP5	$1,440.00	Secretary
47	**Work Packet 6: Test Plan for Demonstrating Specifications Satisfied**	**$3,200.00**	

GANTT CHART

Qtr 1, 2017 (Jan, Feb, Mar) · Qtr 2, 2017 (Apr, May, Jun) · Qtr 3, 2017 (Jul, Aug, Sep) · Qtr 4, 2017 (Oct, Nov)

	Task Name	Total Cost	Resource
48	Develop Test Plan for Project/List of Insturments Needed for Project	$3,200.00	Engineer
49	**Work Packet 7: Detailed Gantt Chart**	**$3,600.00**	
50	Detailed Gantt Chart For SD1&SD2	$3,600.00	Secretary
51	**Work Packet 8: Detailed Outline of Final Report**	**$1,440.00**	
52	Detailed Outline of Final Report	$1,440.00	Secretary
53	**Work Packet 9: Detailed Labor and Material Cost**	**$3,600.00**	
54	Detailed Labor and Material Estimate	$3,600.00	Secretary
55	**Minutes**	**$2,160.00**	Minutes
56	Minutes 1 - Reflection of 3 Project Ideas	$180.00	Secretary
57	Minutes 2 - Reflection of Choosen Concept and Meeting	$180.00	Secretary
58	Minutes 3 - Reflection of Work Packet 1 and Meeting	$180.00	Secretary
59	Minutes 4: Reflection of 2 Alternative Design Concepts + Meeting	$180.00	Secretary
60	Minutes 5: Reflection of Prelimanry Design Concept + Meeting	$180.00	Secretary

GANTT CHART

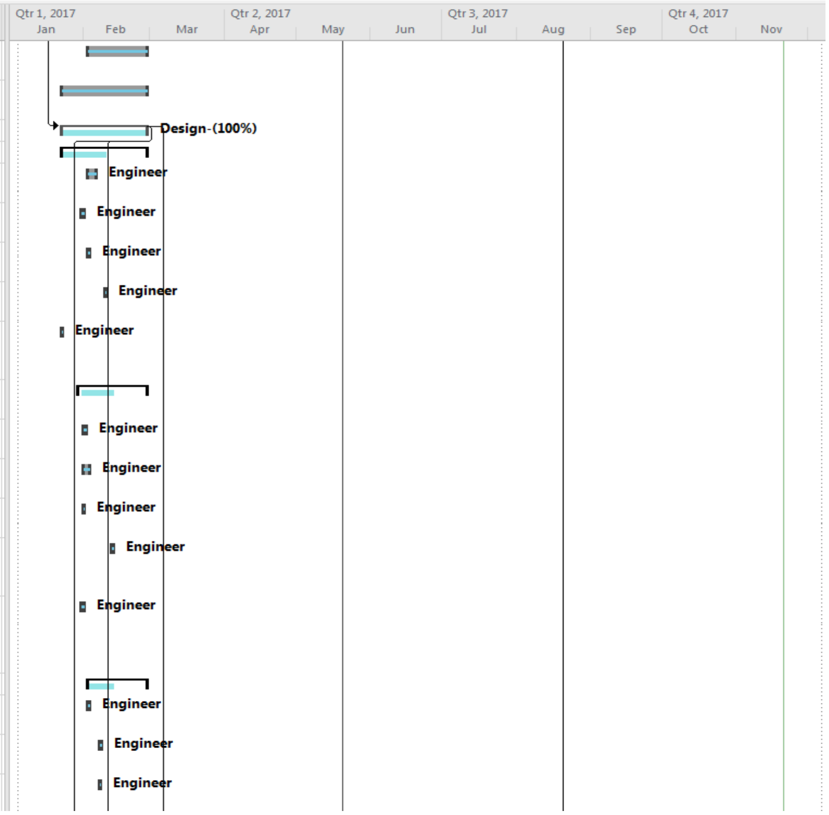
	Task Name	Total Cost	Qtr 1, 2017 – Qtr 4, 2017 (Jan–Nov)
61	Minutes 6: Reflection of Advice for Mideterm Presentation	$180.00	Secretary
62	Minutes 7: Reflection of Fabrication Plan + Meeting	$180.00	Secretary
63	Minutes 8: Reflection of Test Plan + Meeting with Evil Triad	$180.00	Secretary
64	Minutes 9: Reflection of Poster Draft + Meeting	$180.00	Secretary
65	Minutes 10: Reflection of WP7 + Meeting	$180.00	Secretary
66	Minutes 11: Reflection of Final Presentation + Meeting	$180.00	Secretary
67	Minutes 12: Reflection of Setup for TechSymposium + Meeting	$180.00	Secretary
68	**Time Sheets**	**$675.00**	Time Sheets
69	Time Sheet 1 - Indiviudal Time Sheets	$45.00	Secretary
70	Time Sheets 2	$45.00	Secretary
71	Time Sheet 3	$45.00	Secretary
72	Time Sheet 4	$45.00	Secretary
73	Time Sheet 4	$45.00	Secretary
74	Time Sheet 5	$45.00	Secretary
75	Time Sheet 6	$45.00	Secretary

GANTT CHART

	Task Name	Total Cost	Qtr 1, 2017 – Qtr 4, 2017 (Jan–Nov)
76	Time Sheets 7	$45.00	Secretary
77	Time Sheets 8	$45.00	Secretary
78	Time Sheets 9	$45.00	Secretary
79	Time Sheets 10	$45.00	Secretary
80	Time Sheets 11	$45.00	Secretary
81	Time Sheets 12	$45.00	Secretary
82	Time Sheets 13	$45.00	Secretary
83	Time Sheets 14	$45.00	Secretary
84	**Presentations(100%)**	**$6,000.00**	Presentations(100%)
85	**Presentation 1: Team Introductions**	**$800.00**	
86	Making the Power Po	$800.00	Engineer
87	**Presentation 2: Project Introductions**	**$800.00**	2/27
88	Preparing the Power Point	$800.00	Engineer
89	**MidTerm Presentation**	**$2,800.00**	3/8
90	Preparing the Midterm	$2,800.00	Engineer
91	**Presentation 3: Fabrication Plan**	**$800.00**	3/24
92	Preparing Presentatic	$800.00	Engineer
93	**Presentation 4: Detailed Analysis of**	**$800.00**	4/12
94	Preparing Presentatic	$800.00	Engineer
95	**Project Background**	**$2,500.00**	Project Background
96	**Meetings With Dr. Bhounsule**	**$300.00**	
97	Project Idea from Dr. Bhounsule	$300.00	Senior Engineer
98	**Research on Inchworms**	**$2,200.00**	
99	Gait Analysis Research	$2,200.00	Engineer
100	**Conceptualization of Project**	**$0.00**	
101	Purpose	$0.00	

