THE UNIVERSITY OF ILLINOIS AT CHICAGO
ME 397 – SENIOR DESIGN SEMESTER REPORT
SPRING 2020

Project P06:
Quadrupedal Robot

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Abstract

The following design project aims to develop an inexpensive quadrupedal robot capable of being utilized within academic environments to highlight robotic design and manufacturing. The engineered design model adheres to the Dynamic Robust Actuated Passive Ambulation (DRAPA) challenge rules where an established robot must follow dynamic legged locomotion on a flat surface with steady-state repeatable motion. The simulated design is proficient of being easily reproduced using standard accessible building and electronic material costing no more than $200. The finalized quadrupedal robotic simulation is projected to translate 50 meters through one-degree of planar motion with a speed range of 0.25 m/s – 0 .3 m/s autonomously while balancing on two legs at a time. The calculated overall run time reliability of the robot is projected to be upwards of 3 minutes. Through extensive simulation analysis and modeling, the finalized design simulation attests to all intended design specifications.

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Problem Statement

The objective of the project is to create an open source, cheap quadrupedal robot that can be used for a future course on legged robots. The open source software used for the project is Arduino. The cost limit is flexible, but the goal is to maintain cost below $200. The robot must be easy to reproduce. It must use standardized, easily available off-the-shelf components. It needs to follow the design requirements that are clarified in the Dynamic Robust Actuated Passive Ambulation (DRAPA) challenge rules. These are listed below:

- Must be legged locomotion
- Must be dynamic
- Actuation: passive, active, or a combination of both
- A steady-state, repeatable motion on flat ground
- Untethered, self-contained
- Keep it simple, so it is easy to produce, assemble, and control
- Use of commonly available and relatively cheap materials (MDF, ABS, POM, cardboard etc.)
- Use of prototyping grade manufacturing systems (laser cutting, 3D printing, 3-axis milling)
- Bonus features that are optional: cornering/turns, standing up, LEDs, etc.

Scope

The main objective of the project is to design a quadrupedal robot that can move in planar motion. The scope of the project is limited to providing the following deliverables. A proof of concept in the form of a simulation. A motion study of the robot is completed using SolidWorks software to simulate the movement of the quadrupedal robot. Additionally, an ANSYS simulation is completed to justify decisions in the design process. Further details of the scope of the project are provided in the Project Charter as seen in Appendix G.

Main Deliverables:

- CAD drawings of the components used to make the quadrupedal robot
- Computer code used to drive the motors of the robot
- Proof of concept in the form of a simulation
    - Motion Study of the Robot using SolidWorks
- ANSYS simulation
    - Static structural analysis of the acrylic links

Sponsor Background

Dr. Pranav Bhounsule is an assistant professor within the Mechanical and Industrial engineering departments here at the University of Illinois at Chicago (UIC). Dr. Bhounsule has received his Ph.D. in Mechanical Engineering from Cornell University. Dr. Bhounsule's research interests include legged locomotion, general robotics, and optimal control. His interests have greatly translated over his time at UIC as he is the face of the Robotics and Motion Laboratory. One of Dr. Bhounsule's personal hobbies include running half marathons, full marathons, and a triathlon. Dr. Bhounsule is currently the sponsor for the team's Quadrupedal Robotic Project and will contribute his professional knowledge to answer all the team's comments, questions, and concerns.

Metrics & Product Specifications

Metrics provide scales to measure the degree to which objectives are met. For this project, the main objectives are shown below in Table 1. The team established a set of metrics to measure the extent to which the proposed design meets the design objectives. At least one metric has been established for each objective, which will ensure that all objectives are weighted in the design process. These design metrics are shown in Table 2. The design objectives are to model a quadrupedal robot that has a low production cost below $200, is easily reproducible, and functions with open source code. Each objective has corresponding metrics. Quadrupedal motion is measured by the degrees of freedom. The aim is to have the robot be able to at least complete planar motion. There is also a target speed for the robot of 0.25 to 0.3 m/s. The low production cost is measured by the cost of one unit in USD. The aim is to have a total supply cost less than $200.00 USD. The reproducibility of the robot is measured by the cost and the number of parts of the entire assembly. The device must function using open source coding, and the ease of access is measured through a scale of 1-10 where 10 means the code is easy to navigate.

OBJECTIVE(s):
1. Design a model quadrupedal robot: four-legged robot which exhibits quadrupedal motion (legged locomotion)
2. Low production cost (within budget of <$200)
3. Be easy to reproduce and machine and use standardized, easily available off-the-shelf components
4. Device must function using open source software (Arduino etc.)

Table 1. Comprehensive list of the design objectives.

KEY METRICS:	
Metric	**Description**
Cost	Determined by the production cost of one unit measured in USD. The aim is less than $200.
Number of Parts	The objective is to minimize the number of parts for easy assembly. The target part count less than 25 parts.
Degrees of Freedom	The objective is to have a quadrupedal robot that moves at least planar motion.
Speed of the robot	Target speed of 0.25 – 0.3 m/s. Measured by the time the robot takes to move from point A to point B.
Usability of the code for the quadrupedal robot	Measures the ease of access/use of the code. Rated 1-10 (10 = easy to navigate)

Table 2. Comprehensive list of the design metrics.

Design Criteria

In order to contain design metrics and design objectives, design criteria must be set in place as the fundamental base standards. These criteria are integral for generating optimal customer satisfaction and maintaining successful production and operation. The design criteria are all listed below.

Cost

- Total cost of device production and materials be measured in U.S dollars; must cost no more than $200. Low cost is most preferable.

Degree of Freedom

- The robot will successfully operate at 1 degree of forward planar motion.

Weight

- Total weight of the final product will be measured in pounds; lightweight is preferable.

Safety

- Final product must pass classroom safety tests and regulations to avoid harming classmates or other objects.

Durable

- Device is able to withstand multiple uses and remain intact and operable when maneuvering around opposing objects.

Speed

- Device must maintain a steady programmed speed of 0.25 to 0.3 meters per second; increased speed is preferable.

Portability

- Model is easily assembled and capable of maneuvering with little effort. Able to be stored easily and for long periods of time without affecting future operating performance.

Simplicity

- Final product must be easily measured with the metrics of cost, assembly, degrees of freedom, speed, and open source coding.

Fish Bone Diagram

A fish bone diagram is utilized as a cause-and-effect mapping diagram that helps to identify imperfections, variations, defects, or failures for a specific problem. The team's problem is to successfully model and simulate an operable Quadrupedal Robot. Next, factors are identified that greatly contribute to the overall success of the problem. The following factors identified include: Materials & Budget Distribution, SolidWorks Design, Prototype, ANSYS Simulation, and Continuous Improvement. Each major factor contains possible causes of the problem in relation to the factor. Materials must be less than $200 where electronic components are determined to be top priority to ensure the robot successfully operates. The remaining budget will be applied to the supplemental accessories and costs of laser cutting acrylic material for the legs and body of the robot. Once an ideal leg for the robot is sketched and determined, the leg must be design in SolidWorks and then translated into a physical cardboard prototype where the leg's locomotion can be visualized by the team. The robot is 4-legged, and all legs will be identically manufactured with Acrylic sharing exact dimensions. Utilizing ANSYS, a variety of testing will be done to determine the leg's overall durability in a variety of situations. Further design regarding the robotic body and skis will complete the physical assembly of the robot. The finalized robot will be simulated using SolidWorks, where all 4 legs move on a flat terrain. As the robot nears the end of the assembly phase, continuous improvement techniques may be applied to best optimize the motion fluidity of the robot. This includes testing the robot on various terrains and applying weighted loads onto the robot. The testing and experimental phase of the product design will help determine areas of concern and possible improvements to be made before the Design EXPO.

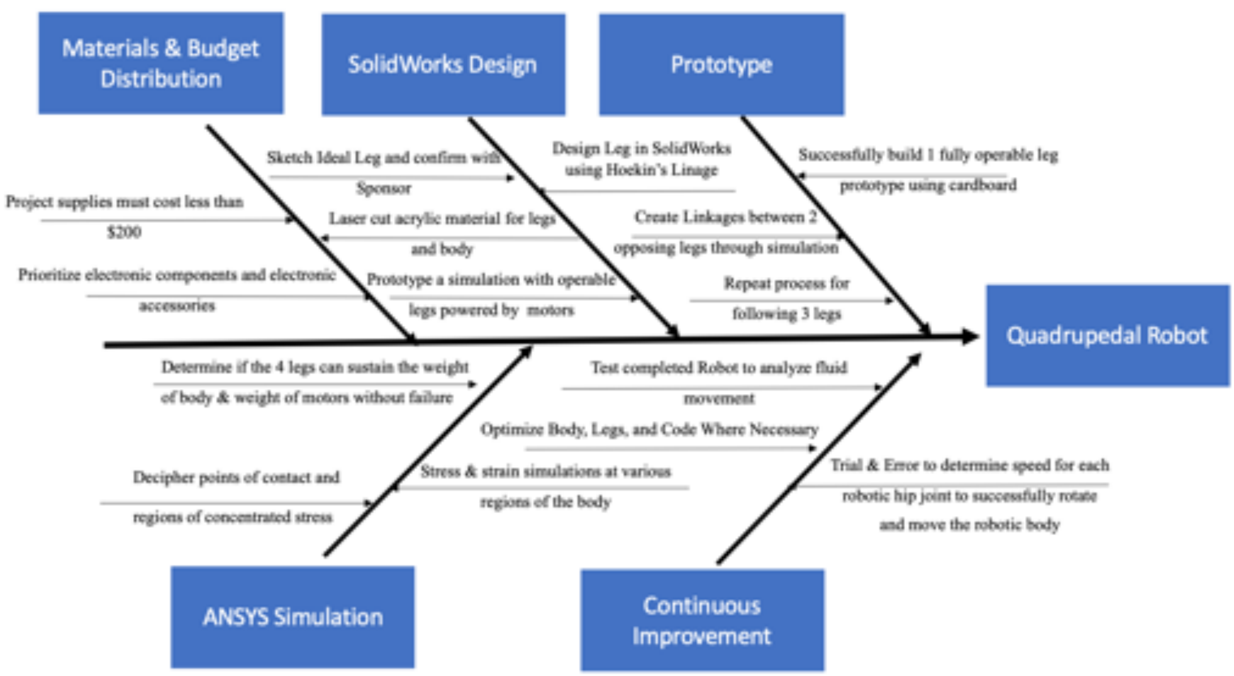


Figure 1. The fish bone diagram created to map the initial stages of design and final stages of production.

Quality Function Deployment

The Quality Function Deployment (QFD) diagram is a visual representation of the customer's design priorities and how technical engineering characteristics meet customer needs. The following Customer Requirements include: Building Materials less than $200, Open Source Code, Usage Life, Size, Speed, Terrain Variability, Ability to Carry Heavy Loads, Agility, Reliability, and Material Quality. The correlating Customer Priority scale can be found to the right of the Customer Requirement Categories. The scale ranges from 0 to 10, where 10 is considered a top priority and 0 is considered a low priority. The Technical Requirements reflect the design criteria. The technical requirements determined to tend to customer needs are of the following: Weight, Motor, Expected Life, Cost of Production, Dimensions, Speed, Temperature Tolerance, Material, Degree of Freedom, and Color. Below the Technical Requirements are Targets that determine what type of relationship is ideal for producing a quadrupedal robot and meeting design standards. The Importance Rating is determined by calculating the sum of the Priority multiplied with the Relationship standard. The higher the Importance Rating, the more important that technical requirement must be.

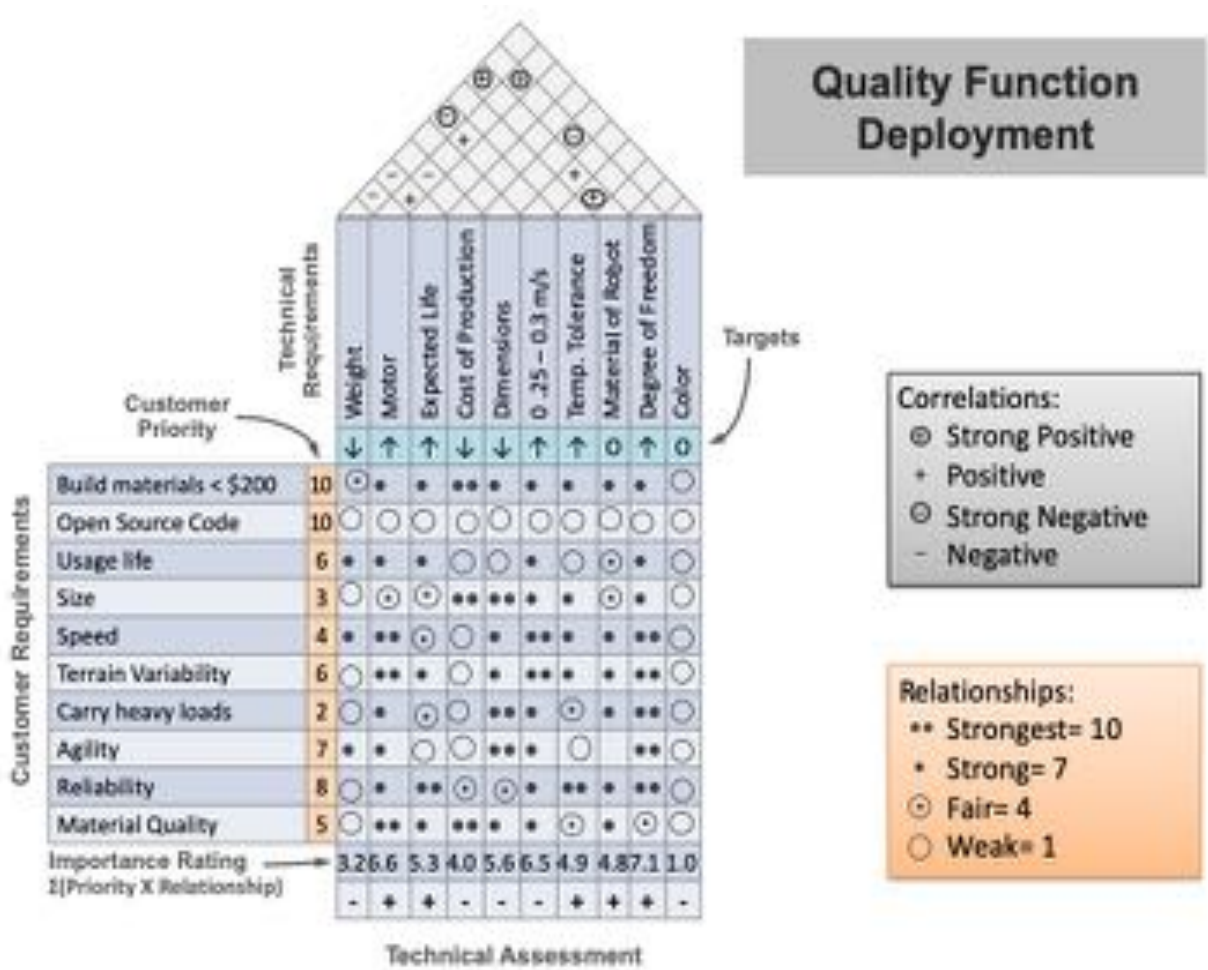


Figure 2. The Quality Function Deployment (QFD) created for the Quadrupedal Robot.

