8 DOF Quadrupedal Hopping Robot

Senior Project Report

June 3, 2021

Spring 2022 ME 430-05 Group F72

The B.R.U.C.E. Bot Engineers

Tyler McCue   Daniel Munic

Clayton Elwell   John Bennett

Technical Assistance: Henry Bouma

8dofseniorproject@gmail.com

Prepared for Dr. Siyuan Xing and Charlie Refvem

Department of Mechanical Engineering

California Polytechnic State University, San Luis Obispo

sixing@calpoly.edu crefvem@calpoly.edu

Statement of Disclaimer

Abstract

The goal of our senior project was to fabricate an eight degree of freedom (DOF) prototypical quadrupedal robot, develop a controller than commands the quadruped to repeatedly jump 10 cm in the air, and fabricate a modular test stand to safely deploy our controller on the quadruped. The creation of a functional quadruped will bring attention to Dr. Siyuan Xing and Charlie Refvem's research group, Cal Poly Legged Robots, and will give future Cal Poly undergraduate and graduate students a learning tool to explore dynamic control of biomimetic robotic systems.

Over the course of our senior project, we successfully manufactured the mechanical quadrupedal prototype, we fabricated a wire harness to power and communicate with the actuators in our system, we developed a controller in MATLAB/Simulink that commands our quadruped to repeatedly jump 10 cm in the air, and we fabricated a modular test stand that holds our necessary electronics and facilitates the quadruped's dynamic motion. This hopping robot will be a platform for future Cal Poly students to develop control algorithms for future senior projects and master theses, with one such being student Patrick Ward's Master's Thesis in which he is developing a bounding gait simulation in MATLAB/Simulink that will be deployed onto the quadruped in a later senior project.

Our success in developing a quadrupedal prototype and verifying its functionality (durability, centered mass, manufacturability) has also drawn attention to Cal Poly Legged Robots from both students at Cal Poly and the Industrial Advisory Board (IAB). This will ensure that future students at Cal Poly are interested in becoming involved with CP Legged Robots and that funding will be available to continue researching and improving our software, electronic hardware, and mechanical system.

Introduction

Our project's goal was to manufacture an 8 DOF prototypical quadrupedal robot and develop a controller to make the robot execute a repeatable jumping motion. In addition, we wanted to fabricate a modular test stand to let us safely test our controller on the quadrupedal prototype. We successfully achieved these goals and were able to manufacture both the quadruped and test stand and develop a MATLAB/Simulink controller that commands the robot to execute a repeatable hopping motion with a 10 cm vertical.

This report is divided into four sections, each a separate report. Below is a list of the four sections that compose our senior project report:

Part I: Scope of Work

Part II: Preliminary Design Review (PDR)

Part III: Critical Design Review (CDR)

Part IV: Final Design Review (FDR)

The first section is our Scope of Work (SOW) document, which convinces our sponsor that we clearly understand what the problem statement and scope of the project are. It also verifies that we have studied existing solutions and performed initial analysis to define the problem. For the SOW document, we also developed a process to effectively solve the problem and acquired the necessary resources and time to complete the tasks related to the project.

The second section of this report is the Preliminary Design Review (PDR) document, in which we describe our concept generation and selection processes, then explain our selected design concept, and lastly provide evidence indicating that our concept will work.

The third section of our report is the Critical Design Review (CDR) document, which contains the full details of our design such that someone else could build it for us. Another purpose of this document is to convince our sponsor that our final design will meet all our specifications. We provide the full details and explanation of our final design, in addition to details explaining how it will meet the design specifications. The CDR document also gives a detailed description of how to produce our verification prototype and describes the planned tests and required resources.

The final section of our report is the Final Design Review (FDR), which contains any new material since CDR. It also describes the manufacturing and design verification activities that we have completed since CDR. The FDR report also contains our final project budget, bill of materials, user manual, and test procedures.

These four reports comprise our entire senior project experience and the process we took to develop the quadrupedal prototype and test stand.

Scope of Work

2021-2022 Senior Project Group F72

California Polytechnic State University

October 20, 2021

Abstract

The key objective of our senior project is to develop a prototypical 8 degree of freedom quadrupedal robot that can execute a repeatable vertical hopping motion. We simplified this overarching objective into smaller functions to make the task of creating a robot easier to manage (functional decomposition). To accomplish these objectives, we performed preliminary summer research to design a single hopping leg and have researched existing quadrupedal robot solutions to understand quadruped designs and their design processes. Furthermore, we have identified key customer requirements and engineering specifications in our robot design. Our research, functional decomposition, and identification of requirements and specifications have guided us in developing a detailed plan outlining the timing of our senior project execution over the next three quarters and has inspired our design process.

A thorough and well-organized project plan will result in a quadruped that attracts members to the Cal Poly Legged Robots research group, as well as the Cal Poly Robotics club; in addition, the quadruped will provide an opportunity for underclassmen at Cal Poly to further their knowledge of robotic design and control. This project's scope will include the development of a tangible quadrupedal robot prototype, an on-board controller that commands the quadruped to execute a vertical hopping motion, and a modular test stand for testing the control algorithms that are developed during our senior project and by future Cal Poly engineers.

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1. Introduction

1.1 Design Challenge

The design challenge for this senior project is to develop a prototypical model of a quadrupedal robot, which will be used to expose underclassmen at Cal Poly to the process of robotic mechanical design and the development of robotic control algorithms.

1.2 Team

The F72 8-DOF quadrupedal robot senior project team consists of three Mechanical Engineers, Clayton Elwell, John Bennett, Tyler McCue, and one Computer Engineer, Daniel Munic. This team's diverse skillset and determination will assist in making an 8-DOF robot hop independently of a test stand. A clear understanding of the problem and scope are needed to efficiently accomplish the projects goals. This document lays out the scope of the project and will help guide and support future decision making.

2. Background

2.1 Customer Research

As described by our sponsor, Dr. Xing, the stakeholder needs relate to the manufacturing cost and functionality of the 8-DOF robot. Our sponsor has allocated $5,000 for the development of the quadruped and accompanying test stand. Regarding the robot's functionality, our sponsor has requested that the inertia of the leg be concentrated on the body frame, which will improve the response time of the robot to input torques from the DC motors that actuate the legs. In addition, the batteries on the robot should allow operation for at least 30 minutes, and the batteries and microcontrollers should be easy to install inside the body frame. The prototypical quadruped should be able to execute a repeated vertical leaping dynamic motion, and the mechanical components of the robot must have the durability to not fail from this repeated fatigue stress.

2.2 Product Research

A variety of businesses and universities have developed quadrupedal robots for commercial and research purposes. The robot that inspired much of the single-leg design that has already been developed during this project is the MIT Mini Cheetah, which was developed by Ben Katz at MIT (Figure 1).