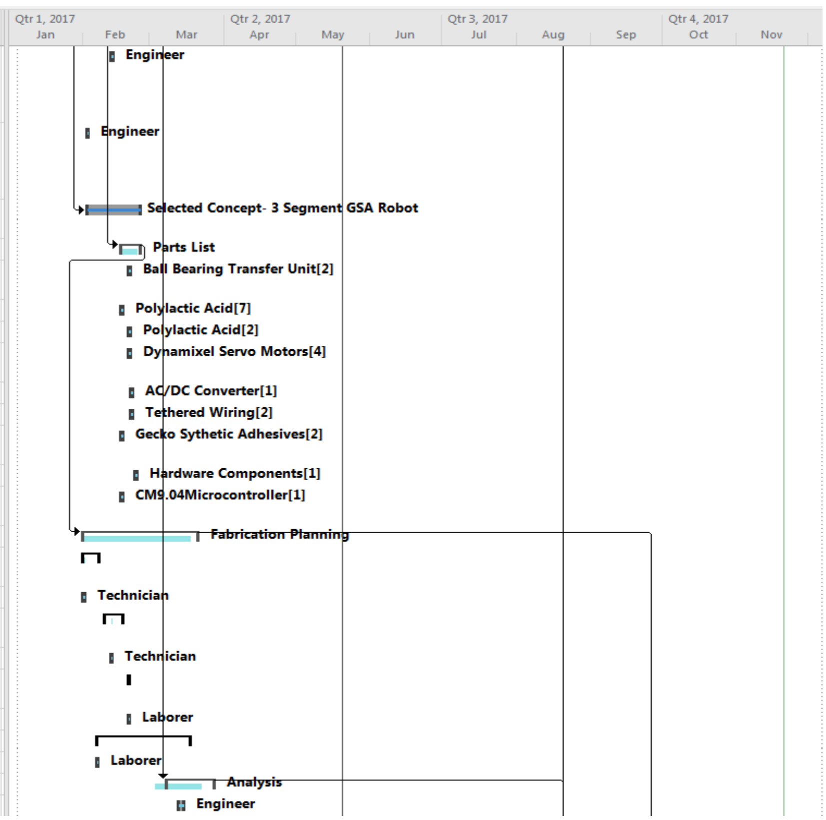
GANTT CHART

	Task Name	Total Cost
102	Performance Specifications	$0.00
103	Design Specifications	$0.00
104	**Design-(100%)**	**$24,800.00**
105	**SMA Robot**	**$8,200.00**
106	Material Selection	$1,800.00
107	SolidWorks Modeling	$2,800.00
108	Dimensioning Phase	$1,400.00
109	Sanity Checking for SMA Robot	$800.00
110	Team Collaboration for SMA Robot	$1,400.00
111	**Gecko Sythetic Adhesive 3 Segment**	**$11,600.00**
112	Material Selection	$1,800.00
113	SolidWorks Modeling	$4,800.00
114	Dimensioning Phase	$1,400.00
115	Sanity Checking for GSA Robot	$1,200.00
116	Team Collaboration for GSA Robot	$2,400.00
117	**Suction Cup Robot**	**$5,000.00**
118	Material Selection	$1,000.00
119	SolidWorks Modeling	$1,600.00
120	Dimensioning Phase	$800.00



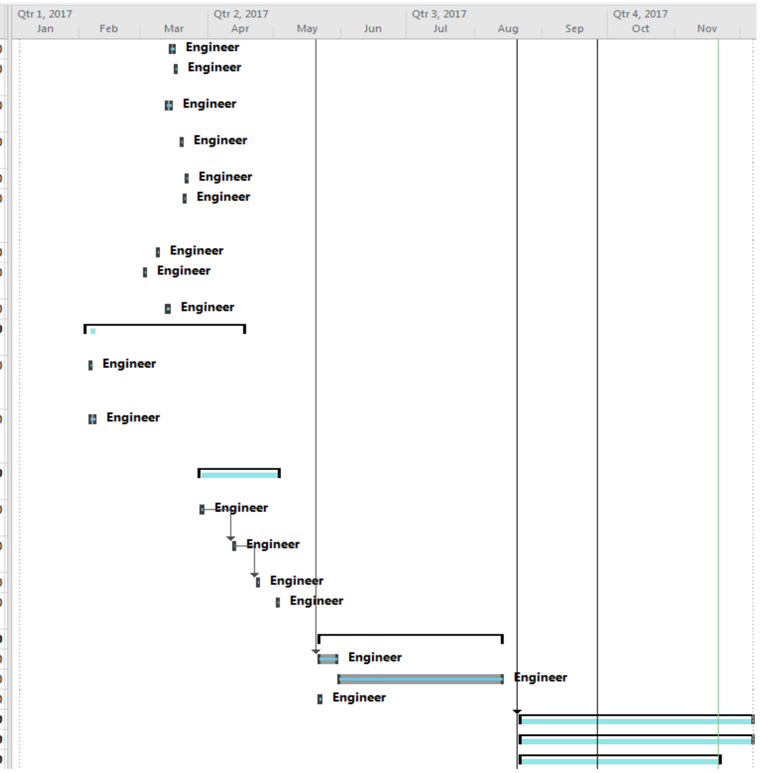
GANTT CHART

	Task Name	Total Cost
121	Sanity Chekcing for Suction Cup Robot	$1,000.00
122	Team Collaboration for Suction Cup Robot	$600.00
123	**Selected Concept- 3 Segment GSA Robot**	**$0.00**
124	**Parts List**	**$1,248.27**
125	Ball Bearing Transfer Unit	$64.36
126	Polylactic Acid	$104.93
127	Servo Arms	$29.98
128	Dynamixel Servo Motors	$179.60
129	AC/DC Conveter	$24.50
130	Tethered Wire	$20.00
131	Gecko Synthetic Adhesives	$800.00
132	Hardware Components	$5.00
133	CM9.04 Microcontroller	$19.90
134	**Fabrication Planning**	**$5,700.00**
135	**Body Material - Polylactic Acid**	**$1,200.00**
136	3-D Printing Process	$1,200.00
137	**Ball Bearing Transfer Unit**	**$3,600.00**
138	OmniTrack	$600.00
139	**Dynamixel Ax-12A Motors**	**$750.00**
140	Trossen-robotics	$300.00
141	**AC/DC Converter**	**$150.00**
142	TechOrbitz	$150.00
143	**Analysis**	**$16,000.00**
144	GSA Friction	$3,400.00



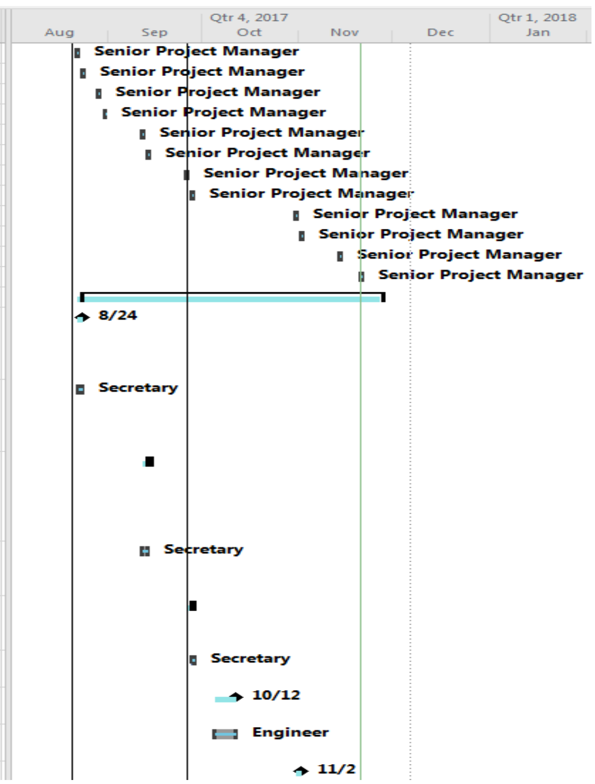
GANTT CHART

	Task Name	Total Cost
145	Velocity of Robot	$2,400.00
146	Torque Output of Motors	$800.00
147	Static/Dynamic Analysis	$3,400.00
148	Inclined Friction for GSA	$800.00
149	Inclined Velocity	$400.00
150	Inclined Static/Dynamic Analysis	$800.00
151	Circuit Diagram	$1,000.00
152	Control System Diagram	$800.00
153	Gait Analysis	$2,200.00
154	**SolidWorks Modeling Tasks To Be Done**	**$6,200.00**
155	Develop Detailed Drawing of All Connections	$2,800.00
156	Develop Drawing of All Hardware Components	$3,400.00
157	**Final Tasks For SD1-(100%)**	**$2,200.00**
158	**Presentation Poster-(100%)**	$1,400.00
159	**Setup for Tech Symposium**	$200.00
160	**Tech Symposium**	$400.00
161	**Turn in Final CD-(100%)**	$200.00
162	**Summer Tasks**	**$31,600.00**
163	Read Ansi Y14.1	$9,600.00
164	Work on Drawing Package	$18,000.00
165	Test Motors	$4,000.00
166	**Senior Design 2**	**$293,895.00**
167	**Senior Design 2 Tasks**	**$293,895.00**
168	**Class Meetings For SD-2**	**$2,250.00**