Decision Matrices

The following decision matrices aim to evaluate potential designs in relation to design criteria. The Simple Decision Matrices should be read as follows. The leftmost column of each table contains criteria that every option will be evaluated against. The top row of each table lists the options available. A score of 1 to 5 will be assigned, with 5 being very good and 1 being very poor. In the bottom row, a total sum of all the scores for each individual option can be found. The option with the highest score is the "winner". It is important to note that the following options and decisions are not final and are subject to change as production process further develops.

Simple Decision Matrix: Motor Type(s) & Model Selection

The following matrix determines the type of motor needed to successfully operate the robot. The criteria consist of the cost, assembly, weight, speed, and angle of rotation. The motor options consist of a Continuous Servo motor, a Stepper motor, a DC motor, combination of Servo and DC motors, or a combination of Stepper and DC motors. Once all motor options are tallied with their corresponding criteria values, a total sum is taken. The Continuous Servo motor receives the highest total of 20 points and therefore is determined to be the motor utilized for the Quadrupedal Robot.

	Options				
Criteria	Continous Servo	Stepper	DC	Servo & DC	Stepper & DC
Cost	5	3	3	3	3
Assembly	4	2	4	3	4
Weight	4	2	3	3	2
Speed	2	3	4	2	3
Angle of Rotation	5	3	5	3	3
TOTAL	20	13	19	14	15

Figure 3. The simple decision matrix created for the types of motors.

The Continuous Servo motor has been selected to be the most optimal motor for the Quadrupedal Robot. Three potential motors have been selected for purchasing: HSR-2645CRH, HSR-2646CR, and HSR-1425CR. They have been selected based on their individual maximum and minimum voltage ranges. Table 4 contains a quantitatively detailed list of each motor's individual specifications. These criteria are of the following: Torque (oz-in) at Minimum Voltage, Torque (oz-in) at Maximum Voltage, Speed (sec/60°) at Minimum Voltage, Speed (sec/60°) at Maximum Voltage, Weight, and Cost.

	Options		
Criteria	HSR-2645CRH	HSR-2648CR	HSR-1425CR
Type	Digital	Digital	Analog
Min Voltage	4.8	4.8	4.8
Max Voltage	7.4	7.4	6
Torque (oz-in) at Min Voltage	111	111	39
Torque (oz-in) at Max Voltage	167	167	47
Speed (sec/60º) at Min Voltage	46 RPM	46 RPM	44 RPM
Speed (sec/60º) at Max Voltage	72 RPM	72 RPM	52 RPM
Weight	53	53	41
Cost	33.39	32.99	17.99

Figure 4. Comprehensive table detailing each motor's individual specifications.

The following matrix detailed in Figure 5, compares the three different Continuous Servo motor models. The criteria consist of the Voltage Range, Torque Range, Speed Range, Weight, and Cost of each individual motor model. The motor model options are the following: HSR-2645CRH, HSR-2646CR, and HSR-1425CR. Once all Continuous Servo motor models are tallied with their corresponding criteria values, a total sum is taken. The Continuous Servo motor model HSR-2645CRH receives the highest total of 22 points and therefore is determined to be the model that is to be purchased to best complement the successful operation of the Quadrupedal Robot.

	Options		
Criteria	HSR-2645CRH	HSR-2648CR	HSR-1425CR
Voltage Range	5	5	3
Torque Range	5	5	4
Speed Range	5	4	3
Weight	4	3	5
Cost	3	4	5
TOTAL	22	21	20

Figure 5. The simple decision matrix created for Continuous Servo motor model selection.

Simple Decision Matrix: Number of Legs Grounded

The following matrix determines the amount of legs to be remaining grounded as the robot moves. The criteria consist of the maneuverability, assembly, weight distribution, speed, and control. The leg options consist of either 1 leg or 2 legs to remain grounded as the robot moves. Once all leg options are tallied with their corresponding criteria values, a total sum is taken. The two legs option receive the highest total of 17 points and therefore are determined to be the amount of legs to be grounded as the Quadrupedal Robot operates.

	Options	
Criteria	1 Leg	2 Leg
Manuevering	1	5
Assembly	4	3
Weight Distribution	1	3
Speed	2	4
Control	4	2
TOTAL	12	17

Figure 6. The simple decision matrix created for the legs of the robot.

Simple Decision Matrix: Production Material Type

The following matrix determines the type of material needed to successfully manufacture the robot. The criteria consist of the cost, assembly, weight, environmental factors, and durability. The material options consist of plastic, wood, or metal. Once all material options are tallied with their corresponding criteria values, a total sum is taken. The material that has the highest total is plastic, with 22 points and therefore is determined to be the manufactured material for the Quadrupedal Robot.

	Options		
Criteria	Plastic	Wood	Metal
Cost	4	3	1
Assembly	4	3	2
Weight	5	4	2
Enviromental Factors	5	3	4
Durability	4	2	5
TOTAL	22	15	14

Figure 7. The simple decision matrix created for the types of material.

Simple Decision Matrix: Robot Footing

The following matrix determines the type of footing needed to allow successful stability of the robot. The criteria consist of the material, cost, shape, and insert type. The material options consist of Robot Coupe 101418 Foot, Robot Coupe 500247 French Foot, or 3-D Printed Stander Walker Skis. Once all material options are tallied with their corresponding criteria values, a total sum is taken. The robotic footing type that has the highest total are the Stander Walker Skis, with 17 points and therefore is determined to be the footing for the Quadrupedal Robot.

	Options		
Criteria	Robot Coupe 101418 Foot	Robot Coupe 500247 French Foot	Stander Walker Skis (3-D Printed)
Material	3	4	3
Cost	4	3	5
Shape	4	4	5
Insert Type	2	4	4
TOTAL	13	15	17

Figure 8. The simple decision matrix created for the types of robot footing.

Financial Analysis

Supply Cost Analysis

The following cost analysis aims to evaluate the total supply costs of potential production materials. The supply cost analysis evaluates material as follows. Electronics and electronic accessories are essential and hold top priority to ensure robot is able to successfully maneuver. Essential Accessories are supplemental accessories necessary for the overall construction of the robot. The remaining budget is allotted for the production material, acrylic, so the physical body and legs of the robot can be manufactured.

Supply Cost Analysis: Electronics

The electronics of the robot are deemed essential and hold top priority when distributing the budget. The electronic components are the following: Continuous Servo Motor, Microcontroller Kit and a Voltage Regulator. The total cost of the essential electronic components is a projected total of $99.87. This indicates that the budget remaining for distribution amongst other production categories is a projected total of $100.13.

Part	Dimensions (cm)	Quantity	Weight (grams)	Vendor	Item Name	Item #	Cost/Unit ($)
Continuos Servo Motor	4.06 x 1.96 x 3.78	2	53	Servocity	HSR-2645CRH Servo	HSR-2645CRH Servo	33.99
Microcontroller Kit	N/A	1	453.592	Amazon	ELEGOO Mega 2560 R3 Project Starter Kit Compatible with Arduino IDE MEGA2560	EL-KIT-008	29.99
Voltage Regulator	2.8 x 1 x 0.0	2	N/A	Sparkfun	L7805 Voltage Regulator	COM - 00107 ROHS	0.95
						Sum of Electronics	99.87
						Budget Remaining	100.13

Figure 9. The cost analysis created for the electronics.

Supply Cost Analysis: Essential Accessories

To ensure electrical and physical components are successfully set-up for optimal performance capabilities, essential accessories must take precedence over production material type. These accessories ensure that the physical body and legs of the robot remain intact and reduce the risk of harming the electronics inside. The total cost of the essential accessories is a projected total of $16.10. The remaining budget for final distribution amongst production materials is $84.03.

Part	Dimensions (cm)	Quantity	Weight (grams)	Vendor	Item Name	Item #	Cost/Unit ($)
10 - 32 Steel Hex Nuts	0.000 x 0.9525 x 0.3175	100	N/A	McMaster-Carr	10 - 32 Low Strength Steel Hex Nuts	90480A195	0.0189
4 - 40 Steel Hex Nuts	0.000 x 0.635 x 0.238	100	N/A	McMaster-Carr	4 - 40 Low Strength Steel Hex Nuts	90480A005	0.0089
10 - 32 Stainless Steel Pan Head Screws	1.905 x 0.947 x 0.338	25	N/A	McMaster-Carr	316 Stainless Steel Pan Head Screws Phillips, 10-32 Thread, 3/4" Long	91735A831	0.2244
4 - 40 Stainless Steel Pan Head Screws	1.905 x 0.556 x 0.203	50	N/A	McMaster-Carr	317 Stainless Steel Pan Head Screws Phillips, 4-40 Thread, 3/4" Long	91735A113	0.1542
						Sum of Essential Accessories	16.1
						Budget Remaining	84.03

Figure 10. The cost analysis created for the essential accessories.

Supply Cost Analysis: Plastic

Determined by the team's simple decision matrix, plastic material is the optimal manufacturing material for building the Quadrupedal Robot. Acrylic material is a type of thermoplastic that is able to be easily cut into and therefore would be the plastic material that the robot body and legs will be constructed from. Two 12 x 12 acrylic sheets will be needed so that all robot parts can laser cut. The total cost of the acrylic material is nearly $34.68.

Material	Dimensions LxWxT (cm)	Quantity	Weight (grams)	Vendor	Item Name	Item #	Cost/Unit ($)	Labor Cost ($)	Total Cost Before Labor
Acrylic	30.48 x 30.48 x 0.635	2	N/A	Mc-Master Carr	Clear Scratch - and UV Resistant Cast Acrylic Sheet	8560K354	17.34	TBD	34.68

Figure 11. The cost analysis created for the Acrylic material.

Supply Cost: Breakdown

The Supply Cost Breakdown table below details the monetary break down of each individual supply cost category. From there, the sum of each cost category is combined to bring the grand total of the supply costs to $151. From the $200 limit, the remaining budget is $49. If additional materials would need to be ordered, the team can be assured that the unused remainder of the budget can cover these costs.

Supply Cost Breakdown	
Electronic Components	$100
Building Accessories	$16
Building Material	$35
Total Cost of Supplies	**$151**
Budget Remaining	**$49**

Figure 12. Supply Cost Breakdown table that details how the budget has been spent.

Labor Cost Analysis

To account for the 4 entry level engineers allocated to work on the design project, the Labor Cost must be accounted for their time. Their responsibilities would correlate to their position titles. Their hourly rate was calculated for each engineers projected entry level salary rate. This salary rate ranged between \$60,000 - \$65,000 where engineers would work 40 hours per week and paid biweekly. The range of the project is hypothesized to run for 3 consecutive weeks. Hours per week would correlate with the difficulty of each engineer's role in this design project. Once each individual cost of labor is calculated, a total sum is compiled. The grand total of the Labor Cost required for the project development and completion would accrue to \$2166.00.

Position	Responsibilities	Hourly Rate (\$)	Number of Weeks	Hours per Week	Cost of Labor (\$)
Continous Improvement Engineer	Cost Analysis, Decision Matrices, Fish Bone Diagram, Quality Deployment Diagram, Gantt Chart	29	3	6	519
Product Development Engineer	Decision Matrices, Solidworks Design, Coding	31	3	6	563
Research and Design Engineer	Solidworks Design, ANSYS Simulation	29	3	4	346
Manufactoring Engineer	Order Submission, Coding, Physical Construction	31	3	8	738
				Total Labor Cost (\$)	2166

Figure 13. The cost analysis created for the total Labor Cost.

Total Cost of Design Project

Total Cost of Project Table details the total monetary break down of the Supply Cost & the Labor Cost. Here, the total Supply cost has accumulated to \$151 and the total labor cost has accumulated to \$2166. The sum of the two brings the total cost of the design project to \$2317.

Total Cost of Project	
Supply Cost	\$151
Labor Cost	\$2,166
Total Cost of Project	**\$2,317**

Figure 14. The total cost of the design project accounting for the supply and labor costs.