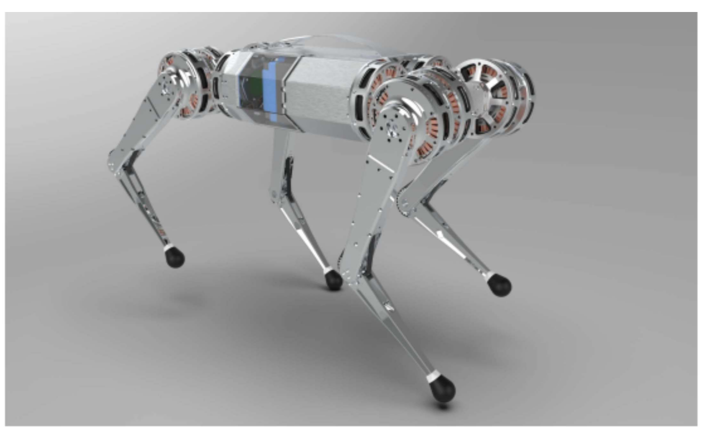

Figure 1. *MIT Mini Cheetah Robot. [Reference 1]*

The Mini Cheetah is a portable robot that can execute a variety of complex dynamic motions. In addition to producing the Mini Cheetah, Ben Katz developed a modular actuator, and proceeded to make his mechanical actuator design and motor driver firmware open source. This open-source information was utilized by a variety of international manufacturers who produced imitations of these actuators and began to sell them commercially. Since all the motor controller hardware and firmware is under the MIT License, the information is free to use by anyone. We purchased two of these actuators from international manufacturers because they provide adequate torque and have a convenient interface to send data to and from the actuators (Figure 2). Currently, Cal Poly Masters student Craig Kimball is working to develop a low-cost actuator of his own. Craig's motor design parameters were based upon the theory developed in MIT's Introduction to Power Systems class [Reference 2]. The eventual goal for the project is to implement his actuator in our robot design and thus reduce the overall cost of the robot.

Figure 2. *MIT actuator (left) and international manufacturer's actuator (right). [Patent 1] [Reference 3]*

Stanford has also produced a quadrupedal robot of their own. The Stanford Doggo is a quadrupedal robot that has four-bar linkages for legs, rather than a two-bar linkage which many other quadrupeds utilize (Figure 3). While the Stanford Doggo's four-bar linkage legs can execute a backflip much like the Mini Cheetah, we decided to make our single-leg prototype a two-bar linkage to minimize the rotational inertia of the leg.

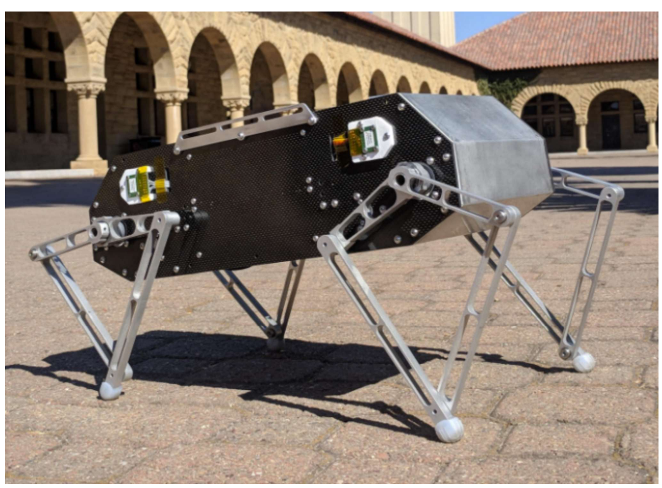

Figure 3. *Stanford Doggo Quadruped. [Patent 2]*

A well-known product that is significantly above our project scope is the Boston Dynamics Spot quadruped. This product is the current premier quadruped and has been utilized by a variety of organizations for surveillance and search-and-rescue missions, to list a few applications (Figure 4). However, since the cost per unit is $75,000 and the scale of the robot is quite large, it does not quite align with the goals of our project.

Figure 4. *Boston Dynamics Spot Quadruped. [Patent 3]*

Another four-legged robot in production that we investigated was the Unitree A1 (Figure 5). This robot is similar in scale to our robot design, as well as the Mini Cheetah. In addition, it is of a more reasonable price when compared to the Boston Dynamics Spot robot, with a price tag of less than $10,000. It has similar functionality to the Boston Dynamics Spot robot, but on a smaller scale.

Figure 5. *Unitree A1 Quadruped. [Patent 4]*

While the Boston Dynamics and Unitree quadrupeds are very aesthetic and highly functional, their extremely high production cost has made our senior project group hesitant to pursue their level of functionality. Instead, we decided to focus more intensely on the quadrupeds produced by MIT and Stanford, as these were produced on a lower budget and by institutions, rather than businesses looking to make profit on their products.

2.3 Technical Research

As mentioned at the beginning of the Product Research section, most of our technical research was focused on the MIT Mini Cheetah mechanical design and control development. Starting with the mechanical design, the first step in developing a four-legged robot is to design a single leg, which can later be manufactured three more times to produce four total legs. Thus, we read through Ben Katz's thesis describing his process of designing the Mini Cheetah legs; his leg design couples the actuators in series at the hip joint, which dramatically reduces the rotational inertia of the leg [Reference 1]. Since the knee actuator is located at the hip, a timing belt driven by two pulleys transfers the actuator torque from the hip to the knee joint to actuate the calf link. A timing belt requires proper tensioning, and thus we referenced SDP/SI's Timing Belt Manual to calculate the appropriate belt tension to prevent tooth skipping and subsequent undesired belt wear [Reference 4]. In addition, we determined that Gates brand timing belts are the best commercial belts, and specifically the Gates Poly Chain GT Carbon belt fits our application due to its incredibly stiff Kevlar/aramid interior; after selecting this belt we consulted Gates's Poly Chain drive design manual which allowed us to select the proper belt length and tooth pitch for our application [Reference 5]. Since these timing belts have a specific tooth profile and pitch, we also consulted Gates's technical bulletin to ensure that we selected the appropriate pulley tooth profile to drive the timing belt and ensure proper torque transmission [Reference 6].

Along with the leg design, the actuator selection is incredibly important. As mentioned in the Product Research section, international manufacturers sell imitations of Ben's actuators for essentially the same price that it costs him to manufacture them (~$300-$350/unit). Due to their reasonable price, high torque density, and preinstalled motor driver boards we used them to actuate our initial prototype [Reference 7]. These actuators are nearly identical to those produced by Ben at MIT, and thus we referenced his motor driver documentation heavily when learning how to command the rotational speed, rotational position, and feed-forward torque via CAN (Controller Area Network) protocol [Reference 8]. Since these motors do have some slight differences when compared to Ben's original actuators, we referenced open-source documentation for these actuators that was produced by a popular robotics YouTuber [Reference 9].