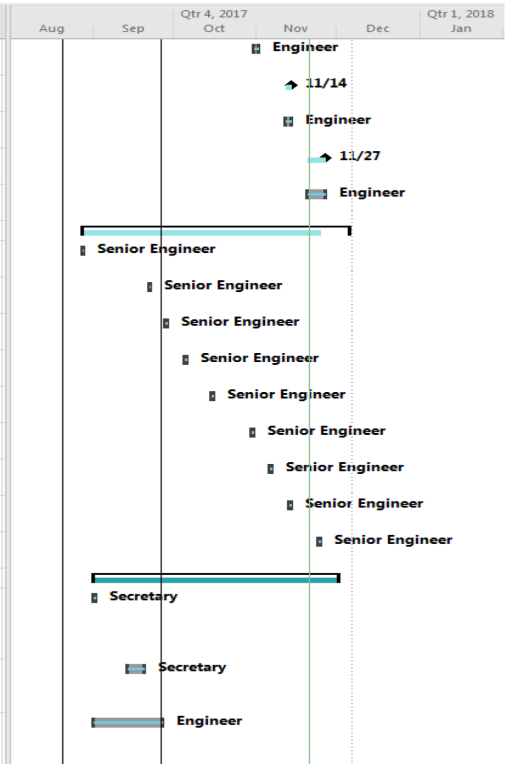
GANTT CHART

	Task Name	Total Cost
169	Class Meeting 1	$187.50
170	Class Meeting 2	$187.50
171	Class Meeting 3	$187.50
172	Class Meeting 4	$187.50
173	Class Meeting 5	$187.50
174	Class Meeting 6	$187.50
175	Class Meeting 7	$187.50
176	Class Meeting 8	$187.50
177	Class Meeting 9	$187.50
178	Class Meeting 10	$187.50
179	Class Meeting 11	$187.50
180	Class Meeting 12	$187.50
181	**Presentations-(100%)**	**$13,970.00**
182	**ICP1 : Accomplishments Over Summer Break**	**$810.00**
183	Preperation for Presentation 1	$810.00
184	**3 Min Verbal Progress Report ICP2**	**$3,040.00**
185	Progress Report Setup	$1,440.00
186	**ICP3: Accomplishments to Date**	**$2,320.00**
187	Powerpoint Setup Presentation 2	$720.00
188	**Midterm Presentation**	**$2,800.00**
189	Setup Presentation for Midterm	$2,800.00
190	**5 Min Progress Report**	**$800.00**



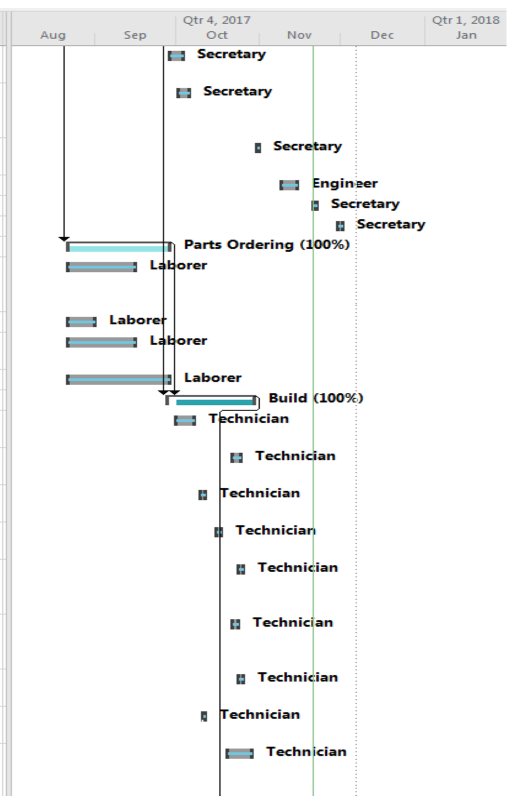
GANTT CHART

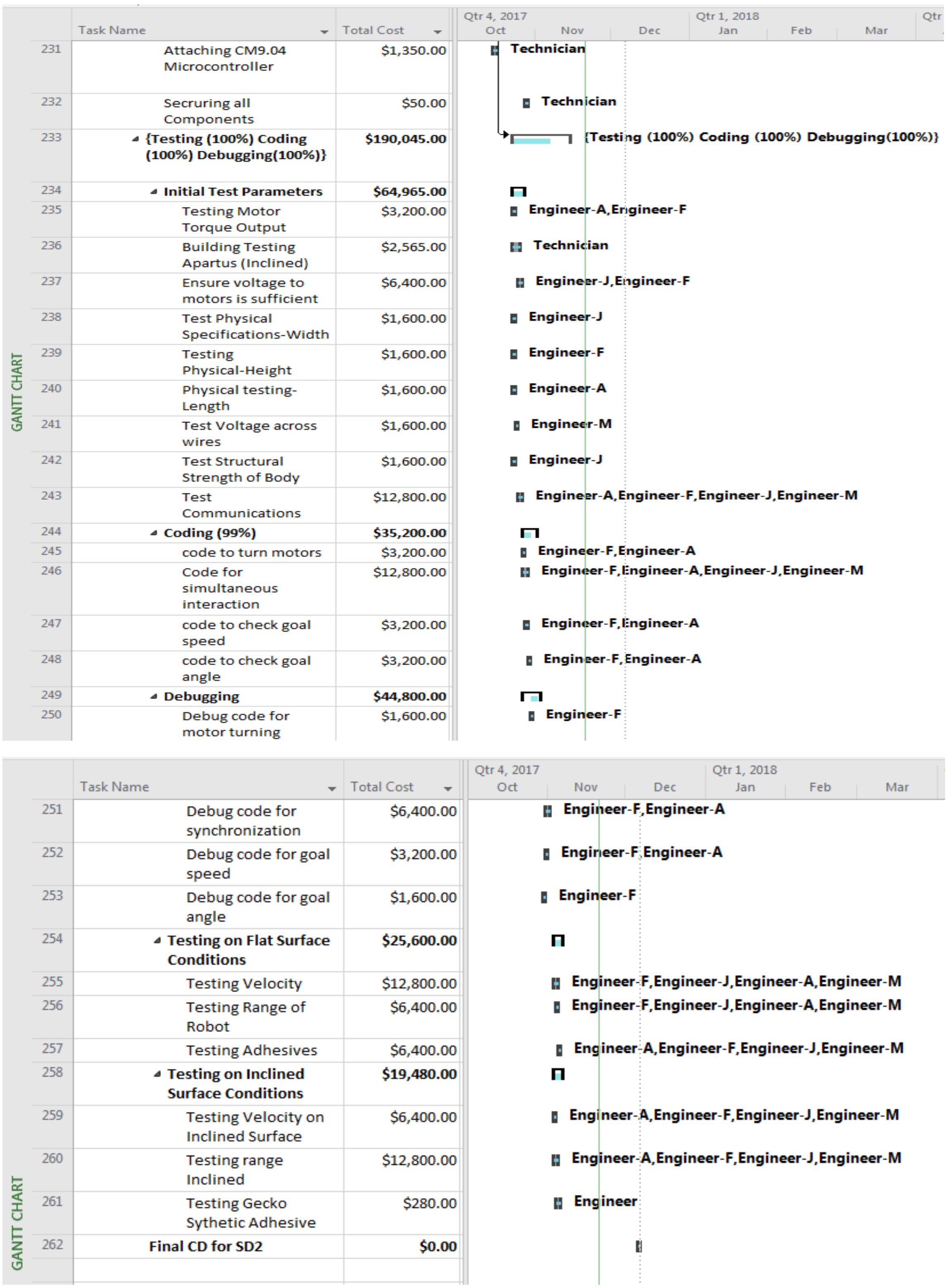
	Task Name	Total Cost
191	Powerpoint Setup for Progress Report	$800.00
192	**4 Min Progress Report**	**$800.00**
193	Powerpoint Setup for Progress Report	$800.00
194	**Final Presentation SD2**	**$3,400.00**
195	Final Presentatioin Powerpoint Setup	$3,400.00
196	**Mentor Meetings**	**$17,400.00**
197	Mentor Meeting 1	$300.00
198	Mentor Meeting 2	$300.00
199	Mentor Meeting 3	$2,400.00
200	Mentor Meeting 4	$2,400.00
201	Mentor Meeting 5	$2,400.00
202	Mentor Meeting 6	$2,400.00
203	Mentor Meeting 7	$2,400.00
204	Mentor Meeting 8	$2,400.00
205	Mentor Meeting 9	$2,400.00
206	**Reports-(100%)**	**$47,530.00**
207	Summer Progress Report: SR1	$720.00
208	Theory of Operations Report	$2,880.00
209	Drawing Package Report	$28,800.00



GANTT CHART

	Task Name	Total Cost
210	Test Plan Outline	$2,160.00
211	September Progress Report	$3,600.00
212	October Progress Report	$720.00
213	Test Plan Report	$6,400.00
214	Draft of Final Report	$900.00
215	Final Report	$1,350.00
216	**Parts Ordering (100%)**	**$300.00**
217	Dynamixel Ax-18 Servo Motors	$75.00
218	AC/DC Converter	$75.00
219	Ball Bearing Transfer Unit	$75.00
220	Adhesive grip pads	$75.00
221	**Build (100%)**	**$22,400.00**
222	3-D Printing of Body Shell	$8,400.00
223	3-D Printing of Servo Arms	$3,450.00
224	3-D Printing Transfer unit Attachment	$1,200.00
225	3-D Printing of L-Bar	$1,350.00
226	Attaching Motors to Exact Locations	$600.00
227	Attaching Servo Arms to Body Segments	$750.00
228	Attaching L-Bar to Motors	$450.00
229	Attaching CM9.04 to Body	$1,200.00
230	Wiring of Motors and Tethered Battery	$3,600.00