Conclusion

The following design project had challenged team members to create a one-degree of freedom, planar motion quadrupedal robot, where dynamic legged locomotion should be expected as the robot moves through steady state repeatable motion. These design expectations must be met under a $200 supply cost limit. Through various iterations of design sketches, visualization diagrams, decision matrices, linkage simulations, SolidWorks assembly, and simulation the team has produced a final design assembly. The final design simulation of the quadrupedal robot model exhibits quadrupedal planar motion up to 50 meters. The robot is expected to move through steady-state repeatable motion for up to 3 minutes on a flat terrain while maintaining a speed range between 0.25 m/s - 0.3 m/s. All expectations are met while maintaining a total supply cost under $200.

The next step of the project is to move beyond the design portion and create a complete physical prototype to test the movement of the quadrupedal robot. From there, the robot could be advanced through many future improvements, such as modifications to the design. For the team's design, modifying the width of the body should be considered to make the body more lightweight. Once assembled it can be seen how much space is left between the motors and other electronics to decide how much width can be decreased. The lengths need to stay around 14 inches for the legs to move without interfering with one another. To change the length, one must change the dimensions of the linkages, which can be done with further calculations and experimentation to give the feet more ground clearance during movement. The diagonal legs are meant to eventually move in sync with each other. This would decrease the motors from four to two motors, which lowers the cost of electronics. Extra advancements could be added to the design, such as object detection, to help control the movement of the robot.

References

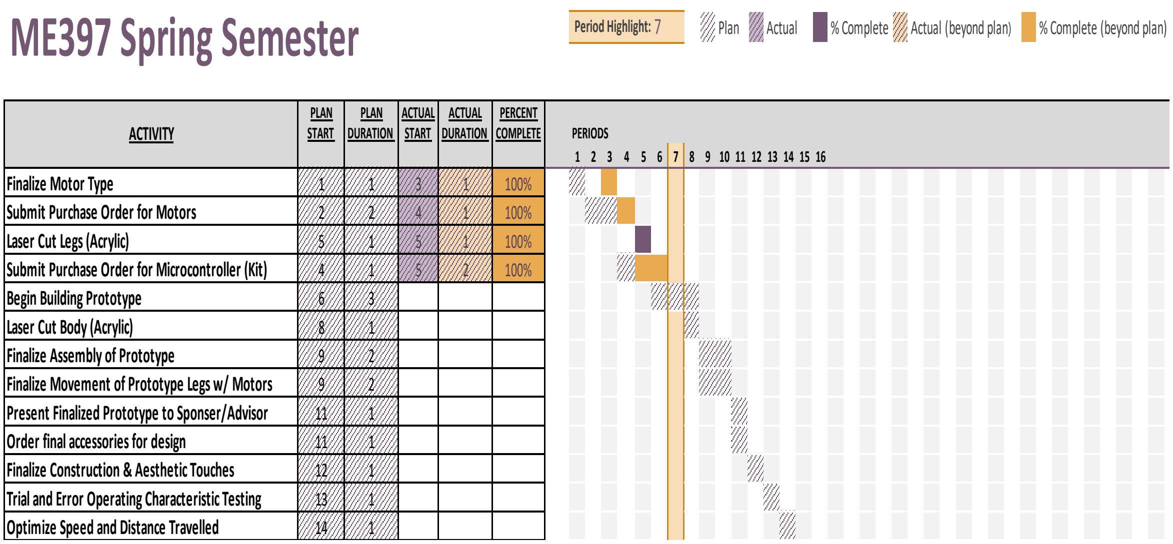
[1] USPTO Office of Public Affairs. "United States Patent and Trademark Office." *United States Patent and Trademark Office - An Agency of the Department of Commerce*, 1 Dec. 1994, www.uspto.gov/.

[2] "Boston Dynamics." *Home*, www.bostondynamics.com/.

[3] ANSYS Inc. "Engineering Simulation & 3D Design Software." *Ansys*, 24 Feb. 2020, www.ansys.com/.

Appendix A: ME 397 Gantt Chart

Figure 15 below represents the Gantt chart and the progress throughout the entire second semester. It involves the final phase of the project which involves final component selections, manufacturing, and prototyping. Up to this point the team has heavily focused on analyses which ensure the functionality of the quadrupedal robot. This is evident by the Gantt chart has all analyses are complete and as well as the manufacturing. Most components were laser cut such as the legs used to support the robot. The prototyping stage is planned took roughly 3 weeks which also involved laser cutting the body of the robot which begins in the 8th week. However, given the stay-at-home order, prototyping transformed into a CAD motion study. This study demonstrated the ability of the quadrupedal robot to the sponsor and judges. After preparing the CAD motion study in the 11th week, the team presented this study to the sponsor and advisor. After getting approval, the team continued by finalizing the report and drawings that constitute the robot in the 12th week. Shortly after this in the 13th and 14th week the team put together the presentation and video recording that outlined our project from start to finish. This included project charter, design alternatives, financial/kinematic/ANSYS analysis on design requirements and stability.



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Finalize Motor Type	1	1	3	1	100%
Submit Purchase Order for Motors	2	2	4	1	100%
Laser Cut Legs (Acrylic)	5	1	5	1	100%
Submit Purchase Order for Microcontroller (Kit)	4	1	5	2	100%
Begin Building Prototype	6	3			
Laser Cut Body (Acrylic)	8	1			
Finalize Assembly of Prototype	9	2			
Finalize Movement of Prototype Legs w/ Motors	9	2			
Present Finalized Prototype to Sponser/Advisor	11	1			
Order final accessories for design	11	1			
Finalize Construction & Aesthetic Touches	12	1			
Trial and Error Operating Characteristic Testing	13	1			
Optimize Speed and Distance Travelled	14	1			

Figure 15. The Team's official Project Gantt Chart created for ME397 taken place within the Spring Semester 2020.

Appendix B: Literature Search

The following patents pertain to a preliminary search on what has already been developed for existing quadrupedal robots. Particularly important is the design of the leg, as the leg dictates the motion of the object. If the leg is mastered, then the robot can move and function as intended by the specifications of this project. The purpose is to find legs, and sometimes a fully created quadrupedal, to demonstrate what is possible and what electronics are currently being employed. Fully mechanical systems are also being investigated. Figure 16 below represents a possible leg design that incorporates an upper and lower link for a singular leg. It comprises of a mechanical knee joint at the center that allows for rotation.

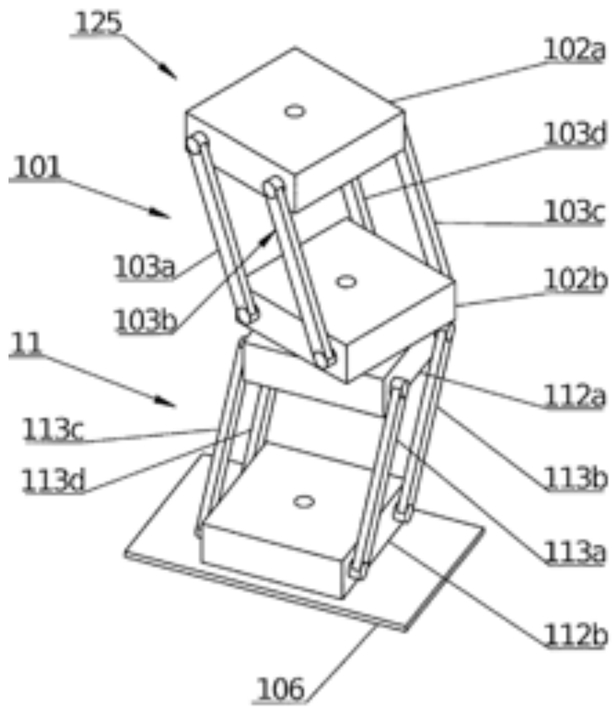


Figure 16. A robot leg that comprises of an upper link and lower link. In the center represents the "knee" of this leg design which allows the leg to rotate [1].

Initially, this leg seems suitable for the team's needs because the design does not incorporate any highly sophisticated mechanics, it simply moves forward and can rotate at the knee joint. However, there are a total of 12 links used in this design, and that is reason enough to create an even simpler design. In the end, this robot must be created by a student for learning purposes. Assembling 12 links to make 1 of 4 legs does not seem reasonable. In fact, the team has agreed on about 21 total links for the entire robot, so this is too much but a good start.

This led the team to investigate alternative quadrupedal robots that may incorporate a unique but simple design. While investigating the United States Patent Trademark Office, the team collided with another design that sparked some attention. Particularly, a quadrupedal that can climb walls. This is seen in better context below in Figure 17. The idea behind this design is the robot resembles a weaver ant, an insect that can carry up to 100 times its body weight. This robot in particular can carry up to three times its body weight. An impressive amount of weight for a small robot.

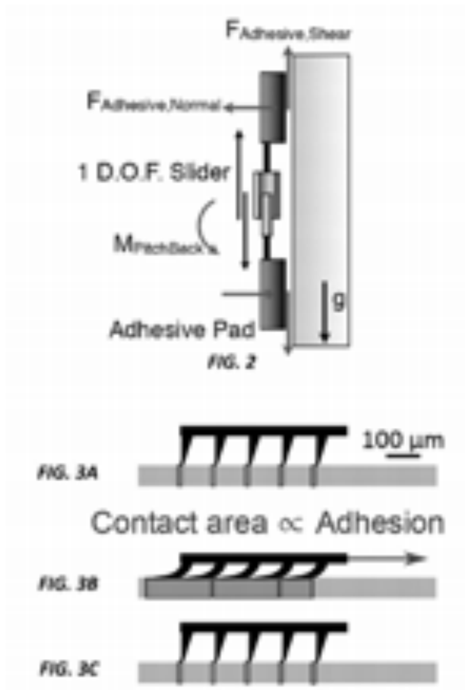


Figure 17a. The physics behind the link [1].

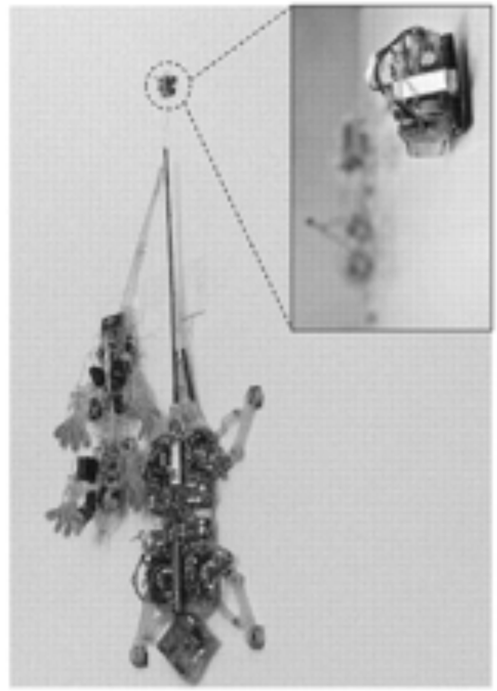


Figure 17b. The weaver ant robot design [1].

Just like a quadrupedal, this robot also has four legs but performs an entirely unique function. It can climb walls and carry up to three times its body weight. Although impressive, it is not required for the project. Instead, the team is most interested in the leg design. This design features a knee joint that acts as a slider. More specifically, the links slide tangentially together as an electronic device provides the energy to do so. This is possibly an idea, but the team also considered the fact that the robot must move at a speed of at least 0.25 to 0.3 m/s. This design does not move quickly; in fact, it does the opposite. Therefore, the design was made not to use these mechanics.

Another patent that quickly caught the group's attention was a fully built quadrupedal design that incorporated flat feet as shown in Figure 18 below.

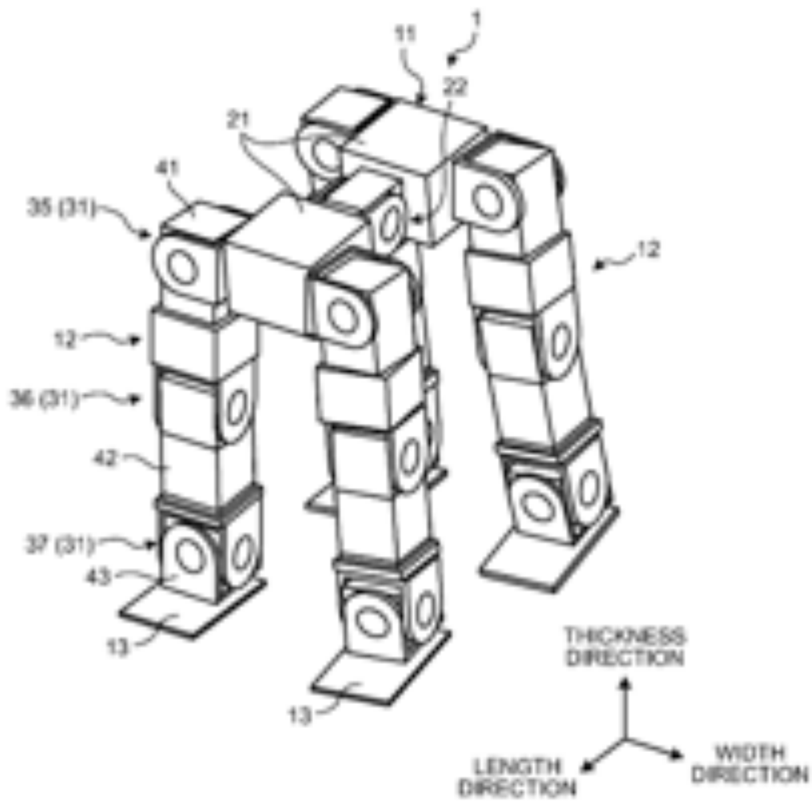


Figure 18. A mobile robot having a plurality of kinds of moving forms including a body unit, front and back face, and four limbs [1].

The benefit to this design is the flat feet keep it stable on the ground. Its hip joint can swivel, and it can bend at the knee. However, the team decided that knee design is not the best option because this option would incorporate electronics that would be over-budget for what the team can afford. Instead, the flat feet design was considered more earnestly. Instead of creating flat feet, the question became what other surfaces for feet would create a stable design? The answer became a design that could traverse train while maintaining its grip like the weaver ant yet maintain its stability like the flat feet. This brought up the idea of using a rubberized foot design that could do just the job. Something either flat or spherical at the base could accomplish both of those objectives.