Arguably the most important consideration in this project is the development of a robust yet efficient control algorithm. Since none of us have taken any classes pertaining to development of control algorithms, both linear and non-linear, our process of developing the controls for the single hopping leg was based heavily upon trial and error. We initially read through the control algorithms developed by engineers at MIT but realized that these graduate level control algorithms were simply unreasonable to implement in the short time span of one summer [Reference 10]. These advanced algorithms have also been utilized by engineers at Boston Dynamics, and usually mandate a gait scheduler which adjusts controller gains to facilitate a smooth bounding or walking motion [Patent 5]. Instead, we utilized a simpler approach given to us by Dr. Xing, which involved using a position control scheme when the leg is in the air, and an impedance control scheme when the leg is in contact with the ground [Reference 11].

3. Project Scope

3.1 Boundary Diagram

The project scope includes the development of a quadrupedal robot and the controls to make said robot execute a vertical hopping motion. Thus, inside of the boundary is the quadruped itself and the software/firmware that controls its motion (Figure 6). To facilitate this motion is a test stand which will stabilize the robot, and a human will be needed to ensure that the robot is functioning as intended.

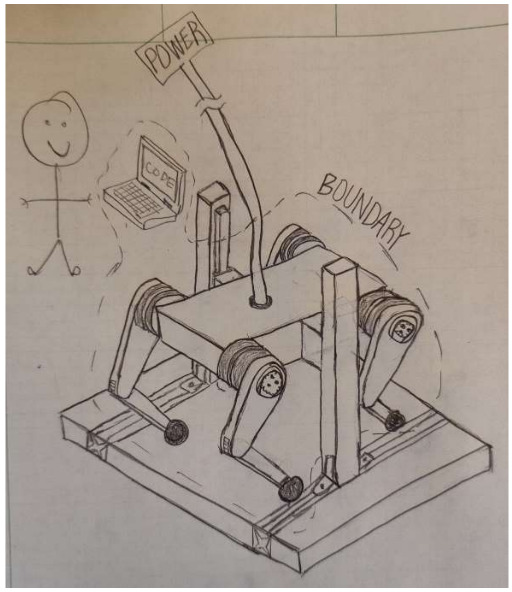

Figure 6. *Senior Project Group F72 Boundary Diagram.*

Since the test stand and human observer only facilitate the motion of the robot, we decided to place them outside of the boundary.

3.2 Stakeholder Needs

As seen in Table 1, the stakeholder needs relate to the dynamic abilities of the robot, as well as its mechanical durability. In addition to this, the robot must be relatively easy and quick to assemble, and able to operate for a prolonged time interval (ideally 30 minutes). Dr. Xing's final requirement is that we remain under his budget of $5,000.

Table 1. Stakeholder wants and needs.

Needs:	**Wants:**
Vertical Leap Control Algorithm	Reasonable Battery Capacity
Functional Test Stand	Ease of Assembly
Within Cost Range	Low Leg Inertia
Manufacturable at Cal Poly	Mechanical Durability
Teachable to underclassmen	Modular/Portable

3.3 Functional Decomposition

Hopping is the key function necessary in the 8-DOF Robot to satisfy the customer. To better understand what must be accomplished to achieve this goal we used Functional Decomposition to break down the function into smaller parts (Figure 7).

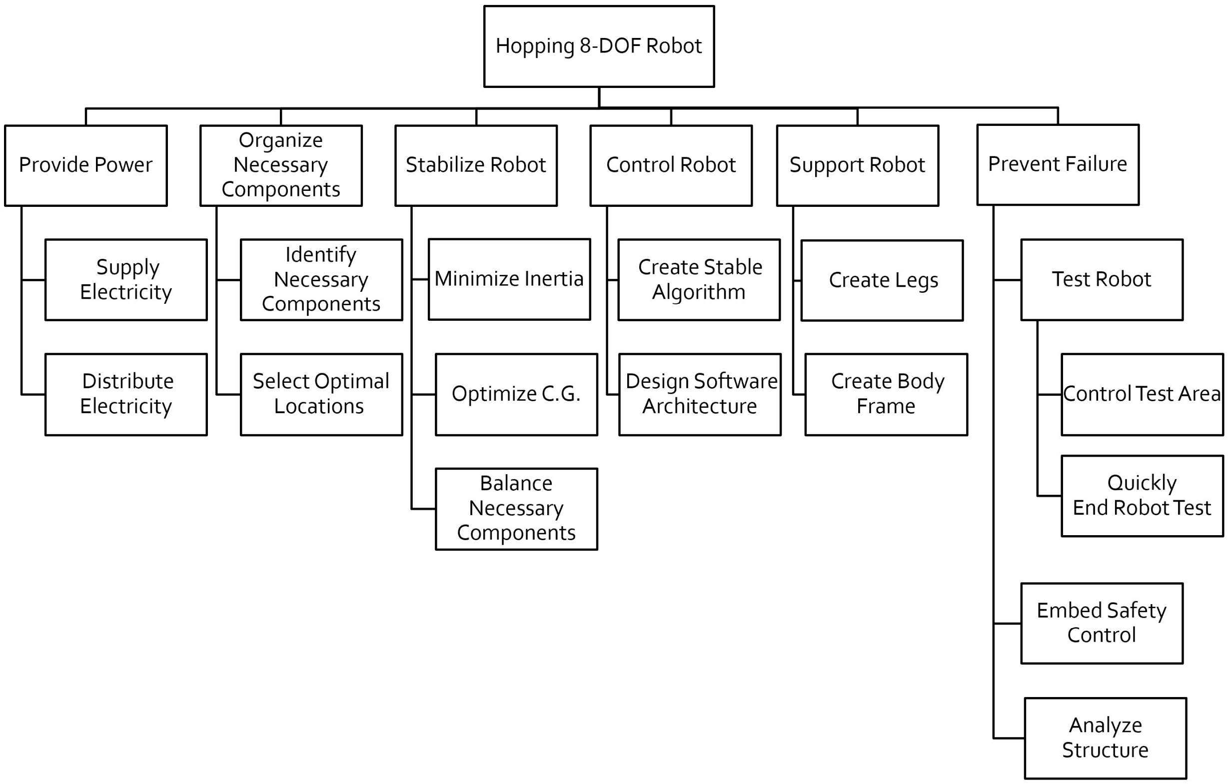

Figure 7. *Senior Project Group F72 Functional Decomposition Diagram.*

Providing power will allow operation of microcontrollers and actuators to control hopping, organized components will assist in ease of assembly, a stable hopping gait will require low inertia and an optimally placed Center of Gravity (CG). Robot Control algorithms and microcontrollers are needed for hopping and hop height logic. The Robots Supports will be the legs to catch the robot and the body frame holds the brains. Preventing failure requires machine durability, safety control logic, and a safe testing zone while optimizing the robot's controls.