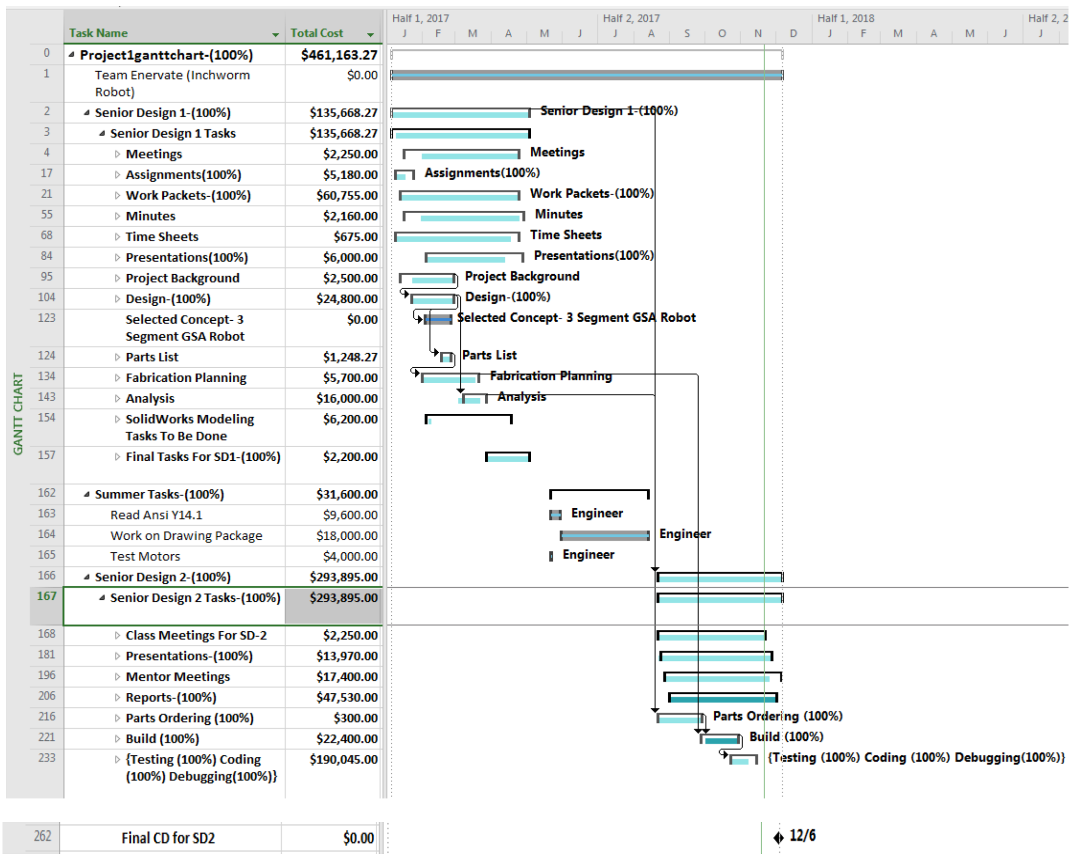


	Task Name	Total Cost	Resource Names
231	Attaching CM9.04 Microcontroller	$1,350.00	Technician
232	Securing all Components	$50.00	Technician
233	{Testing (100%) Coding (100%) Debugging(100%)}	$190,045.00	{Testing (100%) Coding (100%) Debugging(100%)}
234	Initial Test Parameters	$64,965.00	
235	Testing Motor Torque Output	$3,200.00	Engineer-A,Engineer-F
236	Building Testing Apartus (Inclined)	$2,565.00	Technician
237	Ensure voltage to motors is sufficient	$6,400.00	Engineer-J,Engineer-F
238	Test Physical Specifications-Width	$1,600.00	Engineer-J
239	Testing Physical-Height	$1,600.00	Engineer-F
240	Physical testing-Length	$1,600.00	Engineer-A
241	Test Voltage across wires	$1,600.00	Engineer-M
242	Test Structural Strength of Body	$1,600.00	Engineer-J
243	Test Communications	$12,800.00	Engineer-A,Engineer-F,Engineer-J,Engineer-M
244	Coding (99%)	$35,200.00	
245	code to turn motors	$3,200.00	Engineer-F,Engineer-A
246	Code for simultaneous interaction	$12,800.00	Engineer-F,Engineer-A,Engineer-J,Engineer-M
247	code to check goal speed	$3,200.00	Engineer-F,Engineer-A
248	code to check goal angle	$3,200.00	Engineer-F,Engineer-A
249	Debugging	$44,800.00	
250	Debug code for motor turning	$1,600.00	Engineer-F
251	Debug code for synchronization	$6,400.00	Engineer-F,Engineer-A
252	Debug code for goal speed	$3,200.00	Engineer-F,Engineer-A
253	Debug code for goal angle	$1,600.00	Engineer-F
254	Testing on Flat Surface Conditions	$25,600.00	
255	Testing Velocity	$12,800.00	Engineer-F,Engineer-J,Engineer-A,Engineer-M
256	Testing Range of Robot	$6,400.00	Engineer-F,Engineer-J,Engineer-A,Engineer-M
257	Testing Adhesives	$6,400.00	Engineer-A,Engineer-F,Engineer-J,Engineer-M
258	Testing on Inclined Surface Conditions	$19,480.00	
259	Testing Velocity on Inclined Surface	$6,400.00	Engineer-A,Engineer-F,Engineer-J,Engineer-M
260	Testing range Inclined	$12,800.00	Engineer-A,Engineer-F,Engineer-J,Engineer-M
261	Testing Gecko Sythetic Adhesive	$280.00	Engineer
262	Final CD for SD2	$0.00	

Figure 15: Assigned Tasks for Total Gant Chart

9.2.2 Overall percent complete

The overall percent complete is shown below for the entirety of our project and on critical deliverables necessary for the completion of the project. Senior design 1 is shown on the Gantt chart and all the subtasks associated with this phase of the project. Summer and Senior 2 tasks can also be seen showing each major key task associated with the project. Each task below seen on the Gantt chart is determined to be 100% complete to date.