All these creative designs led to the discovery of yet another creative quadrupedal design, a dog. The creativity of the dog design made the team realize not to constrain the design to something boxy or in general, limited. In the end, a student will put together the design, and it needs to be something that will grab the user's attention. Besides being creative, the dog design also rolls at the hip, something that imitates the action of a dog. The dog design is seen below in Figure 19.

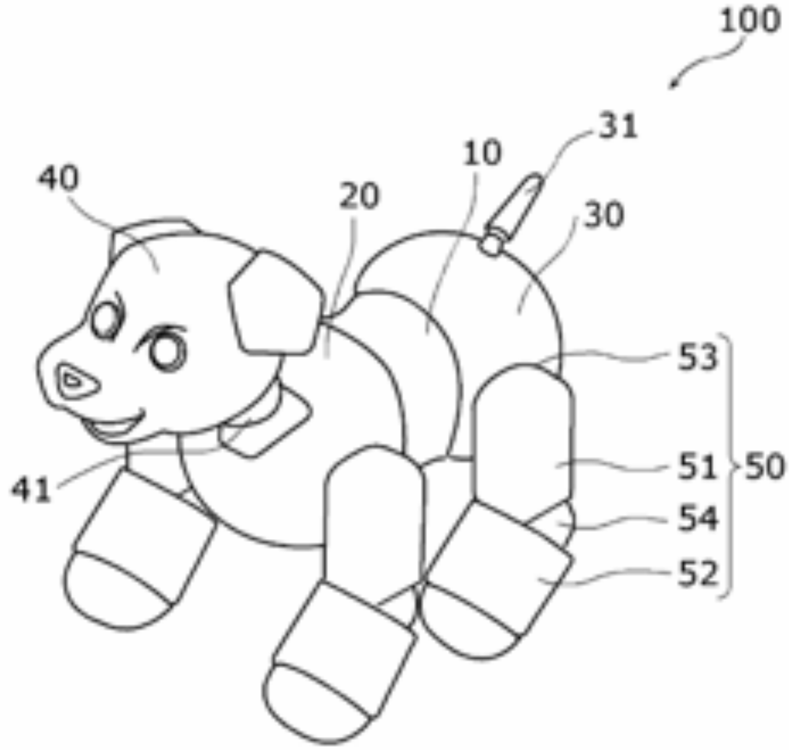


Figure 19. A legged robot that includes a trunk and a leg connected to the trunk. The trunk includes: a first link and a second link connected with each other via a first revolute joint that is rotatable about a roll axis; a third link connected with the first link via a second revolute joint rotatable about a yaw axis; and a fourth link connected with the second link [1].

Although the rolling function proves to be an interesting design, this idea is ultimately rejected because the team is not making a dog. The leg design such as this will be investigated because it has no moveable knee joint. Instead, it has some fixed angle of bend, which is preferred because it increases the stability of the robot.

The next few patents provide very complex and convoluted ideas that did not get used or investigated further by the team. However, they did provide some understanding of how more industrial robotics are created and therefore are a powerful way to demonstrate further areas of improvement way after the robot has already been created. The first is seen below in Figure 20.

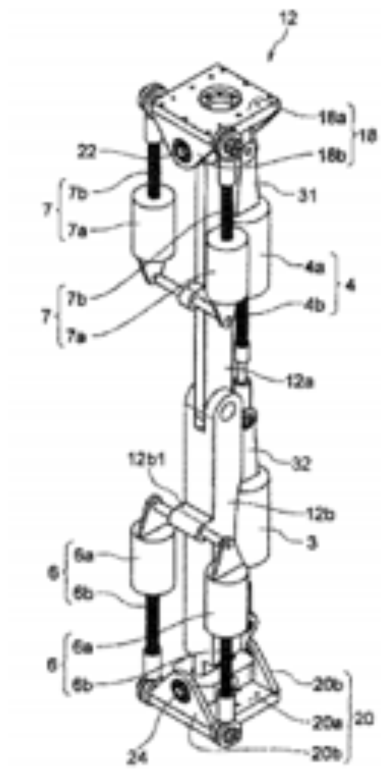


Figure 20. A lower limb structure with many links, electronics, and surfaces achieve the function of bending at the hip, moving in planar motion as well as side to side motion [1].

Based off of what has been presented in Figure 20, the design for this leg is far too complicated, requires too many electronics, and far exceeds the numerical limit of links desired for one leg. Therefore, it is not usable. Similar in complexity, and therefore not usable, but interesting is Figure 21.

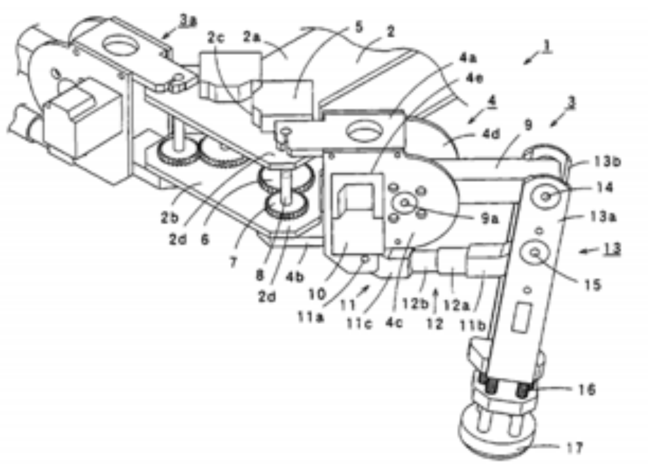


Figure 21. A quadrupedal walking robot, comprising of a body part having a horizontal swing part, a horizontal swing drive part, an upper side upper leg part pivotally supported on the horizontal swing part, a lower side upper leg part disposed parallel with the lower part of the upper side upper leg part [1].

One point though, is the springs that are used to absorb the impact upon landing in this design. It is a good idea to absorb impact, and the team hopes to run an FEA analysis on the rubber used on the feet to understand how much energy is dissipated through the material.

This made the team reconsider what the most important utility of this design is, simplicity. Finally, after some research, the team stumbled upon another design.

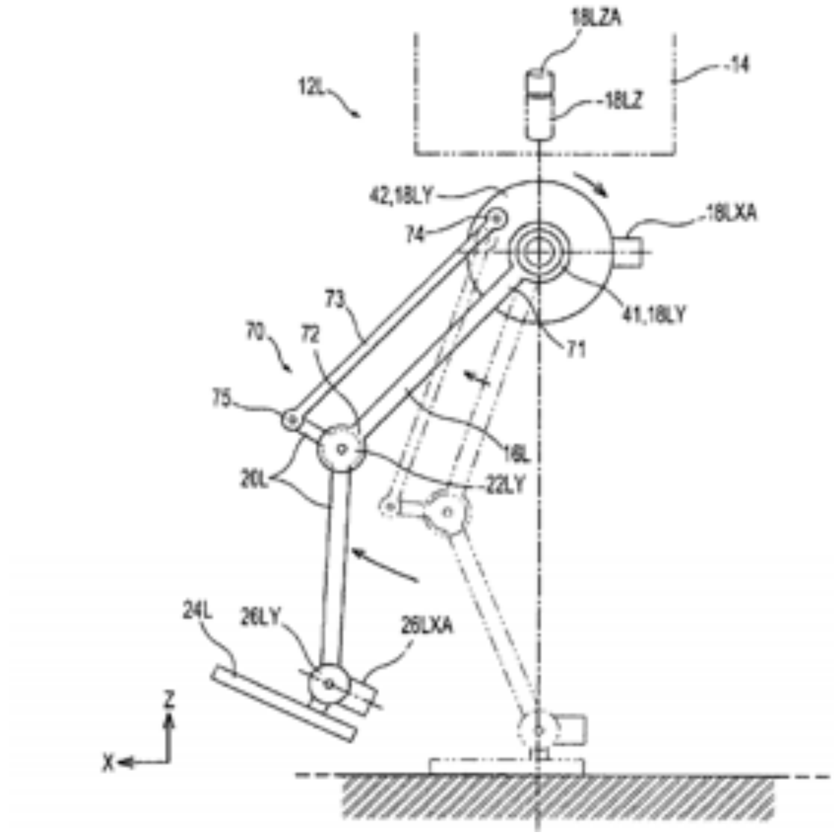


Figure 22. A link that can rotate at the hip through some electronic input. The feet are flat to provide stability, and the knee is fixed as some specified angle. The amount of links is kept to a minimum [1].

This hip joint is rotated with some type of motor. Feet are flat for stability, and the number of links is minimized as well as electronics. This hip joint for the robot's design will be rotated with a DC motor similar to the picture. Flat feet will be replaced with rubber feet for stability, and some fixed angle in the knee will be created to keep the robot even more stable. Perhaps, this design described is best represented by a current robot already in the market by Boston Dynamics, Spot.

Figure 23. Spot, a quadrupedal built by Boston Dynamics, can walk, run, rotate, open doors, and much more [2].

Although Spot is an idea of how the team may build the leg, it is unlikely the team will have the quadrupedal do the same functions. In fact, that is not the point; instead, the rubberized feet and the fixed angle in the knee as well as the simplicity in parts is desired. The team plans having the upper and lower link of the leg being one component. The hip will rotate with a DC brushed motor, and the body is still up for interpretation. However, the motion of the leg is important and therefore a schematic best represents its motion.

Appendix C: Computer-Aided Design Drawings

The legs are arguably the most important part of the design as they convert the electrical energy from the motors into linear motion of the robot. It must bear the load of the body and be durable enough to last many cycles. The linkages are laser cut from acrylic.

Figure 24 below is a CAD drawing of linkage 1, which is connected to the body and linkage 2. It is 1 inch wide and 6 inches long, which is half that of linkage 2. Its thickness is 0.25 inches, which was chosen in the Makerspace after laser cutting the linkages. The two holes are mirrored from each other with a distance of 0.50 inches from the edges. Their diameters are 0.19 inches, specifically made for 10-32 stainless steel screws.

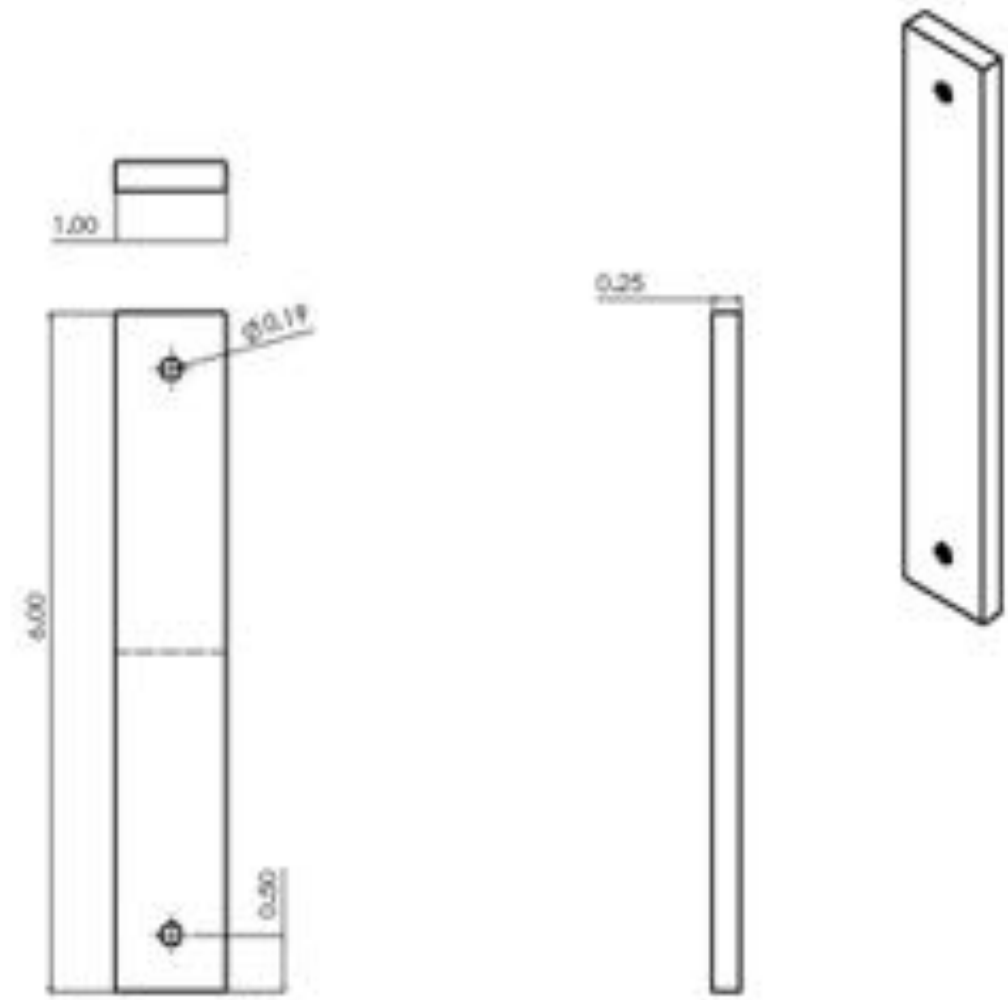


Figure 24. CAD drawing of linkage 1 used in the robot assembly.

Figure 25 below is a CAD drawing of linkage 2, which is connected to the linkage 1 and linkage 3. It is the main part of the leg that touches the ground and pushes the robot forward. It is 1 inch wide and 12 inches long. Its thickness is also 0.25 inches. One hole is at a distance of 0.50 inches from the edge, which is connected to linkage 3. The other hole is at the center of the linkage, which is where linkage 1 is connected. Their diameters are both 0.19 inches, specifically made for the 10-32 stainless steel screws.