3.4 Planned Deliverables

The planned deliverables for this project include the prototypical quadruped, as well as a shared repository containing the relevant control algorithms to command the robot. In addition, a functional test stand will be created to facilitate the vertical hopping motion of the robot. For user ease, a complete BOM and set of assembly instructions will be provided as well. Sufficient documentation of the control algorithm will also be provided so that future engineers may understand the process of how we developed our controller.

4. Objectives

4.1 Problem Statement

Currently Cal Poly students do not have enough exposure to a structured learning environment for robotic design and robotic control outside of class curricula (specifically ME 423). Dr. Xing the project sponsor has requested the development of an 8-DOF quadrupedal robot, which will be the subject of research and development for the Cal Poly Legged Robots club and the Cal Poly Robotics club. These clubs will allow underclassmen at Cal Poly to learn about robots before they decide to take upper division classes such as

ME 423 (Robotics), and thus facilitate extracurricular opportunities to develop their knowledge and passion for robotics.

4.2 House of Quality

The list of QFD requirements was developed to list different ways to test the performance of our quadruped and thus evaluate how well the customer requirements are met. Both the requirements and testing methods may be referenced in the HOQ "customer requirements" section, which is included in Appendix A. Table 2 gives a summary of the information included in the HOQ.

Table 2. Engineering Specification Table.

Spec #	Specification Description	Requirement or Target	Tolerance	Risk*	Compliance**
1	Vertical Leap Height	10 cm	Minimum	L	T
2	Fatigue Durability	30 minutes of operation	Minimum	M	T
3	Assembly Time	5 minutes	Maximum	H	T
4	Weight management	10 kg	Maximum	L	A, I
5	Center of Gravity	< 0.5" From Center	±1 inch	L	A, I
6	Compilation Time	5 Minutes	Maximum	H	T
7	Total cost	<$5,000	Maximum	M	A
8	Avoid Rolling	Δt between side impacts < 0.05 sec	Minimum	M	T
9	Avoid Flipping	Δt between front & back impacts < 0.05 sec	Minimum	M	T
10	Leg Response Overcorrection	< 0.03 radians	Minimum	M	T, A
11	Leg Response Time	< 0.1 seconds	Minimum	M	T, A
12	Leg SS Error	< 0.01 radians	Minimum	M	T, A

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
** Compliance Methods: (A) Analysis, (I) Inspection, (T) Test

Each specification will have testing methods to meet compliance:

1. Vertical Leap Height

The Vertical Leap Height is how high the final robot will be able to jump. This is an important target to meet because anything lower would be an unimpressive height for the robot to jump. This will be tested by measuring the height that the robot jumps once the robot is completed.

2. Fatigue Durability

The Fatigue Durability is how long the robot will be able to operate continuously. This target is important for ensuring the robot may be used for a reasonable amount of time without failure, as well as function for a long time without repairs. We will test this specification for compliance using Endurance Testing by having the robot jump continuously for a set period.

3. Assembly Time

Assembly Time is the time it will take to create the robot from the set of finished parts and test stand. This specification is important for the robot to be promptly used for testing or demonstration purposes. This will be tested by measuring the length of time needed for a person to assemble the robot given that person knows how to assemble it. This is a high-risk specification due to its low priority, and it is least likely out of the specifications to meet the target goal.

4. Weight Management

Weight Management is how much the final fully assembled robot will weigh. This is important for meeting other specifications (Vertical Leap Height and Fatigue Durability). This will be tested by weighing each part of the robot and summing the total weight.

5. Center of Mass Position

The Center of Mass (COM) position is somewhat self-explanatory. Having a centrally located COM is important for reducing the amount that the robot will naturally want to tilt while in the flight phase. We will test the COM location by evaluating it in SolidWorks and with physical tests once the robot is assembled.

6. Compilation Time

Compilation time is how long the code will take to compile and upload to the microcontroller on the robot. This specification is important for ensuring that code that is uploaded to the robot can be tested within a reasonable time frame. This will be tested by measuring the time the code takes to compile on a computer intended to be used to upload code to the microcontroller. This is a high-risk specification because the team has only one computer engineer working on the code.

7. Total cost of components

The total budget for this project is $5000. We will plan our purchases to ensure the sum materials needed for building the robot do not exceed this amount.

8. Avoid Rolling During Flight

While jumping, the robot should avoid rolling (rotating along the robot's transverse axis) while in the air to prevent an undesirable landing. Landing in a level position is crucial for executing a repeatable hopping motion. Analyzing the quadruped's aversion to rolling will be performed on the test stand. This test stand setup will allow rotation about the transverse axis, and translational motion along the z-axis.

9. Avoid Flipping During Flight

Similarly, the robot should avoid flipping (rotating forward or backward from the robot's frame of reference) while in the air to avoid an incorrect landing. An analysis will be performed on the test stand. and will allow rotational motion forwards and backwards and linear motion up and down.

10. Leg Response Overcorrection

During motion or rotation of the leg the robot will avoid overcompensating due to outside forces or a transient response error by less than or equal to 0.03 radians away from the desired output. Analysis of output position data from the actuators will allow us to measure overcorrections

11. Leg Response Time

The leg response time should be less than 0.1 seconds. This means that the time elapsed from when the CAN messages are sent to the actuators and when the actuators execute the input torque/position should be no more than 0.1 seconds. Analysis of input commands and output data with respect to time allows us to quantify response time.

12. Leg Steady State Position Error

While rotating to a final position the difference or error between the wanted position and actual position should be less than 0.01 radians. Analysis of input positions commands compared to output position data from the actuators will allow us to measure steady state errors.

5. Project Management

5.1 Design Process Description

The design process will begin with modeling a test stand, a single-leg, and the robot body in SolidWorks. After manufacturing, testing for the single leg and robot will be done on the test stand. microcontroller code will begin once the first leg is assembled, before testing the controller the Speedgoat (a real-time simulation tool) will be used to verify the leg design. Then the leg will verify the microcontroller. Once the whole robot is assembled and functioning, testing will then transition to be independent of the test stand. Tables 3a, 3b, and 3c show our quarterly objectives and milestones. See Appendix 8.2a, 8.2b, 8.2c for each table's respective Gantt charts.

Table 3a. Outline of Fall Quarter Objectives and Milestones.

Quarter	Objectives	Milestones
Fall	Concept Generation and Selection:	Single Leg Design Review
	Prepare For Design Review	TBD
	Improve Single Leg Design (SW)	Preliminary Design Review (PDR)
	Plan 'Geometric' Robot Body Outline	11/19/2021
	Adapt Test Stand For 8-DOF Hopping	
	Design Test Stand to Body Mount	
	Design Leg to Body Mount	
	Plan Body	

Table 3b. Outline of Winter Quarter Objectives and Milestones.

Winter	Manufacturing:	Interim Design Review (IDR)
	Create BOM	1/13/2022
	Order Parts	Critical Design Review (CDR)
	Assemble Single Leg	2/18/2022
	Assemble Robot	Manufacture & Test Review
	Coding:	3/10/2022
	Code Controllers in C++	
	Testing:	
	Single Leg Speedgoat Testing	
	Single Leg Controller Testing	

Table 3c. Outline of Spring Quarter Objectives and Milestones.