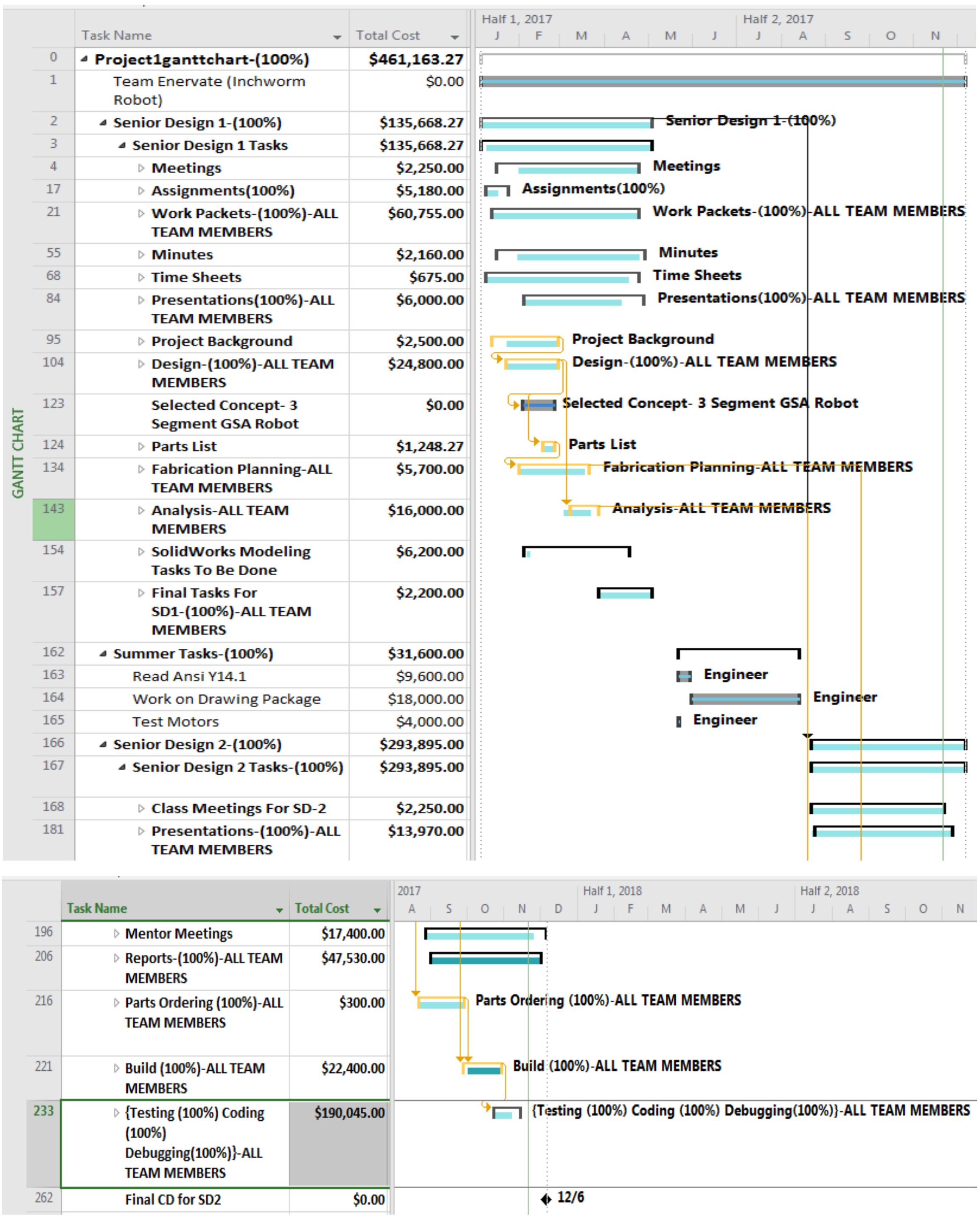


Figure 16: Overall Percent Complete of Each Tasks

9.3 Financial Performance (Including Senior 1 and Senior 2)

9.3.1 Overall Planned Cost vs. Time Compared to Actual Cost vs. Time

The overall planned cost vs time compared to the actual cost vs time, essentially represents the accuracy of our monetary prediction for the project. The X and Y axis represent the time and cost of our project on the graph below, respectively. The actual cost is represented in blue as the determined cost of Senior-1, summer, and Senior-2. The grey line represents the baseline cost or the cost associated with the predication expense of our project. The yellow line is the representation of the actual cost of the work for three major phases in the project. The remaining cost is indicated in the key cannot be seen since there was no remaining cost for the project necessary for its completion.

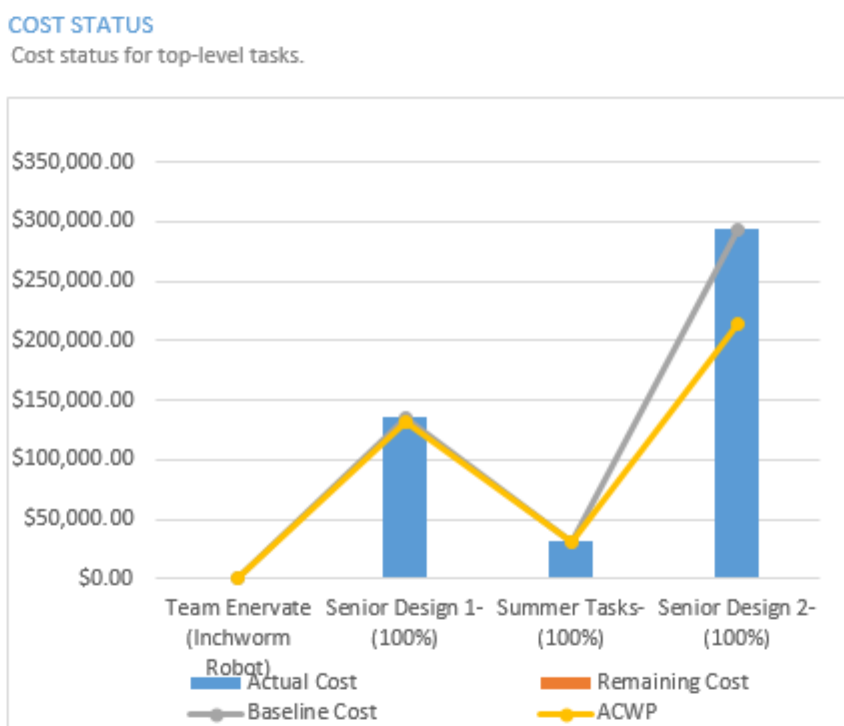


Figure 17: Planned Cost vs Time Compared to Actual Cost vs Time Graph

9.3.2 Planned Labor Cost by Task vs. Actual Labor Cost by Task

Below is the planned labor cost vs. the actual labor cost. This graph, basically represents the quarterly expenditure amount for the planned and actual labor cost. It is shown in the graph below that the planned labor cost exceeded the actual labor cost, indicating we were under budget for each quarter in the project.

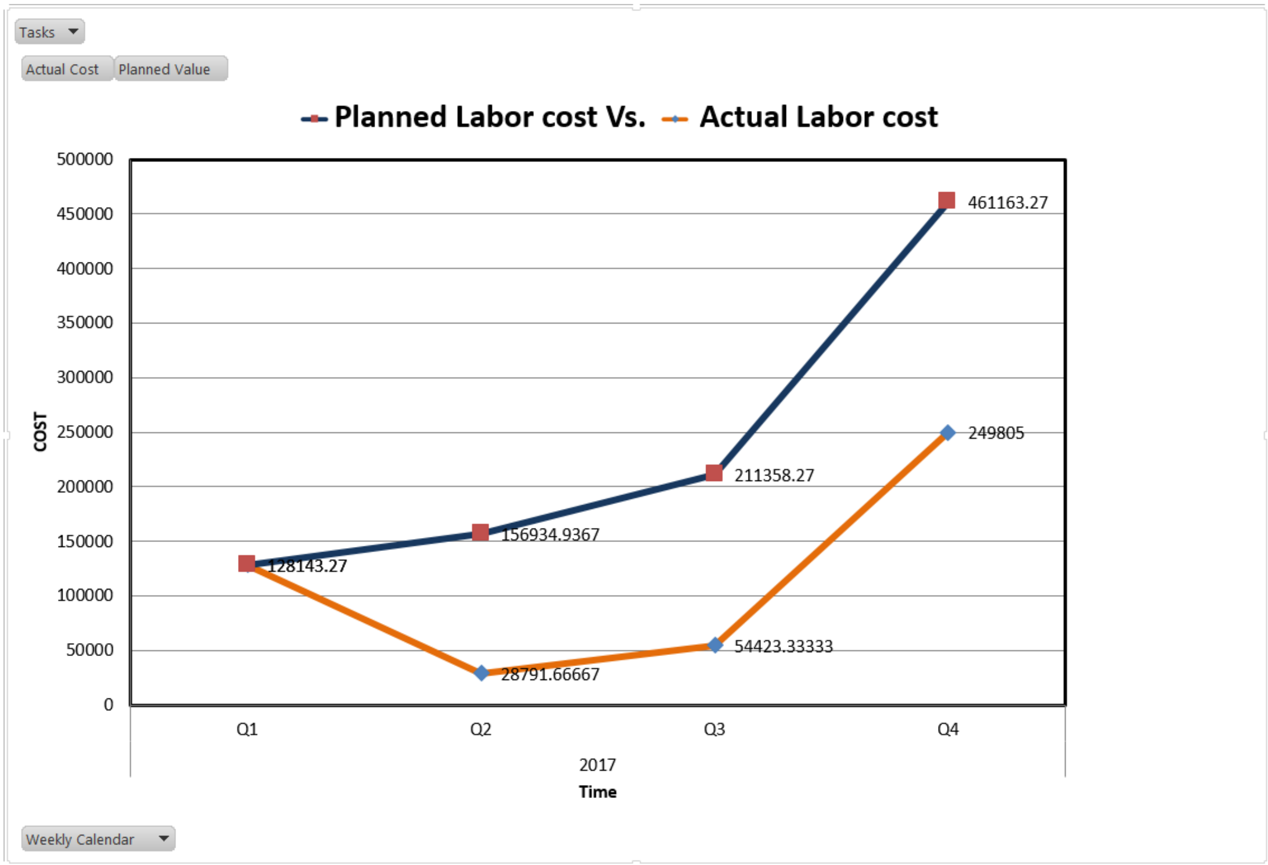


Figure 18: Planed Labor vs Actual Labor

9.3.3 Planned Material Cost vs. Actual Material Cost

The graph below represents the actual cost vs the planned cost associated with each material necessary for the construction of our robot. It can be seen how the actual material cost for the robot is far less than the predicted planned material cost. This is mostly due to finding alternative, less expensive solutions to achieve the same desired result.