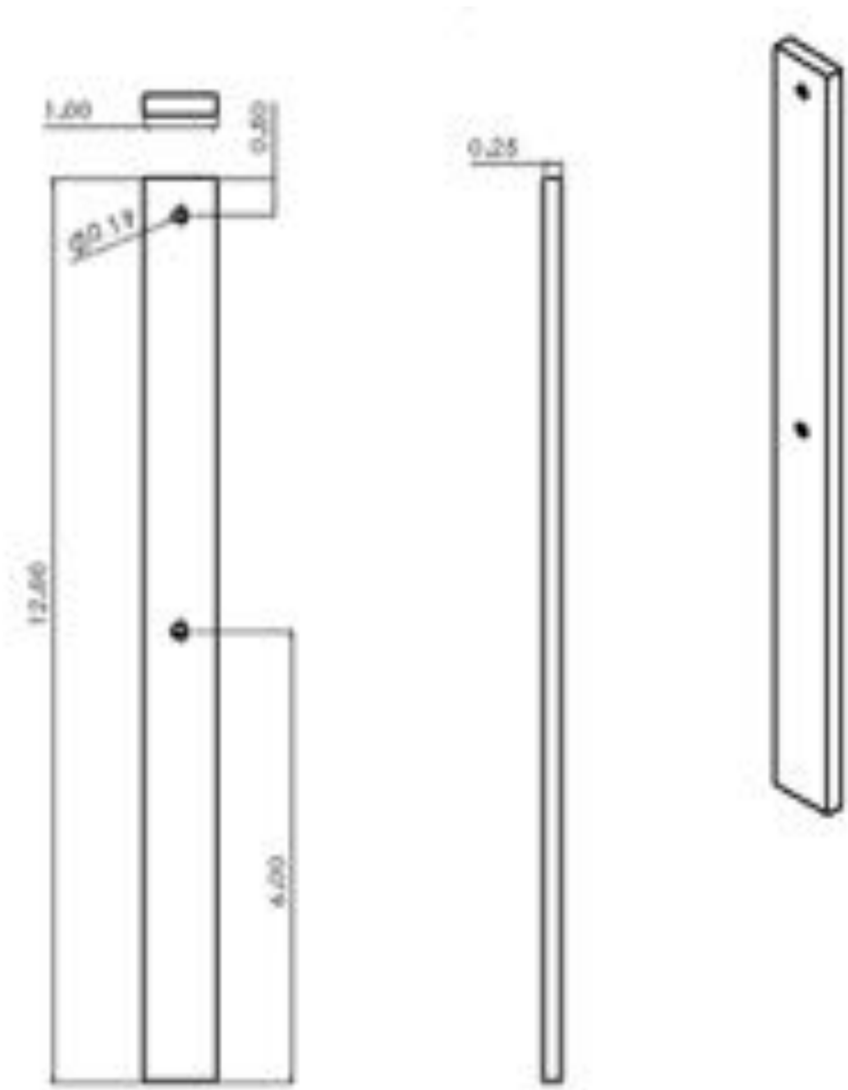


Figure 25. CAD drawing of linkage 2 used in the robot assembly.

Figure 26 below is a CAD drawing of linkage 3, which is connected to the body and linkage 2. It is 2 inches wide and 1 inch long. Its thickness is also 0.25 inches. This linkage is connected to the motor, so it will be spinning 360 degrees to move the leg assembly forward. The two holes are mirrored from each other with a distance of 0.50 inches from the edges. Their diameters are 0.19 inches, specifically made for the 10-32 stainless steel screws.

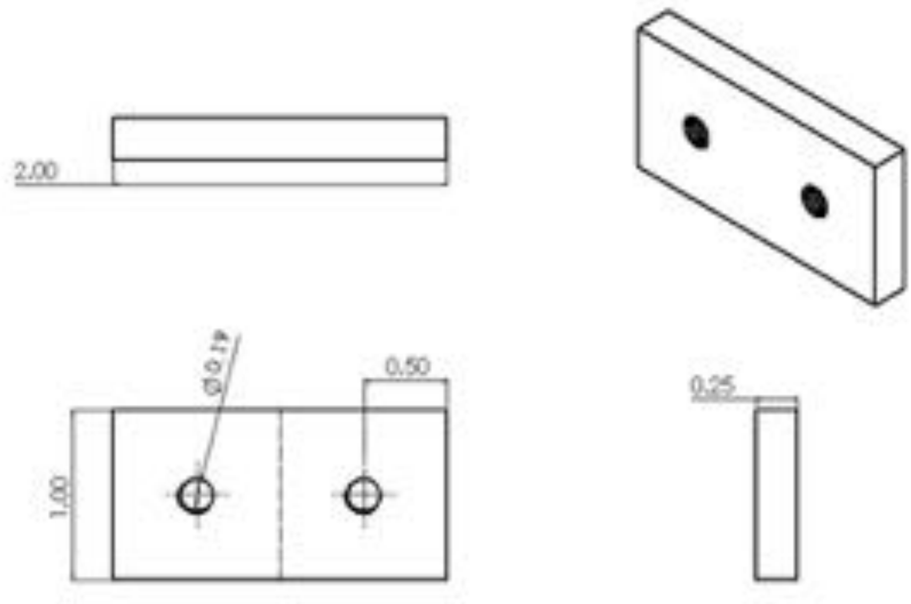


Figure 26. CAD drawing of linkage 3 used in the robot assembly.

The body is also made from acrylic. The width and length sides are laser cut along with the bottom before being welded together with acrylic glue. The pieces are cut into specific “puzzle pieces” that can latch onto each other before being glued. Figure 27 below is a CAD drawing of the body, which is 12 inches wide and 14 inches long with a height of 4 inches. Its thickness is 0.25 inches, which was also chosen in the Makerspace to resemble the thickness of the linkages. This is the housing of the motors and wiring, so it has four sides enclosing it with the top being open to work inside the box. The four holes are mirrored from each other with two being a distance of 0.50 inches from the edges and the more inner holes are 5 inches from the edges. Their diameters are 0.19 inches, specifically made for the 10-32 stainless steel screws. This gives enough spacing for the linkages to fully rotate and move without encountering one another.

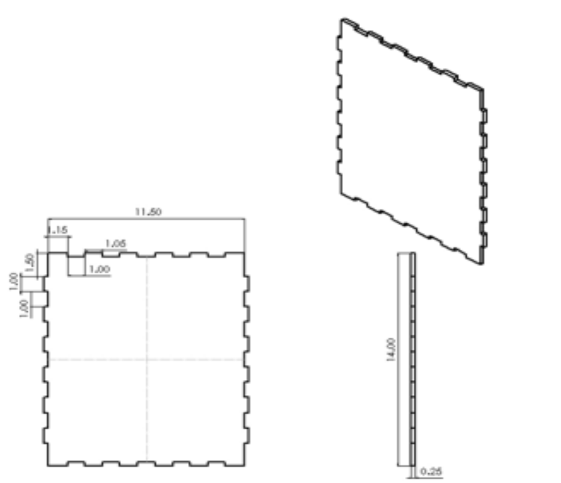


Figure 27a. CAD drawing of the bottom of the body used in the robot assembly.

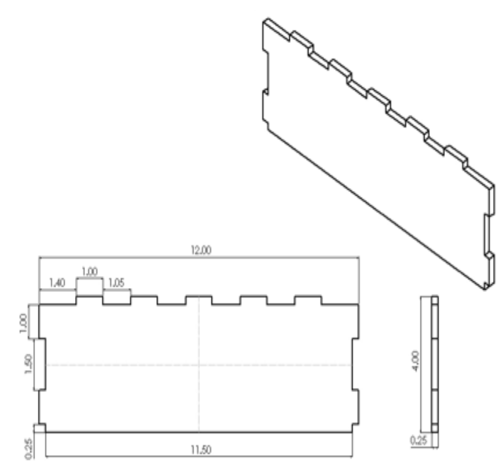


Figure 27b. CAD drawing of the width of the body used in the robot assembly.

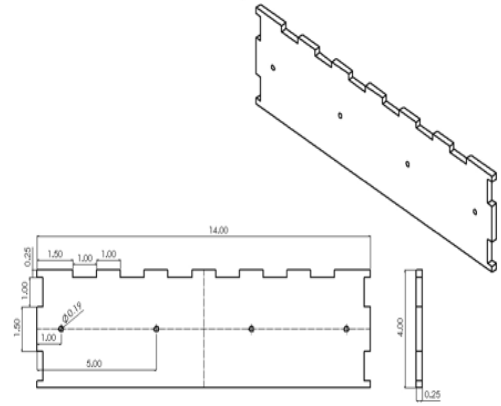


Figure 27c. CAD drawing of the length of the body used in the robot assembly.

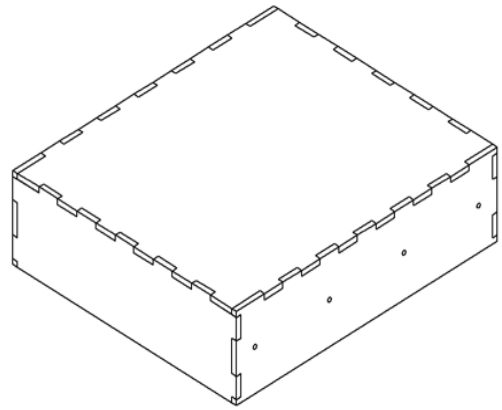


Figure 27d. CAD drawing of the welded together body used in the robot assembly.

Figure 28 below depicts the CAD drawing for the feet. These feet slip onto each leg of the robot. The primary purpose is to provide protection, but also to ensure even torque through the full range of motion. As seen each foot has an arch on either side. As the leg rotates, the load distribution is on the circular path of the arch rather than a sharp, rectangular edge. This foot is 3-D printed from PETG plastic.

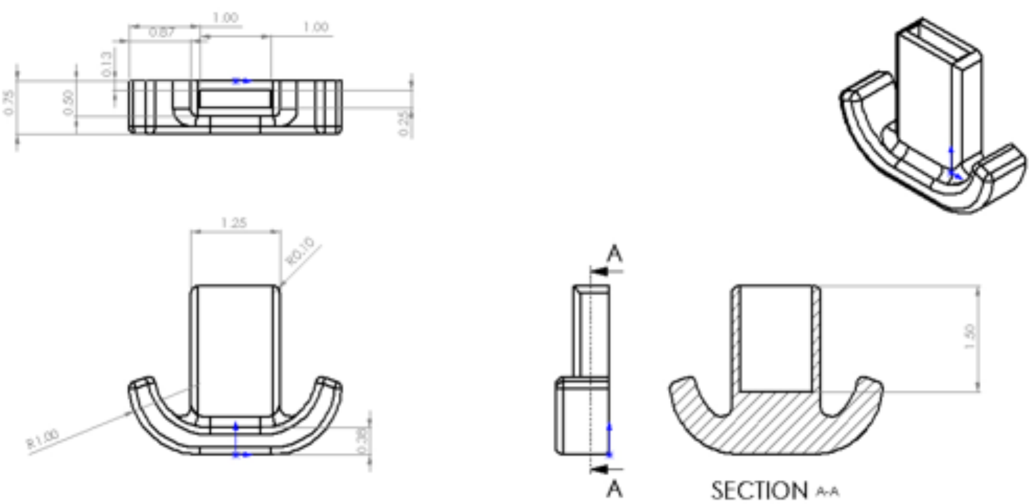


Figure 28. CAD drawing of the feet used in the robot assembly.

Figure 29 shows the CAD drawings for the motors. These motors are responsible for converting electrical energy into rotational mechanical energy. Each continuous servo motor rotates a linkage. This linkage converts rotational mechanical energy into horizontal, translational movement. These motors were purchased from servo city.

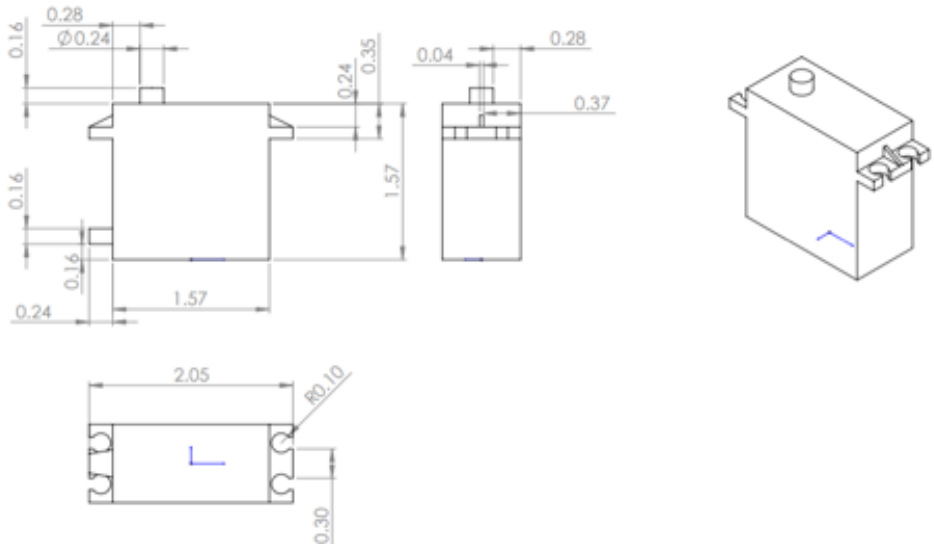


Figure 29. CAD drawing of the motor used in the robot assembly.

Figure 30 depicts drawings for the coupling rods. These coupling rods cover the rotor of the motor and transfers power to the linkage. It is used for power transfer, and it can extend through the acrylic wall of the robot to reach its destination. Another reason for its importance is to mount onto the linkage. As shown below, there are eight mounting holes which ensures it is safely attached.