Spring	Testing:	Verification Prototype Sign-Off
	8-DOF Robot Control Testing	4/26/2022
	Independent Hopping Robot	DVPR Sign-Off
	Project Wrap-Up:	4/30/2022
	Create Expo Report	Final Design Review (FDR)
		6/3/2022

6. Conclusion

The design challenge for our senior project is to develop a quadrupedal robot prototype and a control algorithm to command said quadruped. The purpose of this Scope of Work document is to verify with our sponsor, Dr. Siyuan Xing, that the stated project scope satisfies his goals for the robot's development. Key elements of this document include the project scope and problem statement, as well as the customer requirements and our intended plan to evaluate our eventual prototype's ability to meet these requirements. Upon Dr. Xing's approval, we will conduct a design review of the current single-leg prototype in addition to starting work on the process of communicating with the actuators via C++, rather than MATLAB/Simulink. This will occur before PDR, which is scheduled for the end of Fall Quarter.

7. References (Journals, Documents, and Patents)

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8. Appendices

8.1 Appendix A: QFD HOQ

Correlations	
Positive	+
Negative	−
No Correlation	

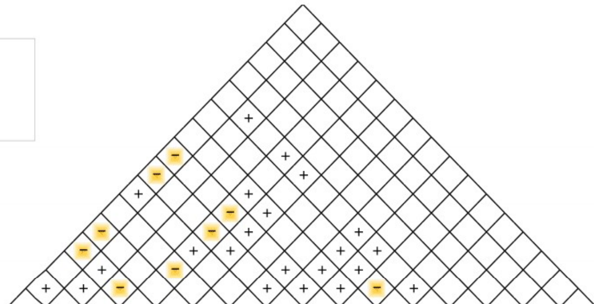
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: 8-DOF Quadruped