The difference in the 3D printed parts are due to Dr. Bhounsule providing Polylactic Acid necessary for the 3D printing process. The only material cost associated to be higher than the planned cost were the motors. Since our client was worried about the motor output, he wanted stronger motors to ensure a properly functioning device we switched to slightly more expensive motors to mitigate this problem. The ball bearing transfer units were planned to be larger than the actual units used on the robot, which reduced the cost of this material parameter.

The major difference which caused our project to me much less than expected were the grip pads. Originally, we were going to use a gecko synthetic adhesive process estimated to cost $500. Since we found we could achieve our desired result with grip pads which were far less expensive, we opted for the transition. The other material roughly followed the same cost estimation which can be seen on the graph where the lines are close together.

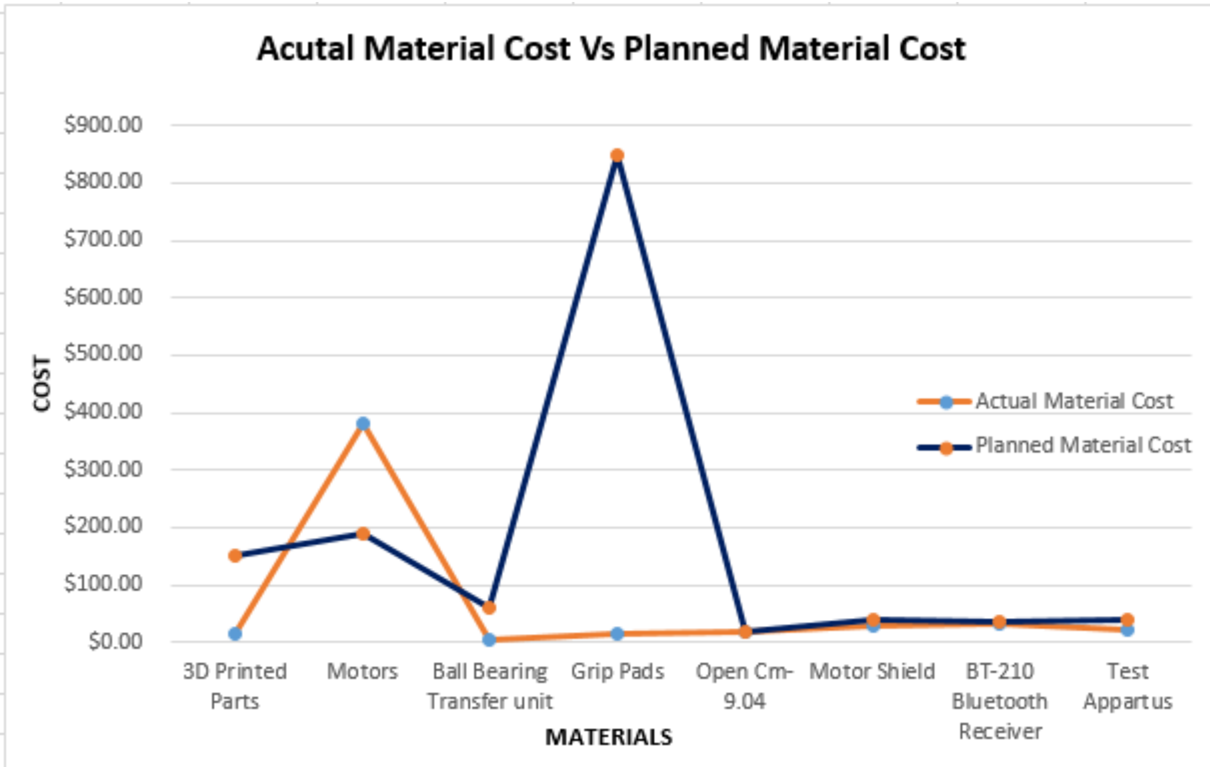


Figure 19: Actual Material Cost vs. Planned Material Cost

10. Conclusion

Enervate has successfully built an inchworm robot that has met and exceeded eight of out the nine specifications. Although this one test was failed, the team's client is still very happy with the test results. Enervate prides themselves on being one of the few teams to design and create a robot capable of scaling vertical surfaces without utilizing pneumatics, magnets, or wheels.

11. Appendix A – Operations Manual

12. Appendix B – Test Plan

13. Appendix C – Test Report

14. Appendix D – Assembly Design

References

[1] Autumn, Kellar. "Properties, Principles, and Parameters of the Gecko Adhesive System." *Biological Adhesives* (2006): 225-56. Web.

[2] Robotis. "Dyanamixel AX-18A Servo Motors." *AX-18A*, 1 Jan. 2010, www.robotis.us/dynamixel-ax-18a/

Contents

TABLES

FIGURES

1. Introduction

Testing is the act of ensuring a created product is capable of meeting pre-determined parameters. It can involve a number of different testing procedures all eventually leading up to two possible outcomes, pass or fail. Determining whether a product has passed or failed can be a little complicated depending on the product being manufactured. When products have the potential of affecting the wellbeing of species, there are strict guidelines. If the device isn't so life threating, the outcome is in the hands of the creator and the goals set performance wise. The reason society cares so much about testing products is in reliability. When purchasing a product, the first couple questions that come to mind is will this do the job, how long will this last, and how reliable is this product. This is because people enjoy getting the best bang for their buck. If the product purchased ends up failing too soon or not working properly the customer then loses interest in the product eventually letting other customers know the product is a sham. This leads to the manufacture of the product losing credibility as well as money.

2. Scope

The testing of this product will require different procedures to be conducted as well as a varying attendance of personal. In regards to testing location, an indoor environment would be sufficient, but testing can be conducted outside in a dry environment so long as the robot is still connected to a power source of 12 volts. The required amount of personal per test will vary but no more than two will ever be needed. A testing apparatus will also need to be built to test the robot's capability of scaling inclined surfaces. This will be built from wood as it is cheaper and easier to work with, but can be made with any material so long as it is still capable of changing angles. Ceramic tile will then be glued onto the incline apparatus to test the robot's ability to meet the specification of climbing an incline tile surface.

Equipment needed for testing procedures will change per test. For instance, a multimeter will be needed to measure voltage across the servo motors. All equipment needed should already be found in the RAM engineering lab so there shouldn't be a need to purchase any outside products.

3. Features to be tested

3.1. Features to be evaluated

The most important features to be tested first and foremost are the product specifications. These are the claims that enervate says the robot will meet. Other than the physical and functional specifications, Team Enervate will also do extensive testing with the software of the robot. Different code sequences such as synchronized movements, movement speeds, and timing of motion need to be tested and tweaked to insure proper gait motion of the robot. The coding of the robot is arguably the most important part of the robot. Ensuring the code is bug-free and operational will lead to a better final product. Along with code testing, a data analysis utilizing the software serial print data will be done to find values of power, voltage, torque, and other electrical parameters.

3.2. Compliance Matrix

Table 1: Compliance Matrix

Item No.	***Feature to be Tested***	***Specification Ref. in Appendix A***	***Testing or Verification Procedure***
1	Segment Length	1	Ruler (Pass or Fail)
2	Overall Length	4	Ruler (Pass or Fail)
3	Segment Width	2	Ruler (Pass or Fial)
4	Segment Height	3	Ruler (Pass or Fail)
5	Lifted Height	6	Ruler (Pass or Fail)
6	Overall Weight	5	Scale (Pass or Fail)
7	Inclination	7	Incline Apparatus (Pass or Fail)
8	Minimum speed	8	Speed Apparatus (Pass or Fail)

4. Test Facility

All testing will be done in the Robotics and Motion (RAM) Laboratory at the University of Texas at San Antonio. Enervate and Dr. Bhounsule are in a partnership that allows the team to utilize the RAM laboratory and any equipment available in that particular lab. While, the Arduino IDE will be the developing environment to code the robot.

4.1. Configuration

Majority of the evaluation for the specifications will be done on an apparatus that will be built by the engineers of enervate inside the RAM Lab. The apparatus will allow the team to measure the robot's adhesive ability as well as the inchworm's capability of scaling incline surfaces. To do so, the team will build a flat surface, resembling the properties of ceramic tile, with the ability to adjust the levels of inclination. To measure velocity, a black and white background with marked inch increments will be placed perpendicular to the robot as it moves in one direction. While Physical specifications will be measured by a ruler or digital caliper provided by RAM Lab. The software setup will be the Arduino IDE and can be accessed on any computer or laptop that has the program installed.