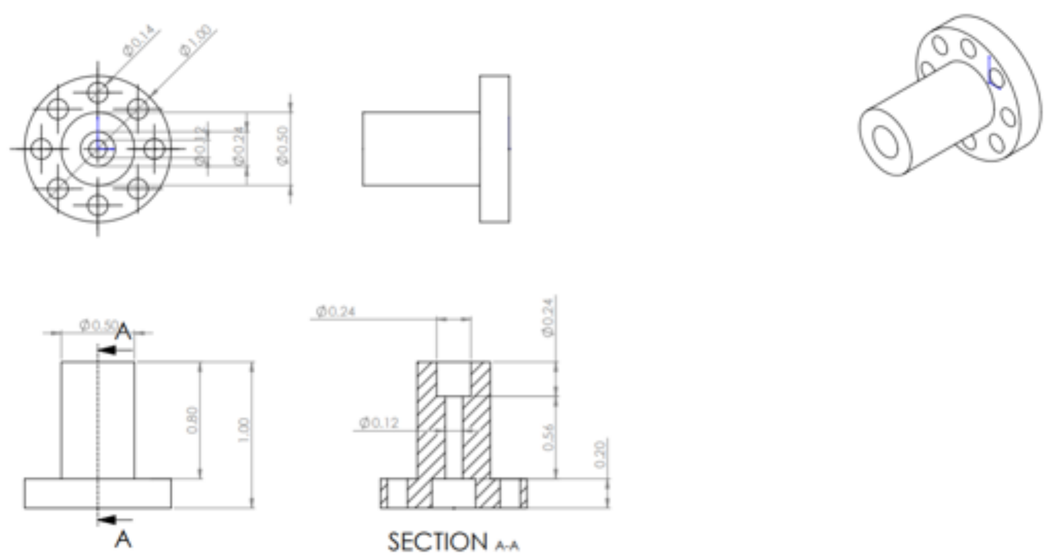
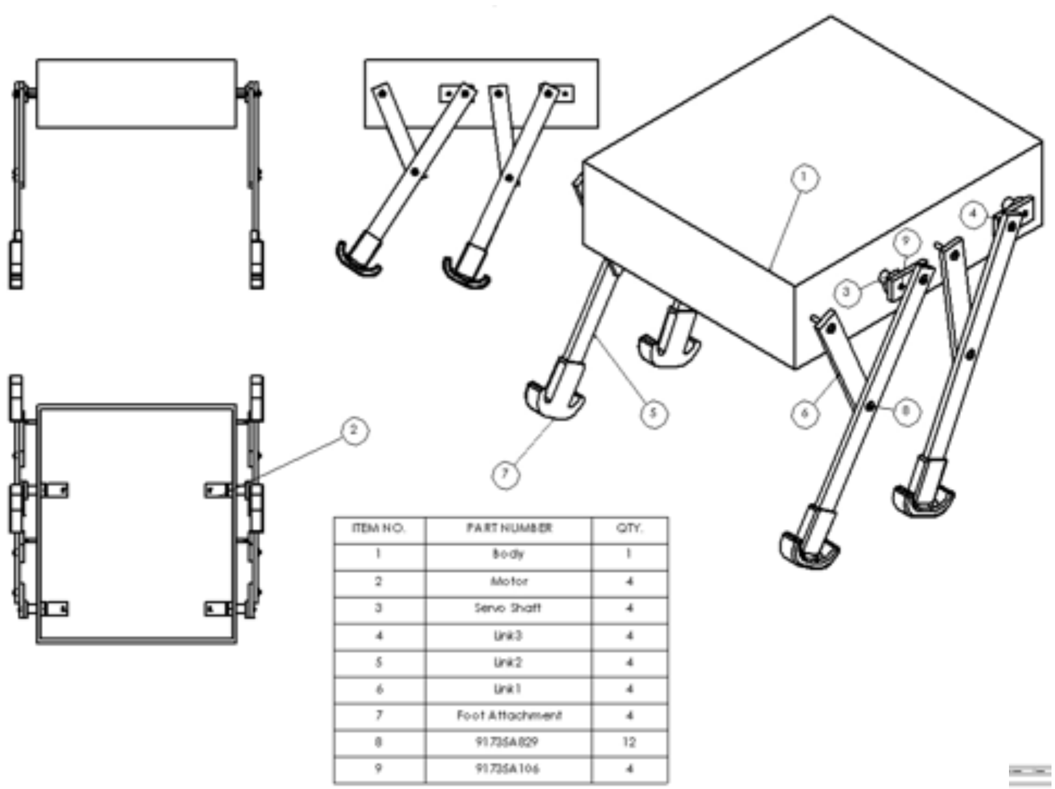


Figure 30. CAD drawing of the servo shaft used in the robot assembly.

The entire quadrupedal robot assembly is presented below in Figure 31. It is assembled from four of each linkage and screws connecting them to one another and to the body. The legs are made to replicate the four-bar mechanism known as Hoeckens mechanism. The purpose of the mechanism is for the smallest linkage, linkage 3, to spin a full 360 degrees, pushing linkage 2 forward as the main part of the leg touching the ground and launching it off of it. Linkage 1 is used as the joint connecting linkage 2 to the body, which offers more control over its movement. The motor is connected to linkage 3 by its specific servo shaft, which need 4-40 stainless steel screws as fasteners. The feet are placed at the bottom of linkage 2, which lets the leg move smoothly on the ground for the entire range of motion before the arch helps "rock" the robot forward.



ITEM NO.	PART NUMBER	QTY.
1	Body	1
2	Motor	4
3	Servo Shaft	4
4	Link3	4
5	Link2	4
6	Link1	4
7	Foot Attachment	4
8	91735A829	12
9	91735A106	4

Figure 31. CAD drawing and bill of materials of the quadrupedal robot assembly.

Appendix D: Motion Study

The Hoeken's mechanism, as shown below in Figure 32, is what the team is using to design the leg motion. This mechanism is a straight bar mechanism that will accomplish the basic needs of this quadrupedal. It is a way for the robot to move in planar motion and to do so quickly and without much error. Its motor rotation is the input whereas the linear motion is the output.

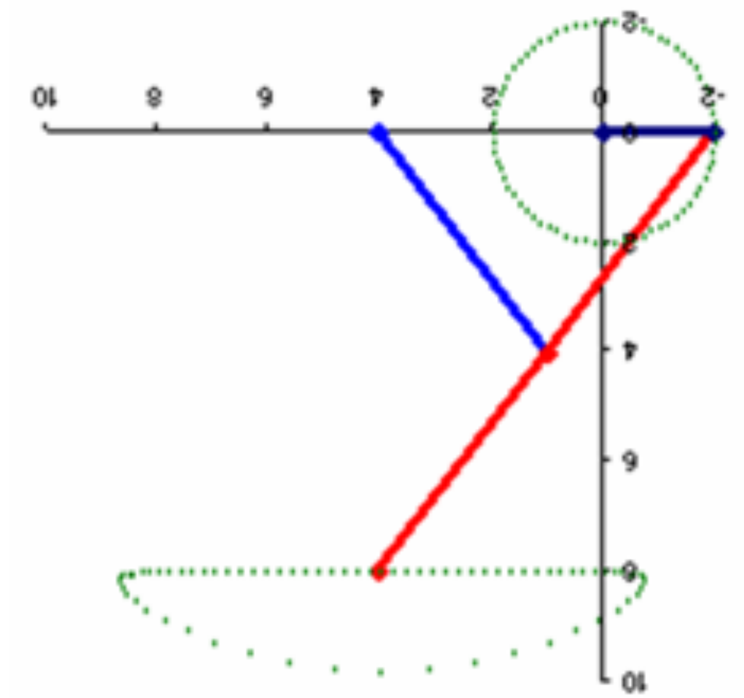


Figure 32. Arrangement of the three linkages in the Hoeken's mechanism.

Figure 33 shows the screenshots taken of the motion study created from the robot assembly. It is assembled, so that each leg has an arched foot to push the robot forward and gives it a wider grip on the terrain. Using Hoeken's linkages, the robot's legs become dynamic and move without the need of a knee joint to lift the feet off the ground. The plan is also to code for the diagonal legs to move together, so the robot has more balance when in motion.

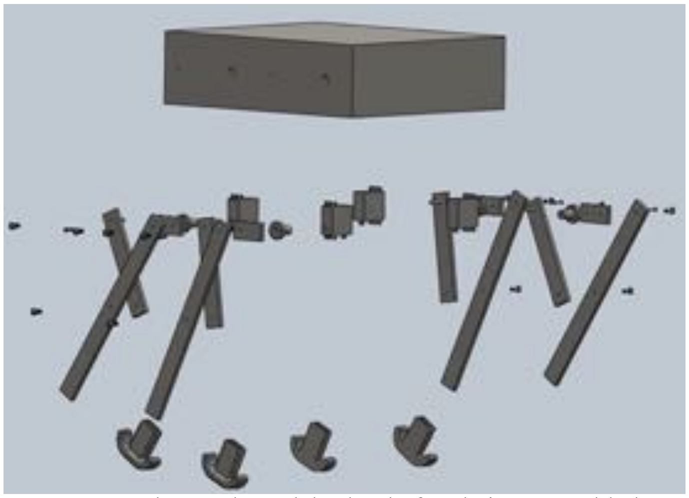


Figure 33a. The quadrupedal robot before being assembled.

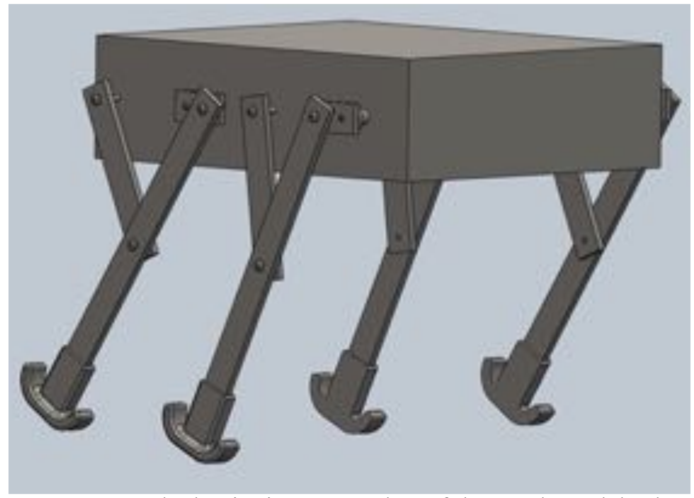


Figure 33b. The beginning screenshot of the quadrupedal robot assembly before movement.

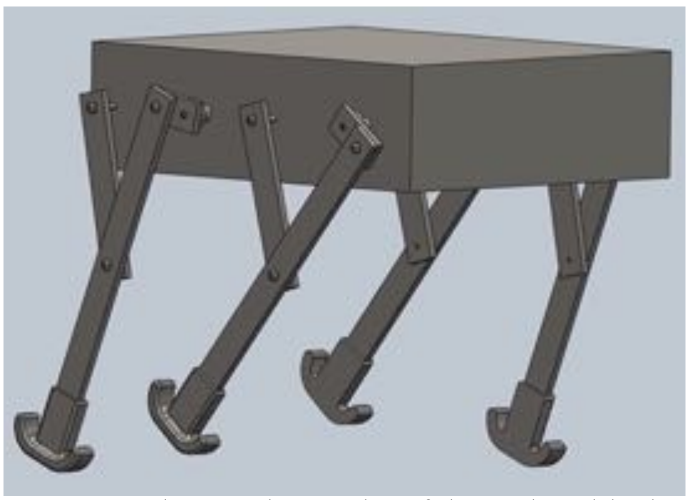


Figure 33c. The second screenshot of the quadrupedal robot assembly once in motion.

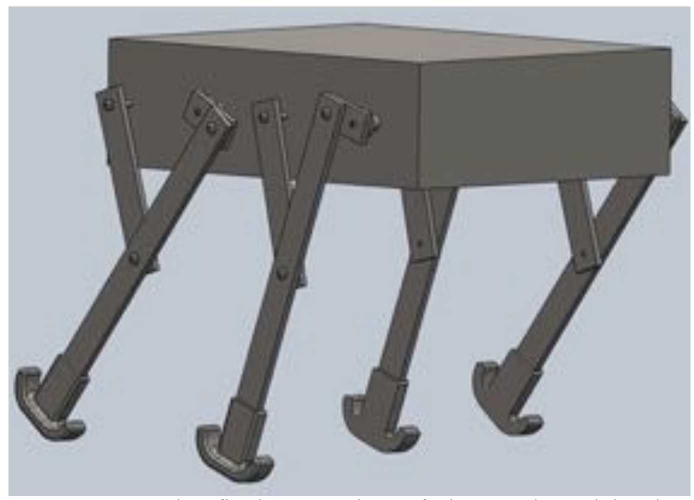


Figure 33d. The final screenshot of the quadrupedal robot assembly once in motion.

Appendix E: Kinematic

Figure 34 depicts the torque required to rotate a single linkage of this design. This is important for determining the motor specifications because each motor will need to output enough torque to rotate a single linkage. This is done by first estimating the entire mass of the robot. This includes the weight of the acrylic, fasteners, and electronics. Then, dividing the weight into four equal components and analyzing a single linkage. Some torque calculations are performed after setting up a free body diagram. The result shows that 136 oz-in of torque is needed from a continuous servo motor. Because the motor really outputs a torque of 167 oz-in this provides a factor of safety of 1.23.