Revision Date: 10/13/2021

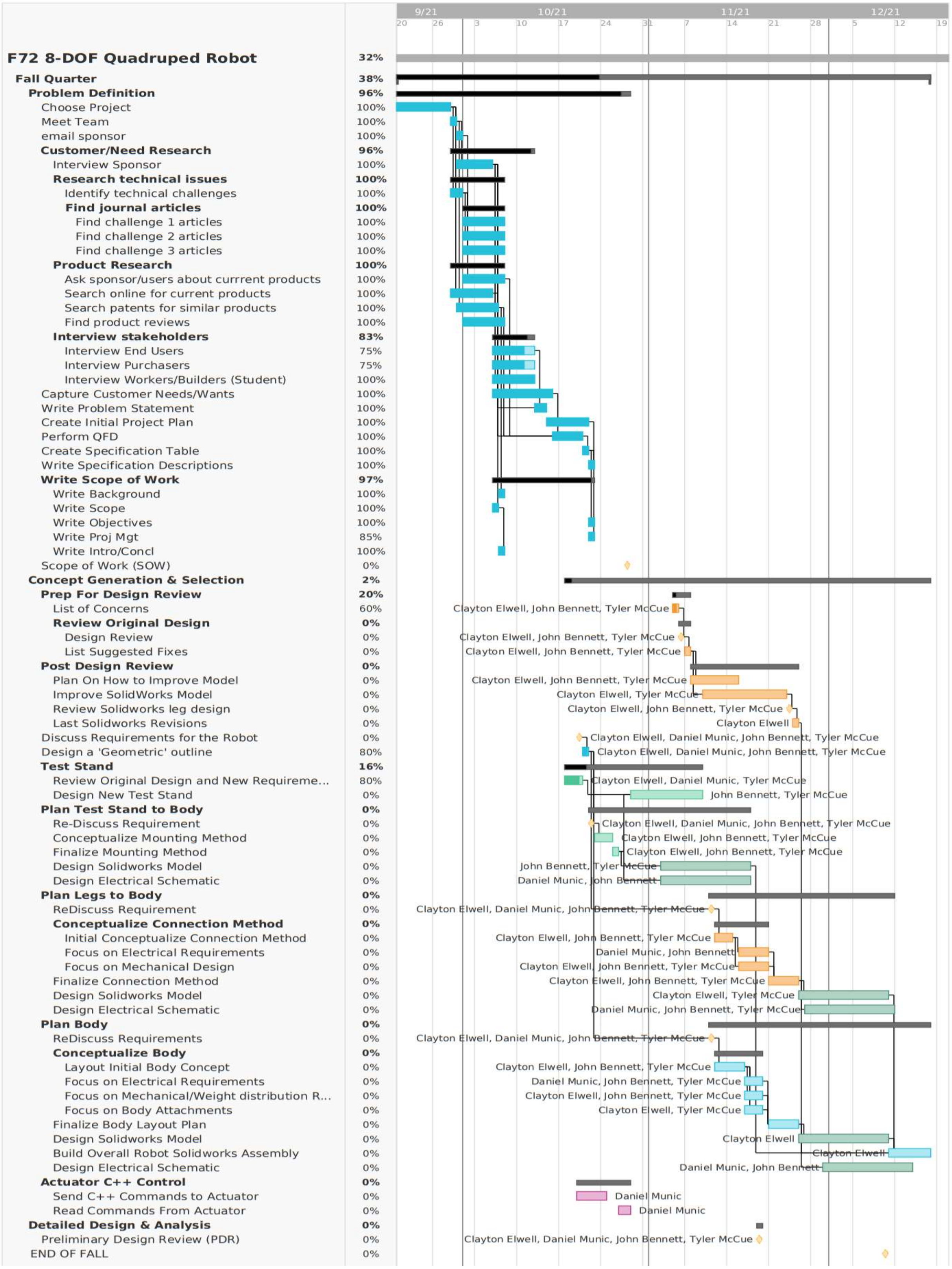


	WHO: Customers								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	NOW: Curr. Products					
									Direction of Improvement	▲	▲	◇	▼	▼	▼	◇	▼	▼	▼	▼	▼										
Row #	Weight Chart	Relative Weight	Dr. Siyuan Xing	Cal Poly Legged Robots Club	Cal Poly Robotics Club		Maximum Relationship		HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Vertical Leap Height	Fatigue Durability	Assembly Time	Weight mag.	Controller Compilation Time	Total cost of components	Locate Center of Mass	Avioding Rolling During flight	Aviod Flipping During Flight	Leg Response Over Shoot	Leg Response Time	Leg Response SS error Position					Our Current Product	MiT Mini Cheetah	Stanford Doggo	Boston Dynamics Spot	Unitree Robotics A1	Row #
1		9%	5	8	8		9		Ease of Assembly			●														2	3	4	1	1	1
2		8%	7	5	5		9		Low Leg Inertia				●			▽			○	●	○					4	5	5	5	4	2
3		11%	9	8	7		9		Vertical Leap Control Alg.	●				●			●	●	●	●	●					3	5	1	5	5	3
4		12%	9	9	9		9		Functional Test Stand	○	▽	●					▽	▽								5	5	5	5	5	4
5		4%	3	3	3		9		Battery Capacity		○		●	▽					○	○						5	5	3	5	4	5
6		11%	8	8	8		9		Mechanical Durability	▽	●		○	▽												3	4	3	5	4	6
7		9%	6	7	7		9		Cost						●											5	3	4	1	2	7
8		6%	4	5	5		9		Modularity / Portable				●													5	5	5	4	5	8
9		11%	8	7	9		9		Teachable to underclassmen			○		●			▽	▽								4	2	4	1	2	9
10		11%	6	9	9		9		Manufacturable at Cal Poly		●															5	3	4	1	2	10
11		9%	9	6	6		9		Stable Flight Phase	○						○	●	●	▽	○	●					3	5	5	5	4	11
12		0%																													12
13		0%																													13
14		0%																													14
15		0%																													15
16		0%																													16

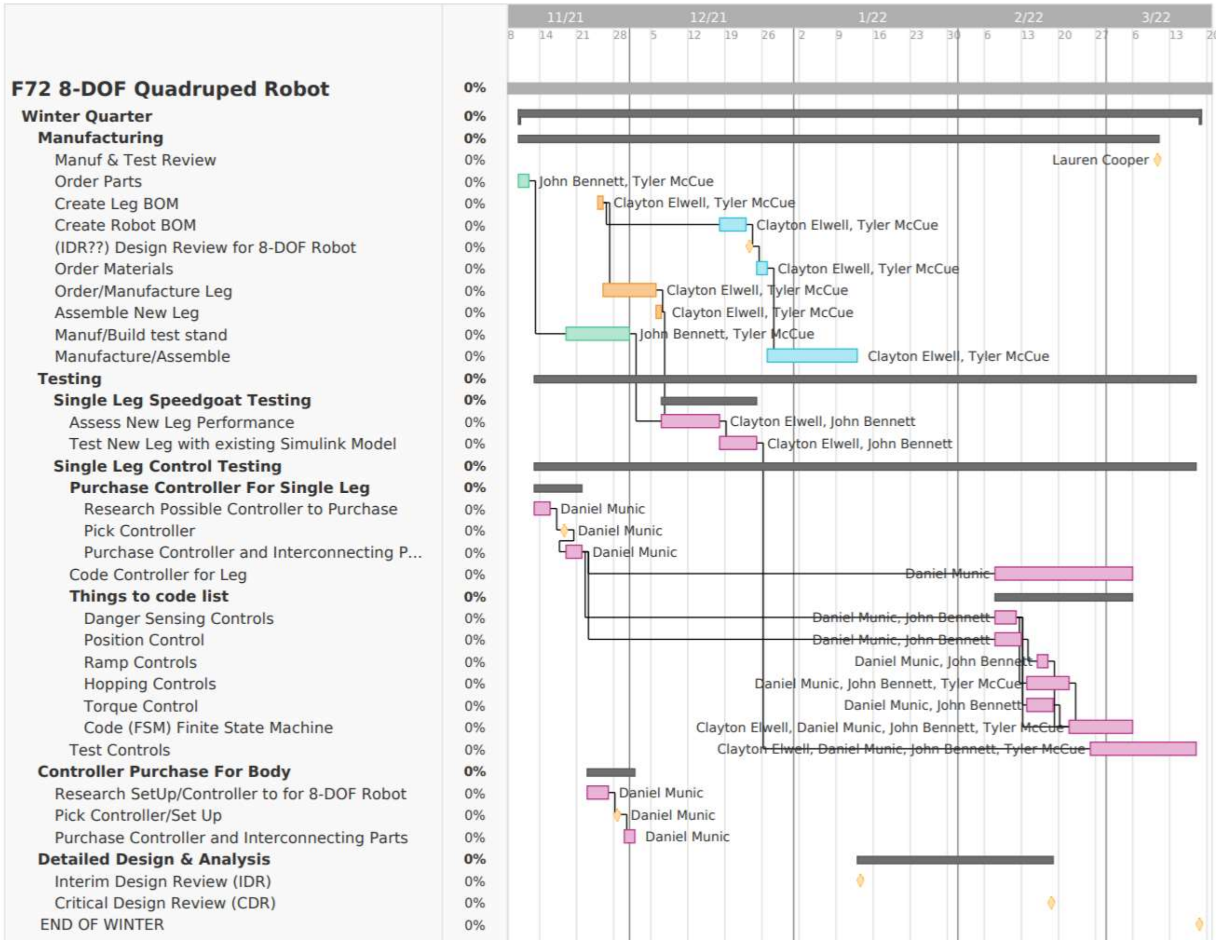
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	10 cm leap height	30 min of cont. hop. w/o deformation	Less than 5 minutes	Less than 10 kg	5 minute compilation time	Less than $5,000	< 0.5" from center	Δt less t	Δt less then 0.05sec between front and	Less then 0.03 rad	Less than 0.1sec	Less then a .01 rad				
	Max Relationship	9	9	9	9	9	9	3	9	9	9	9	9				
	Technical Importance Rating	171	215.9	223.8	192.1	206.7	79.96	35.63	203	203	140.2	204.3	203	0	0	0	0
	Relative Weight	8%	10%	11%	9%	10%	4%	2%	10%	10%	7%	10%	10%	0%	0%	0%	0%
Curr. Products	Our Current Product	3	5	3	2	5	5	1	1	1	3	3	3				
	MiT Mini Cheetah	5	3	2	5	5	4	5	5	5	5	5	5				
	Stanford Doggo	1	3	3	1	5	5	5	5	5	5	5	5				
	Boston Dynamics Spot	5	5	1	4	5	1	5	5	5	5	5	5				
	Unitree Robotics A1	5	5	1	3	5	1	5	4	4	4	4	4				
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