4.2. Data Acquisition

To make sure that the robot will get the proper power to move forward and lift it's three body segments, measurement of the voltage and amperage will need to be acquired. This will be done using a digital multi-meter. Dr. Bhounsule has went ahead and agreed to let us use the multi-meter in the lab. Photography and Video recording will be used to determine speed as well as the maximum angle of incline that robot will be able to move forward. Record of all measurements and evaluation will be inputted on a excel spreadsheet and be compared to the various tests that will done on the robot.

4.3. Calibration

Using a protractor, the engineers will measure the incline angle and confirm that the incline apparatus has the correct level inclination that it will need to properly test the robot's incline capabilities. Calibrating the multimeter can be done by following the instructions on the multimeter's manual to accurately configure the measuring device. In addition, another multimeter will be used to compare the readings to the voltage and amperage readings from the device that the engineers will use. There is no need to calibrate the camera as long as the engineers will use the same recording device.

5. Testing

5.1. Test Preparations

To commence assessment on the robot's performance and physical specifications the following equipment or software will need to be prepared:

- Incline apparatus
- Speed-tracking background
- Camera (with video recording capabilities)
- OpenCM IDE
- Digital multimeter
- Caliper
- Ruler

5.2. Test conditions

Verification that each evaluation task is meet, constraints are applied when testing for each application. Physical and performance measurements should meet or not exceed the specifications listed in appendix A. While the conditions for the software are listed below:

- No movement if controller is not on.
- Dynamixel Motors must go to preprogrammed goal position with goal speed, once controller is being used.
- Code will loop instructions until microcontroller is off.
- Code will loop until Bluetooth controller ceases movement
- Two servo motors must attain simultaneous movement to programmed angle position when initiate by Bluetooth controller.
- OpenCM microcontroller must be active with Bluetooth communications with the controller.

5.3. Test Parameters

All Parameters that will be tested are listed on Table 2 and Table 3.

5.4. Test Matrix

Parameters	Recorded Value	Required Value	Pass/Fail
Overall Length		3 feet	
Segment Width		4 Inches	
Segment Height		5 Inches	
Segment Length		5 Inches	
Lift Power		2 lbs	
Range		3 Feet	
Min. Inclination		45 Degrees	
Min. Speed		0.4 Inches per Sec	
Max. Weight		8 lbs	

Table 2: Physical/Performance Test Matrix

Parameters	*Recorded Value*	*Required Value*	*Pass/Fail*
Overall Length		3 feet	
Segment Width		4 Inches	
Segment Height		5 Inches	
Segment Length		5 Inches	
Lift Power		2 lbs	
Range		3 Feet	
Min. Inclination		45 Degrees	
Min. Speed		0.4 Inches per Sec	
Max. Weight		8 lbs	

The software test matrix only evaluates if the parameter was meet by the programmed code or fails to meet the specific task as illustrated in Table 3.

Table 3: Software Test Matrix

Parameters	*Pass*	*Fail*
Movement when Bluetooth controller is active		
Simultaneous Movement (From Dynamixel motors 2 & 3)		
Movement in the same direction as controller indicates		

Movement of rear motors as controller is active		
Servo motors move to predetermined goal position		

6. Data Analysis

Data analysis will first need to be performed analytically to ensure the robot is not producing any torque, power, or amperage greater than the servo motors abilities. This must be conducted before performing any movement from the servo motors to prevent failure. After this has been managed, the procedure can be executed. While the procedure is in motion the Robotis software can serial print the actual torque, power, and amperage each servo motor is producing, which can then be compared to the analytical calculations. Below is a detailed description of how each analysis will be conducted manually.

6.1. Torque Analysis

Torque, represented by tau (TAU), plays a huge role in the functionality of this robot, and as seen below is the product of force and lever arm in units of lb.*in.

$$\tau = F * l$$

Four Dynamixel AX-18A servo motors will be the muscles of this robot, granting it movement. These motors all possess a stall torque of 15.93 lb.*in, meaning any torque produced greater than this number will result in failure. Two of these servo motors will be used to lift the middle block upward while the other two will be used to lift the outer blocks upward. These two actions will be split up and analyzed differently to determine the torque being generated.

For the inner servo arms, the torque being produced will differ slightly in regards to force. Here, the force being created will be due to gravity rather than an outside applied force. To calculate this the robot will be weighed and the number on the scale will take the place of force. This force will be used as an even distribution, basically giving a resultant force centered on the block. Since the hinges are located on the edges of the block, reaction forces will need to be calculated to determine the weight being lifted from each inner servo arm. A visual aid of this force distribution can be seen in the figure below.

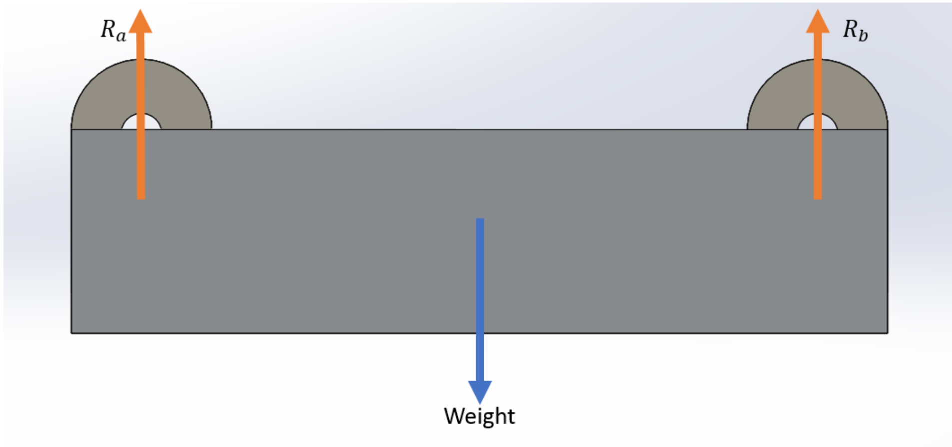


Figure 1: Force Distribution of Servo Arm

The outer servo arms will again differ in the force being used for torque. In this case a portion of the weight of the outer block as well as the reaction force from the inner servo arm will now take the place of this reaction force. This force can be observed on the roller bearing on the outer servo arm. This is done by a force balance between the roller bearing, inner servo arm, and the weight of the robot. A visual aid can be seen in the figure below.

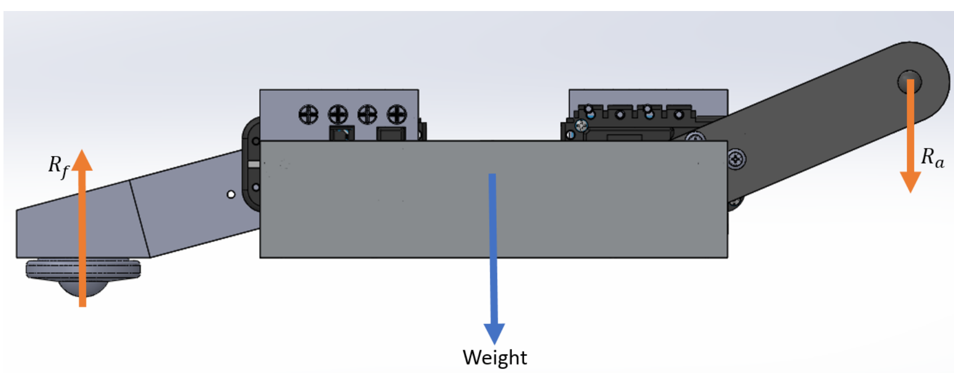


Figure 2: Free-Body Diagram of end segment

In the case of this project the lever arm will be the perpendicular distance from the force being used to the center of the servo motors rotational wheel. Since the servo motor will be rotating throughout the robots' movement, the value of the lever arm will change. The maximum value the lever arm will be is from the initial lifting of the both outer and inner blocks, here is also where the maximum torque is experienced.

6.2. Power Analysis

Power in regards to electrical components, as seen below, is the product of angular velocity [OMEGA] and torque.

$$P = \omega * \tau$$

Since the servo motors will be controlled via software coding, the angular velocity can be manipulated to create a desired speed. This speed is inputted in the OpenCM IDE as rotations per minute, so this will be converted to radians per second so that when multiplied by torque produces watts. Since both angular velocity and torque are proportional to power, the maximum power will again be experienced in the initial lifting of both blocks.