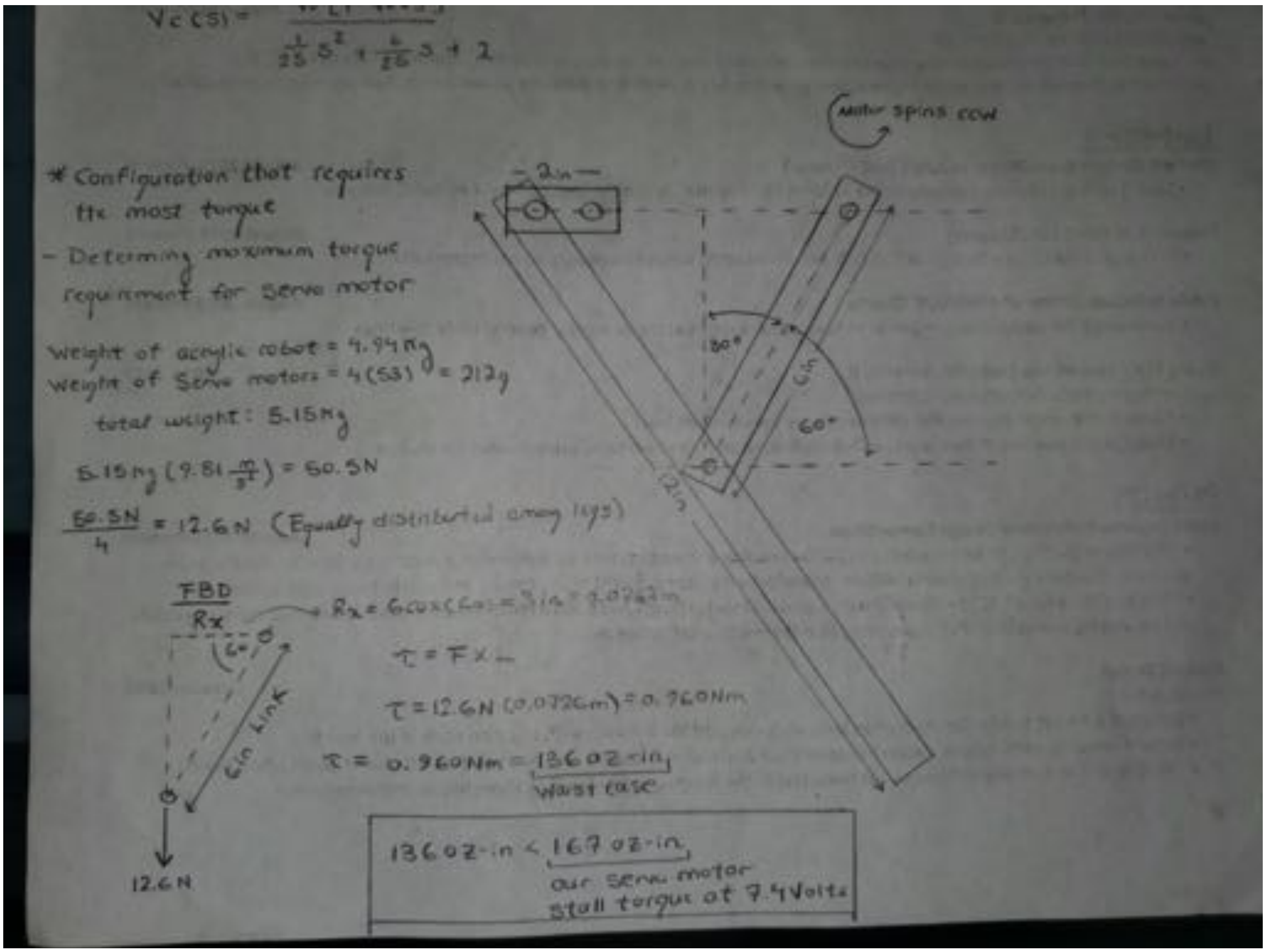


Figure 34. A kinematic analysis depicting the estimated torque required to rotate a single linkage. This is done by estimating the total weight and converting this miss into Newtons. By equally distributing the load among four linkages, some simple torque calculations are performed to get an idea of what is required. The result is 136 oz-in, which is less than the output torque on the motor.

Appendix F: Finite Element Analysis

Configuration 1 (Worst Configuration):

ANSYS workbench is used to determine the von-mises stresses and total deformation that the linkages of the robot experience. To simplify the model some assumptions had to be made. The holes where the bolts would be placed were treated as frictionless supports, the bottom edge labeled B in Figure 37 is treated as a fixed support. The contact regions of the links are treated as frictionless joints as shown in Figure 38. The linkages are made of acrylic and the properties are taken from an online source, the averages for density, Young's Modulus, Poisson's Ratio Tensile yield strength compressive yield strength and tensile ultimate strength are calculated to be 1.19 g/cm^3, 3.2 GPa, 0.370, 75.4 MPa, 120 MPa, and 74.4 MPa, respectively [3]. The weight of the robot is estimated to be 5 kg, and it is assumed that at any given moment the weight is equally distributed between all 4 legs of the robot. Each linkage mechanism has a load of approximately 1.25 kg. For the static structural analysis, a remote force of 12.265 N is placed at the center of gravity of the linkage system. This simulates the moment that the robot takes an initial step. The mesh is set to the finest quality and the element size is reduced to 4.5E-003 meters for link 3.

The total deformation and equivalent von-mises stresses are calculated and shown in Figures 35 and 36. The maximum deformation for the worst configuration is calculated to be 1.138×10^{-6} m, and the maximum Von-Mises stress is approximately 0.28 MPa. The maximum stress occurs along the edge of the fixed support. The deformation plot and Von-Mises stress plot give a general idea of how the material is going to deform and the general weak points of the structure. It shows that there is a need for a cushion/dampening device at the bottom of the links to minimize the stresses in the acrylic links. The resulting design of the dampening device is shown in Figure 36. Further analysis is done for other configurations of the quadrupedal robot. For the second worst configuration, the corresponding total deformation and equivalent von-mises stresses are shown in Figure 37 and Figure 38. The maximum values for deformation and stresses are 1.046×10^{-6} m and 10.24 MPa, respectively. There are limitations to the ANSYS simulation. This is a static structural analysis for a single configuration of the robot; therefore, it only shows the results in one instant of the entire movement. A dynamic rigid body analysis would be an improvement to the simulation that would provide more information about how deformation changes throughout the motion. If the body plastically deforms in one instant this does not carry over to a separate simulation in a static structural analysis.

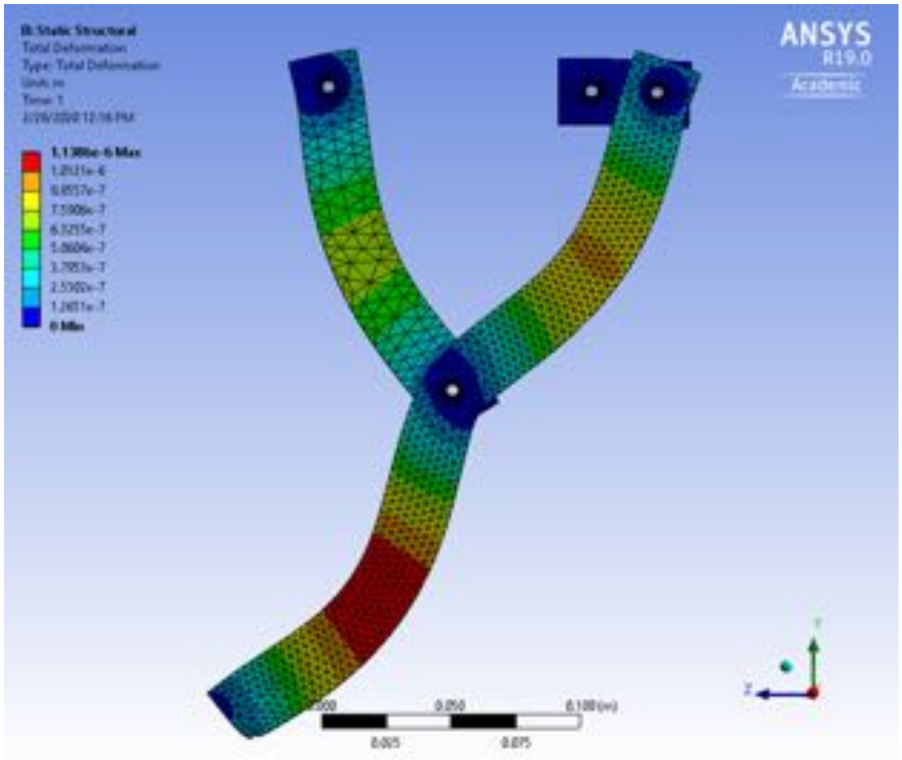


Figure 35. The Total Deformation of a singular leg at the worst position configuration.

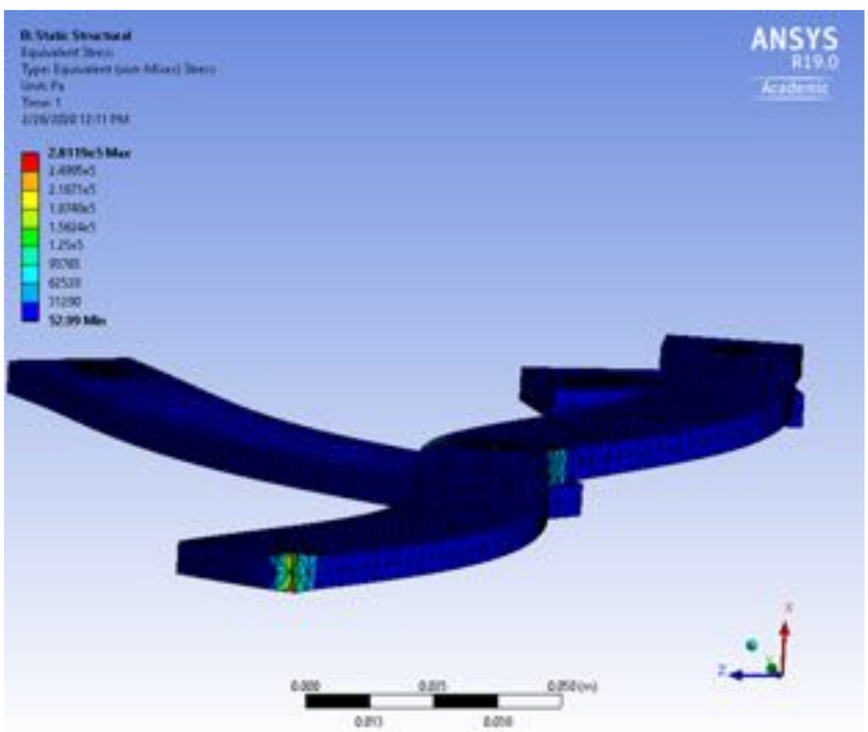


Figure 36. The Equivalent Von-Mises Stresses of a singular leg at worst position configuration.

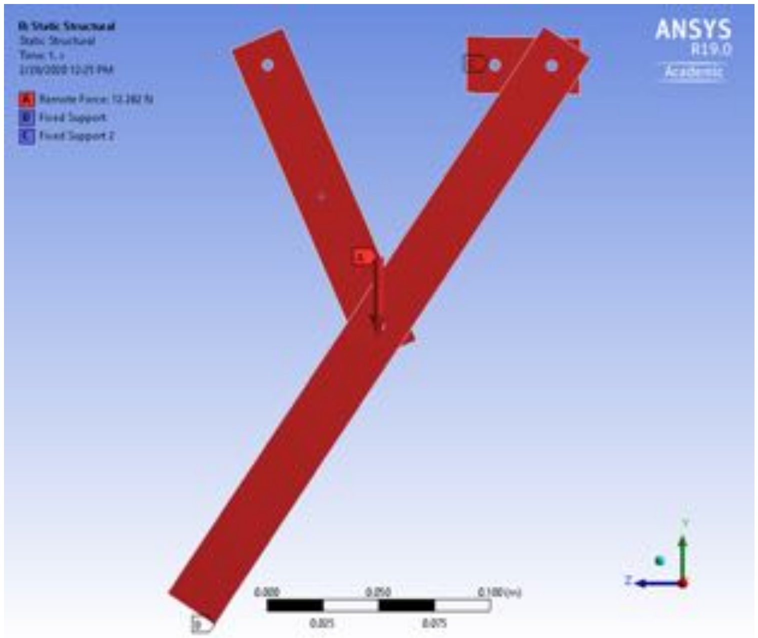


Figure 37. The boundary condition's fixed supports and a remote force of 12.265 N when a singular leg is at worst position configuration.

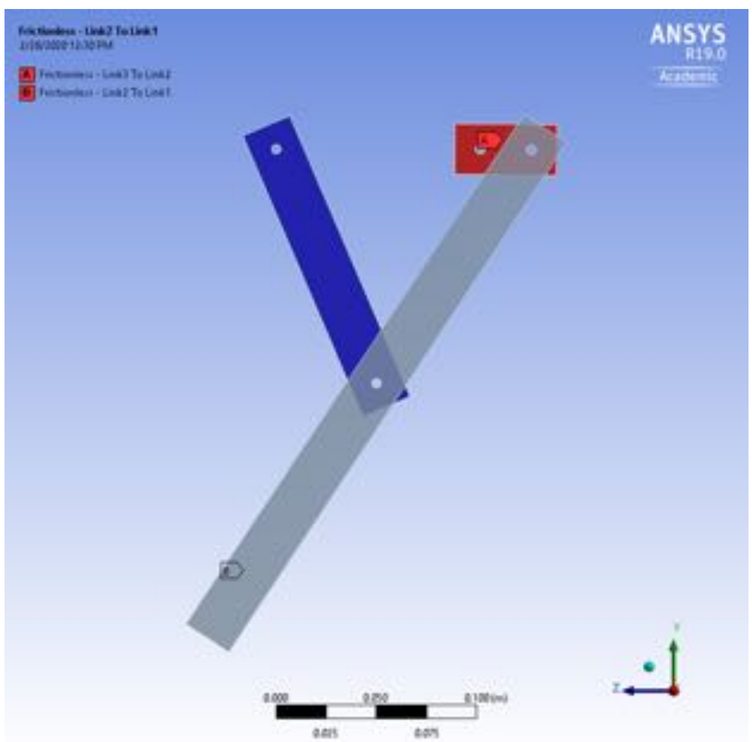


Figure 38. The boundary condition contact region is defined as Frictionless joints when at worst position configuration.