8.2 Appendix B: Gantt Chart

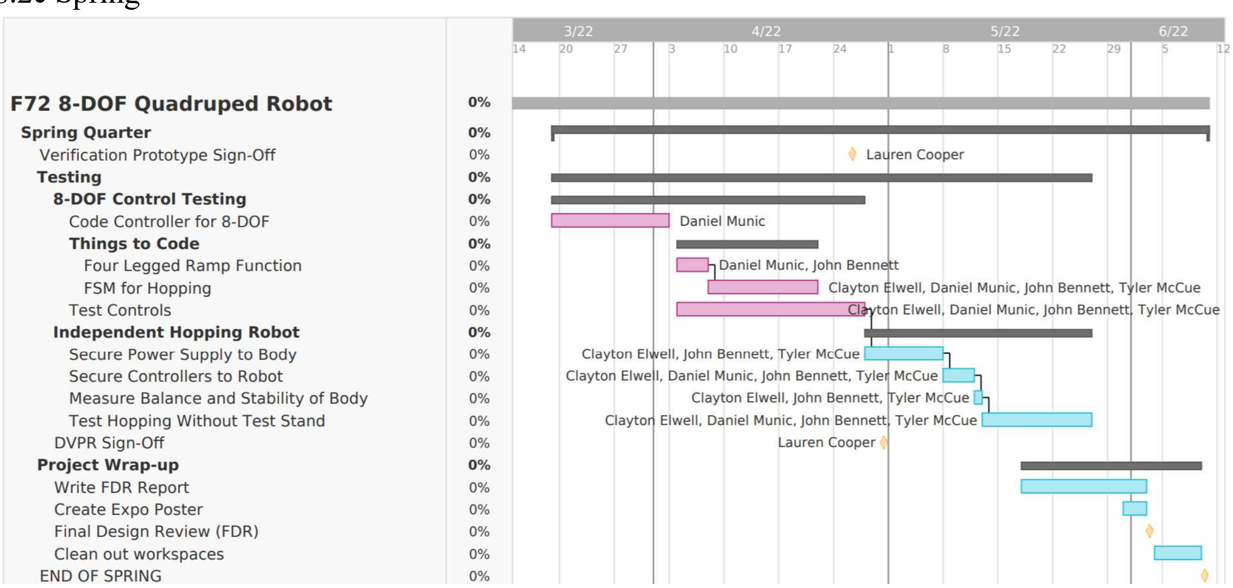
8.2a Fall



8.2b Winter



8.2c Spring



8 DOF Quadrupedal Hopping Robot
Preliminary Design Review

November 12, 2021

Fall 2021 ME 428-05 Group F72

The B.R.U.C.E. Bot Engineers

Tyler McCue   Daniel Munic
Clayton Elwell   John Bennett
8dofseniorproject@gmail.com

Prepared for Dr. Siyuan Xing and Charlie Refvem

Department of Mechanical Engineering

California Polytechnic State University, San Luis Obispo

sixing@calpoly.edu crefvem@calpoly.edu

Abstract

California Polytechnic State University does not offer lower division robotics courses, which prevents underclassmen from accessing a structured learning environment that focuses on the field of robotics. Our senior project aims to create an organized and intricate project within Cal Poly Robotics, a club that gives underclassmen hands-on positions on robotics projects, and simultaneously bring awareness to our sponsors' (Dr. Siyuan Xing and Charlie Refvem) research group – Cal Poly Legged Robots. The quadruped will include adequate assembly instructions and controller documentation so that underclassmen at Cal Poly may learn from the project and explore the field of robotics with a more structured curriculum.

The key objective of our senior project is to develop a prototypical 8 degree of freedom quadrupedal robot that can execute a repeatable vertical hopping motion. This document outlines our ideation process, and subsequent refinement until we reached a system-level design concept that achieves this objective. The document subsequently outlines our system-level design and how it satisfies our design specifications. Lastly, a timeline for testing, material purchasing, and final design construction is presented.

Contents

1. Introduction

1.1 Team

Dr. Siyuan Xing and Charlie Refvem, professors in the mechanical engineering department at Cal Poly are interested in developing an 8-DOF Quadruped. Dr. Xing and Charlie have been coordinating projects for the Cal Poly Legged Robots research group. Dr. Xing proposed the fall F72 senior project to build upon the 2 DOF robotic leg summer research. The team consists of three mechanical engineers, Clayton Elwell, John Bennett, Tyler McCue, and one Computer Engineer, Daniel Munic.

Clayton initially took interest in Dr. Xing's quadrupedal robot research at the beginning of Spring quarter 2021. Throughout the duration of Spring 2021, he developed a SolidWorks model of a single robotic leg, which he manufactured and developed a controller for during Summer 2021 with the assistance of John Bennett. This single-leg prototype was a precursor to the quadruped that is the goal of this senior project.

John Bennett's interest in controls, mechatronics, and mechanical design drew him to the project. Building an 8-DOF robot provides exciting challenges and requires a variety of engineering skills.

Tyler was drawn in due to the challenge of the project. With mechanical design, coding, and controls being an important aspect of the quadruped, this project was a gateway into the rigorous field of robotics.

Daniel was interested in the project due to the control system and electrical design complexity of the project. Building those systems from scratch is a difficult but attractive way to learn the embedded systems side of robotics.

1.2 Design Challenge

The design challenge for this senior project is to develop a prototypical model of a quadrupedal robot, which will be used to expose underclassmen at Cal Poly to the process of robotic mechanical design and the development of robotic control algorithms. The goal for this project is to manufacture the prototypical quadruped and subsequently develop a controller that commands it to execute a vertical hopping motion. To facilitate this dynamic motion, our team will also develop a modular test stand that provides external power to the quadruped. Upon completion of the quadruped prototype and test stand, proper documentation and assembly guidelines must be created so that future Cal Poly students may understand the technical details of our project and continue to improve upon the results of our senior project.

1.3 Report Overview

This document outlines our concept development process, including our initial ideation and subsequent refinement of those ideas to arrive at a final system-level design. We then provide an overview of our chosen concept design and its related functions, materials, and manufacturing processes. In addition, we identify areas in the design that require further refinement. To justify our concept design, we address the engineering specifications that we defined in our Scope of Work document, and how our chosen concept design satisfies those requirements. The project management and project timeline are then discussed, including planned analyses, planned purchases, and preliminary plans for the construction and testing of our final design.

There were no significant changes to our scope since the submission of our SOW. We have considered moving our CDR date forward to late January in Winter 2022 to order parts and begin manufacturing early; however, this depends on what we accomplish over winter break in terms of developing our detailed design and creation of a Bill of Materials.

2. Concept Development

We evaluated several sub-functions of our quadrupedal robot during the ideation process. Functions of particular interest are the battery/power supply for the quadruped, the test stand to be used in conjunction with the quadruped, the knee joints of the quadruped, and the lower (calf) links of the quadruped.

2.1 Battery

2.1.1 Research and Weighted Decision Matrix

The battery and/or power supply must power the quadruped for thirty minutes. With an external power supply tether this will be simple; however, when our project transitions to a completely wireless setup, we must carefully select a battery that can provide a constant voltage to the actuators for the intended operation time. This means we need a battery with a high capacity that is easy to charge while still being able to power all eight actuators and the microcontroller. The battery should also be safe and cost effective.

During single leg-prototype, we determined the robot would need a high current output from the power source, above one ampere per leg. The weighted decision matrix reflects this as the highest weight criterium is the discharge current. The battery should be able to supply above four times the current that one leg draws, and it is standard practice to double that amount for tolerance.