6.3. Amperage Analysis

When measuring amperage two different factors come into play, power and supplied voltage. Amperage is the amount of current being supplied to each servo motor and is the quotient, as seen below, of power to voltage.

$$A = \frac{P}{V}$$

Voltage should not change as each servo motor should be receiving roughly 12 volts since they are connected in series. Power will change as torque changes due to the angular movement of the servo arms. The servo motors being utilized all contain a stall currant of 2.2 amps meaning a current equal to or greater than this number will result in no movement. It is important to ensure that the amperage does not equal or exceed this value before operating these motors to prevent damaging their circuit boards.

6.4. Presentation of Results

Below are two testing tables, one analytical and the other experimental. The analytical table is to be filled out before experimental to insure the safety of each servo motor.

Table 4: Analytical Testing

Motor	Weight Lifted	Lever Arm	Torque	Angular Velocity	Power	Supplied Voltage	Amperage

Table 5: Experimental Testing

Motor	Weight	Lever Arm	Torque	Angular Velocity	Power	Supplied Voltage	Amperage

7. Schedule

The detailed testing schedule consist of 18 working days. Within the time frame of October 23 through November 9 of 2017 the following major tasks listed below will be conducted with respect to specification testing.

1. Test Plan Outline
2. Initial Test Parameters
3. Coding
4. Debugging
5. Testing on Flat Surface Conditions
6. Testing on Inclined Surface Conditions

The test plan outline seen in this document is a necessary guideline to be followed for proper testing evaluations. Each major task has several subsections that must be tested to ensure a properly working device. From initial test parameters to testing on inclined surface conditions there are a total of 23 test to be conducted. The engineers of Enervate can be seen on the working Gantt chart. Each test conducted has an assigned engineer which will conduct the respective test.

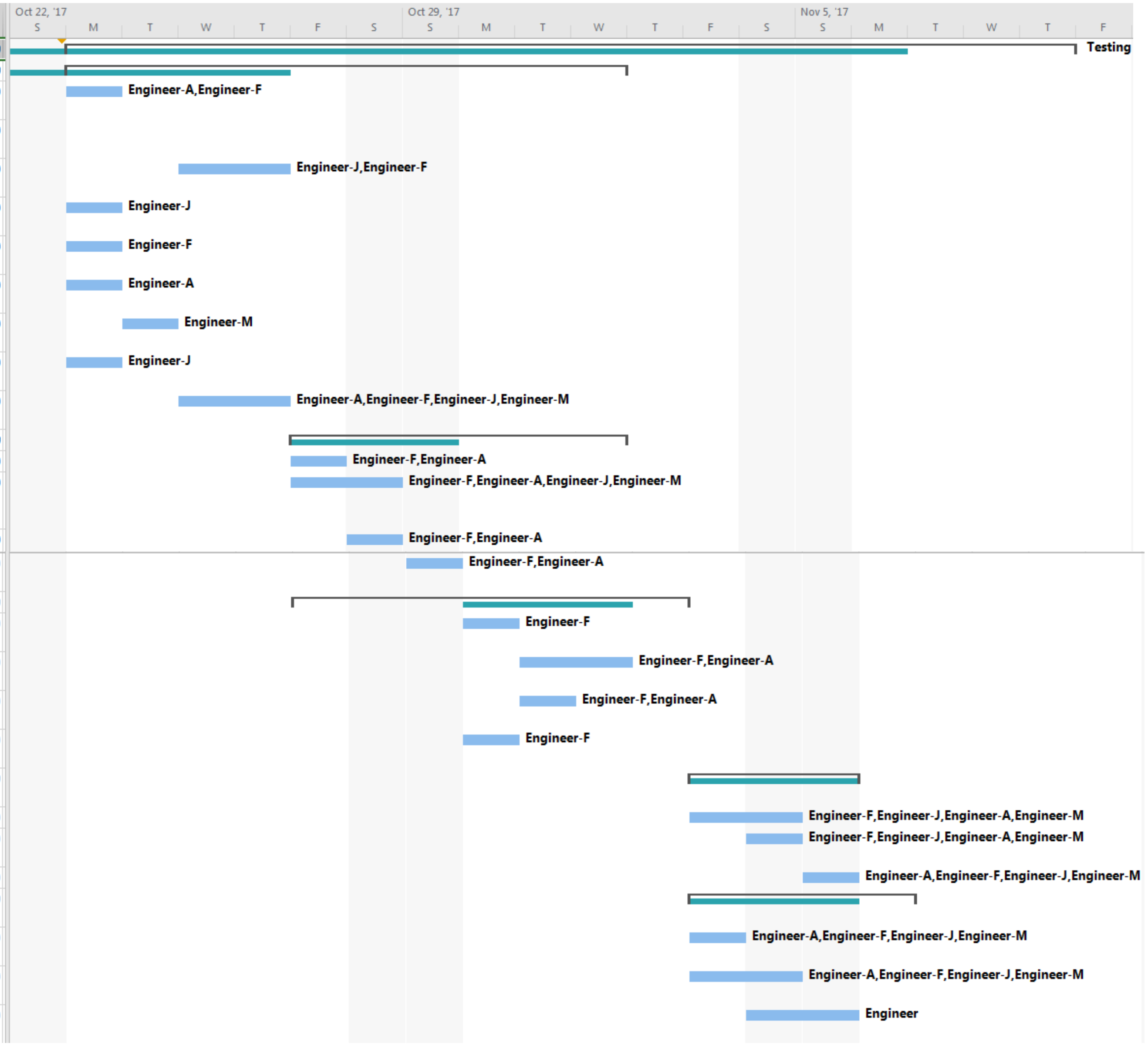
The engineers of Enervate strongly agree the successful specification testing will produce a properly working device to be presented during the final tech symposium.

GANTT CHART

	Task Name	Total Cost
232	Testing	$208,330.00
233	Initial Test Parameters	$83,250.00
234	Testing Motor Torque Output	$3,200.00
235	Building Testing Apartus (Inclined)	$1,650.00
236	Ensure voltage to motors is sufficient	$6,400.00
237	Test Physical Specifications-Width	$1,600.00
238	Testing Physical-Height	$1,600.00
239	Physical testing-Length	$1,600.00
240	Test Voltage across wires	$1,600.00
241	Test Structural Strength of Body	$1,600.00
242	Test Communications	$12,800.00
243	Coding	$35,200.00
244	code to turn motors	$3,200.00
245	Code for simultaneous interaction	$12,800.00
246	code to check goal	$3,200.00

GANTT CHART

	Task Name	Total Cost
247	code to check goal angle	$3,200.00
248	Debugging	$44,800.00
249	Debug code for motor turning	$1,600.00
250	Debug code for synchronization	$6,400.00
251	Debug code for goal speed	$3,200.00
252	Debug code for goal angle	$1,600.00
253	Testing on Flat Surface Conditions	$25,600.00
254	Testing Velocity	$12,800.00
255	Testing Range of Robot	$6,400.00
256	Testing Adhesives	$6,400.00
257	Testing on Inclined Surface Conditions	$19,480.00
258	Testing Velocity on Inclined Surface	$6,400.00
259	Testing range Inclined	$12,800.00
260	Testing Gecko Sythetic Adhesive	$280.00



8. Program Risk

There are several program risks that must be discussed. The first risk is associated with the 3-D printed components of the body segments and hinge connections. Enervate must ensure areas of minimum thickness on the body segments will be rigid enough to support the load acting upon them. Hinge connections must also be analyzed to ensure they are a proper fit. The result of the thickness being too small could cause failure of that component leading to a malfunctioning device. Another program risk is associated with the ball bearing transfer unit. This is the component that allows the forward propagation of the robot. We must ensure the surface contact area around the lip of the ball bearing will have enough area to make contact with the surface and break adhesion from the grip pads. The consequence of an improper contact with the roller bearing and surface will not allow the robot to traverse forward. The last major risk is toward the programming issues that may arise. Since the robot motors will be daisy chained together, the motors will have to work simultaneously to achieve the desired result. Enervate will have to invest a fair amount of time to ensure the four motors are working in unison to achieve looping gait desired.

9. Communications

Communications on all aspects of the test program on a regular basis are encouraged. The primary technical contact at Enervate is Flavio T. Moreira, Project Manager, (561) 414-9767. Moreiraft@gmail.com

10. Appendix A Specifications

Appendix A		
Ref. #	***Functional Specifications***	***Value***
1.	Max segment length	5 Inches
2.	Max segment width	4 Inches
3.	Max segment height	5 Inches
4.	Max total length	3 Feet
5.	Max Weight	8 lbs
6.	Max Height on forward movement	6 inches
7.	Min. Inclination angle	45 degrees
8.	Min. Speed	0.4 in/sec