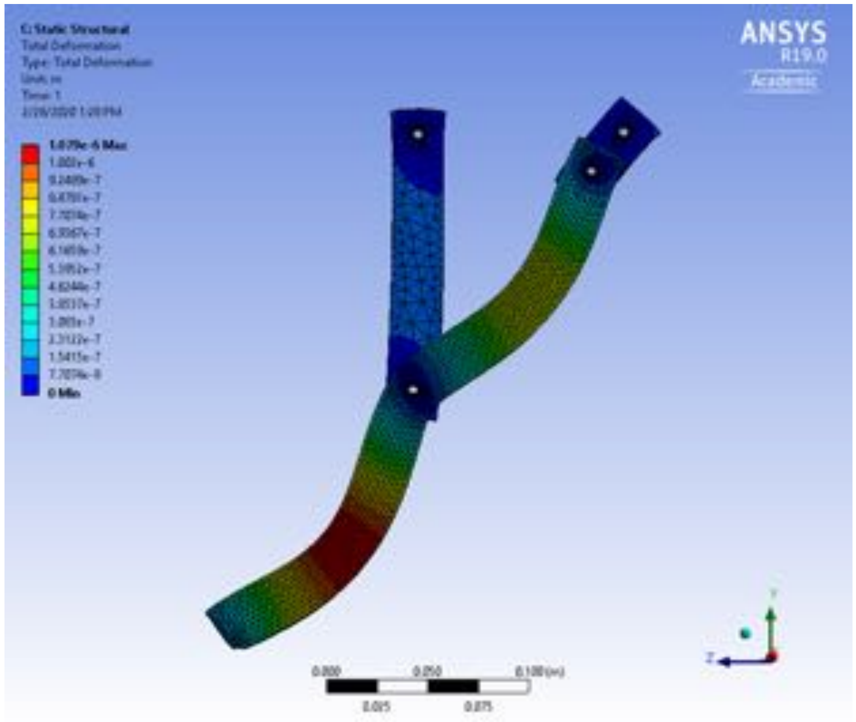


Figure 39. The Total Deformation of a singular leg at the second worst position configuration.

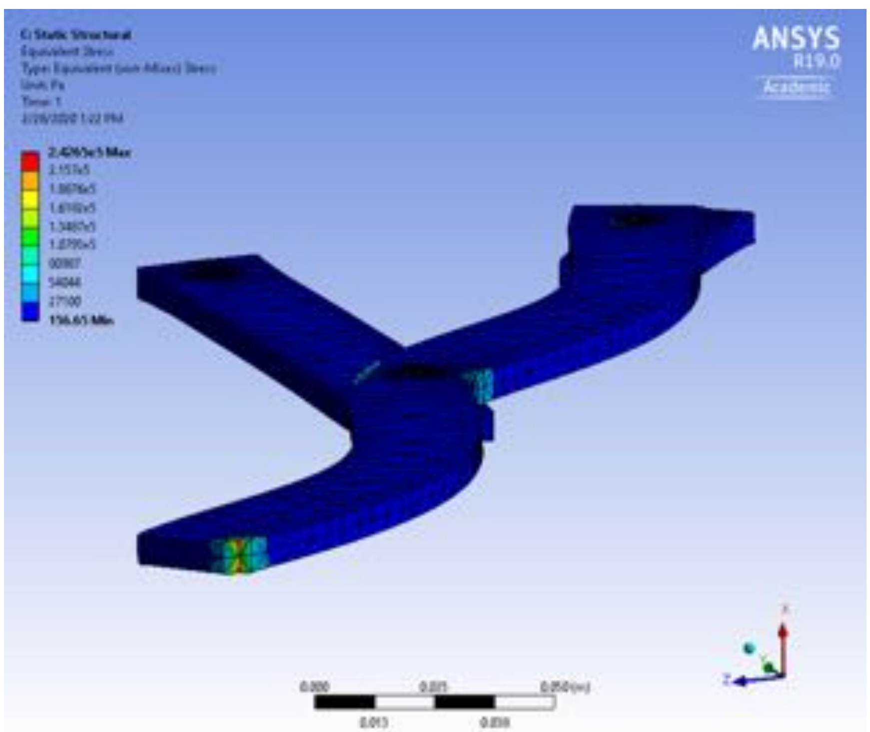


Figure 40. The Equivalent Von-Mises Stresses of a singular leg at the second worst position configuration.

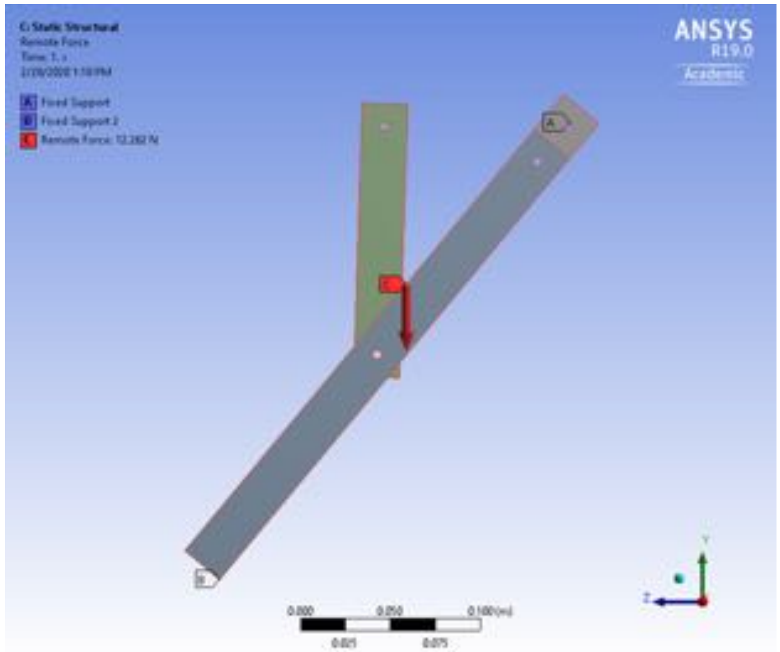


Figure 41. The boundary condition's fixed supports A & B. Ribbon C identifies a Remote Force of 12.262 N located at the center of gravity for the second worst leg position configuration.

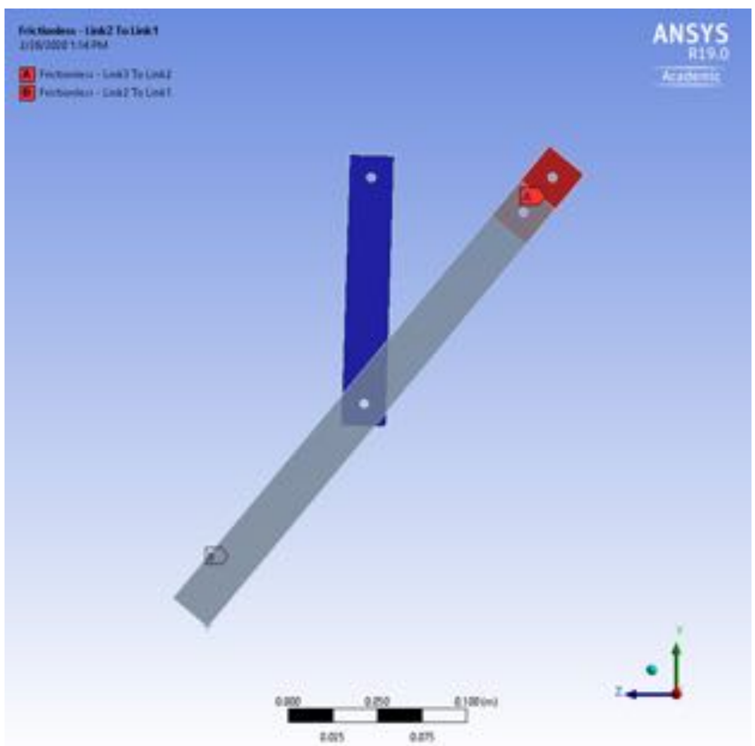


Figure 42. Boundary conditions for the contact regions are defined as Frictionless joints for the second worst leg position configuration.

Appendix G: Project Charter

1. **Sponsor:**

Pranav Bhounsule
Robotics and Motion
Laboratory

2. **Project Title:** P06 Quadrupedal Robot

3. GOAL(s)/ OBJECTIVE(s):
1. Design a quadrupedal robot: four-legged robot which exhibits quadrupedal motion (legged locomotion)
2. Low production cost (within budget of <$200)
3. Be easy to reproduce and machine and use standardized, easily available off-the-shelf components
4. Device must function using open source software (Arduino etc.)
This Project does not include: (if needed to clarify goal)

4. DEFINITION(s) OF DONE:
1. Complete CAD/ANSYS for finalized design
2. Motion study of the quadrupedal robot, completed through SolidWorks
3. Project Binder/Final Report

5. KEY METRICS:	
Metric	**Description**
1. Cost	Determined by the production cost of one unit. The aim is less than $200
2. Number of Parts	The objective is to minimize the number of parts for easy assembly. Target part count less than 25.
3. Degrees of Freedom	The objective is to have a quadrupedal robot that moves at least planar motion.
4. Speed of the robot	Target speed of 0.25 – 0.3 m/s.
5.Usability of the code for the quadrupedal robot	Measures the ease of access/use of the code. Rated 1-10 (10 = easy to navigate)

6. PROJECT TEAM:	**Primary Name/Phone #s:**	**Email Address**
Sponsor	Pranav A. Bhounsule 312-355-8991	pranav@uic.edu
Faculty Advisor	Atif M. Yardimci 630.460.6779	atify@uic.edu
Project Manager		
Project Team and function	Liridona Ashiku	lashik02@uic.edu
	Maha Mohammad	mmoham46@uic.edu
	Nick Pippin	npippi2@uic.edu
	Eric Silva	esilva21@uic.edu

7. KEY ASSUMPTIONS and NECESSARY CONDITIONS:
1. Must be legged locomotion (quadrupedal)
2. Actuation of the device, it can be either passive/active actuation.
3. Steady-state, repeatable motion on flat ground
4. Code used for the device must be open source

8. TIMELINE/SCHEDULE:			
Major Project Milestones	Plan Date	Latest Best Estimate	Completion Date
Patent/Literature Search	11/13/19	11/19/2019	11/19/2019
Linkage Design and Analysis	11/13/2019	11/19/2019	11/19/2019
Cost Analysis	11/19/2019	12/03/2019	12/03/2019
Proof of Concept	01/14/2020	01/21/2020	01/20/2020
Motion Study of the robot	02/11/2020	02/25/2020	02/21/2020
Coding Planar Motion	02/11/2020	02/25/2020	02/19/2020
Finalize Design	03/24/2020	04/03/2020	04/01/2020

9. RISKS:		
Risk Description	Risk Owner	Plan to address
1. Terrain Limitations	Liridona A.	Change foot material to increase/decrease grip.
2. Quadruped motion diverts from path	Nick P.	Adding stopping mechanism.
3. Linkages do not clear grounding	Maha M.	Change number and location of linkages.
4. Coding fails	Eric S.	Troubleshoot and fixing bugs.

10a. DOCUMENTATION:			
Document #/Name	*	Person(s) Responsible	Description
1. Specifications	Objectives/constraints	Liridona A.	QFD and Fish bone diagram.
2. Quantitative Analysis	Cost Analysis	Maha M.	Bill of materials, and decision matrix.
3. CAD design	3D design	Eric S./Nick P.	Modeling with Solidworks and linkages software
4. Final Product Drawings	Finalizing Design	ALL	CAD drawings for each part.

10b. DOCUMENTATION: **KEY ASSUMPTIONS**	
1. Bill of Materials/ Cost analysis	Specific parts used in design and materials for production cost
2. Patents	Similar design and inspiration for the robot
3. Simulation from Linkages	Analyzing the angles of motion,
4. CAD drawings	Detailed design of parts and assembly with dimensions

10c. DOCUMENTATION TIMELINE/SCHEDULE:	
Document #/Name	Key Dates:
1. Bill of materials	12/03/19
2. Patents	11/19/19
3. Simulation from Linkages	11/19/19
4. CAD drawings	02/27/20
5. Motion Study Simulation	04/01/20
6. Results from Testing	04/03/20

10d. DOCUMENTATION RISKS:	Risk description, owner, and plan to address (in order of significance).	
Enter "All" or Document #/Name	Risk Description / Plan to Address	Risk Owner
1. Linkages Simulation	Simulation does not match what actually occurred	All
2. Cost Analysis	The price is more than expected – the team can see what items could be cut down in material cost	Maha
3. Not usable for classroom objectives	Product not ideal for classroom demonstration. Address concern if it too complex, address code and parts list	All
4. Device Fails	Find failure mode example speed limit, give recommendations on future design. If not balanced it might need to be tethered	All

11. PROJECT CHARTER APPROVALS:		
Project Sponsor: Pranav A. Bhounsule	PBhounsule	Nov 19, 2019
Team Members: Liridona Ashiku	Liridona Ashiku	date: 11/19/19
Maha Mohammad	[signature]	date: 11/19/19
Nick Pippin	Nick Pippin	date: 11/19/19
Eric Silva	Eric Silva	date: 11/19/19
Other: ATIF YARDIMCI	[signature]	date: 11/15/19