Battery types commonly used for robots are alkaline, NiMH, lithium-ion, and lithium-poly batteries. These are compared in Table A4.3, the battery weighted decision matrix. Alkaline batteries are the standard AA you can get in stores. NiMH batteries are like Alkaline but are more efficient, rechargeable, and larger. Lithium-Ion batteries are the kind you see in phones, they're very small and easy to charge. Then there are two types of lithium-poly batteries, one is meant for high current usage and the other for safety as it has no flammable gases inside and so if punctured it will not explode. [1][2]

The lithium-poly battery would be the best suited battery for our robot due to its high current output, low cost, and light weight. The safety type lithium-poly battery can provide enough current to our robot that we would not need to use the current-type battery; thus, we conclude it is the best suited battery for our robot.

2.2 Test Stand

2.2.1 Body Mount Ideation and Pugh Matrices

When developing concepts for the test stand, we focused on the connectors between the robot and the test stand. Since we want to evaluate the robot's ability to execute a vertical leap without pitching or yawing, the adapter between the robot and test stand must allow the robot to rotate. Additionally, the test stand must be configurable to restrain the robot's pitch and yaw for initial controller testing. Using ideation models, in Appendix 2 Figures A2.9-2.13, of testing set ups revealed practical design methods. In Figure A2.11 mounting needs to be symmetric and aligned through the robot's center of gravity. With this insight, we developed the ideas seen in Appendix 1 Figure A1.5, which proposes tabs that will fasten to the top and bottom of the robot. Figure A1.4 proposes guide rails that slide onto an extended portion of the robot's body and will connect from the side. Figure A1.4 also proposes using rotating cylinders to allow rolling motion during the flight phase. Figure A1.6 proposes using a harness to prevent direct impact with the ground while not impeding motion.

The Pugh matrix, Appendix 3 Figure A3.2, compares promising concepts to a two linear-bearing datum. The guide rails scored high due to cheap cost. rotating mounts scored well due because it allows different flight phase tests. The results of the Pugh matrix prompted more criteria regarding test stand mounting in the weighted decision matrix.

2.2.2 Power Location Ideation

Our sponsor is allowing us to use an external power supply for early testing. Supplying power to the actuations and controllers is essential for testing. During ideation we focused on developing concepts for feeding power without complicating the assembly or risking wires getting tangled. Ideation models in Appendix 2 Figures A2.6-2.7 showed how the cables would interact with the test stand. Figure A2.7 poses feeding power up from above the robot. Figure A2.7 poses feeding power into the side of the robot adjacent to the linear slider.

Since there were few reasonable options all the power connection methods were used in our combined weighted decision matrix

2.2.3 Body Mount and Power Location Weighted Decision Matrix

The decision matrix Appendix 4 Figure A4.2 includes guide rails, tabs, rotating mounts and a harness and power could be fed from the top and next to a mount or we could use internal power. Testing, cost, and manufacturing were the highest weighted criteria. The best option is the rigid mount with guide rails mounted on two linear bearings with power fed from the top. The cost of manufacturing a simple mount significantly outweighs the benefit of testing multiple kinds of motion in the robot. Incorporating internal power will cost money and time, but the advantage of simplifying the assembly, organization, and eliminating the chance of the robot's wires getting tangled incentivizes switching to internal power. To avoid testing delays we plan to gradually transition from external power feeding into the top of the body frame, to an internal power supply (a battery).

These selections did not strongly address the need to reducing pitching and yawing. We will need to consider other methods of fine tuning our flight phase.

2.3 Lower Leg

2.3.1 Knee Joint Ideation and Pugh Matrices

Appendix 5 describes our results from the single-leg prototype testing. The setscrews galled the aluminum driveshaft, producing assembly issues. We ideated designs to prevent this galling, while prioritizing manufacturability and assembly ease. As seen in Appendix 1 Figure A1.3 we proposed permanently fixing the knee pulley to the driveshaft. In contrast, Figures A1.1-1.2 proposes keeping the keyway for torque transmission, and removing the setscrews. The ideation models in Appendix 2 Figures A2.2-2.4 display methods of torque transmission from the knee pulley to the driveshaft, and subsequently to the lower link (calf).

We took the best ideas and used a Pugh matrix to compare them to the single-leg prototype datum. As seen in Appendix 3 Table A3.1, the driveshaft and hub that are one solid part, and not welded together, was the most promising design because of its low manufacturing complexity, mechanical durability, and simplistic design.

2.3.2 Lower Link Ideation and Pugh Matrices

Reducing the inertia of the lower link is also a goal for the second revision of the robot’s legs. Currently, a significant portion of the lower link’s mass is concentrated at the foot of the robot, thus undesirably increasing the rotational inertia of the leg which in turn increases the torque required. While ideating for the lower link, we prioritized ideas that had less mass concentrated at the foot to reduce the rotational inertia of the leg and thus improve control response time while keeping structural durability. Durability and manufacturability are also key aspects of the leg which are reflected in both the Pugh matrix and weighted decision matrix. The figure shown in column 5 of the Pugh matrix found in Appendix 3.4 shows a bulkier leg to increase durability.

2.3.3 Knee Joint and Lower Link Weighted Decision Matrix

We combined the lower link and knee joint functions in a decision matrix to develop our design direction. Appendix 4 Table A4.1 reveals that the designs utilizing a solid aluminum lower link and no driveshaft outperform the forked lower link with a driveshaft. Thus, we decided to deviate from the results of our knee-joint Pugh matrix and not use a driveshaft. A solid lower link has significantly lower inertia, and while its manufacturing is more complex it is still achievable with the resources available at Cal Poly. Since we will manufacture it at Cal Poly, it will also be teachable to underclassmen. Its material cost may be higher than the solid shaft and forked link design, but aluminum's mechanical durability will allow one lower link to outlast many polycarbonate lower links.

3. Concept Design

Our concept design utilizes a solid lower link, and no longer requires a driveshaft. Instead, the knee shaft facilitates the rotational motion of the lower link and will not transmit torque from the knee pulley to the lower link. Additionally, the knee shaft will be part of the upper link rather than the lower link, like the forked leg design. This will prevent surface galling that was observed during our testing day. The knee pulley will be mechanically fastened to the lower link, instead of the driveshaft; in addition, bearings will be press fit into the inner bore of the pulley. The knee shaft will mate with these bearings to allow rotation of the lower link. The choice to use a solid lower link will also reduce the rotational inertia of the leg, thus improving the leg's response to torque inputs from the actuators.

Figure 1 displays a labeled isometric view of our initial concept design for the quadruped. We plan to manufacture the lower link from aluminum to further reduce its mass, and thus minimize inertia. While the CAD render presents cylindrical rods for the lower links, another option would be to use an I-beam profile, which would have the same strength as a solid rod but with less mass. While this leg design is more complex to manufacture than the solid knee driveshaft and hub, we still can execute all the manufacturing processes at the Cal Poly machine shops whether via manual machining techniques and 3D printed jigs, or CNC Services offered at the machine shops.

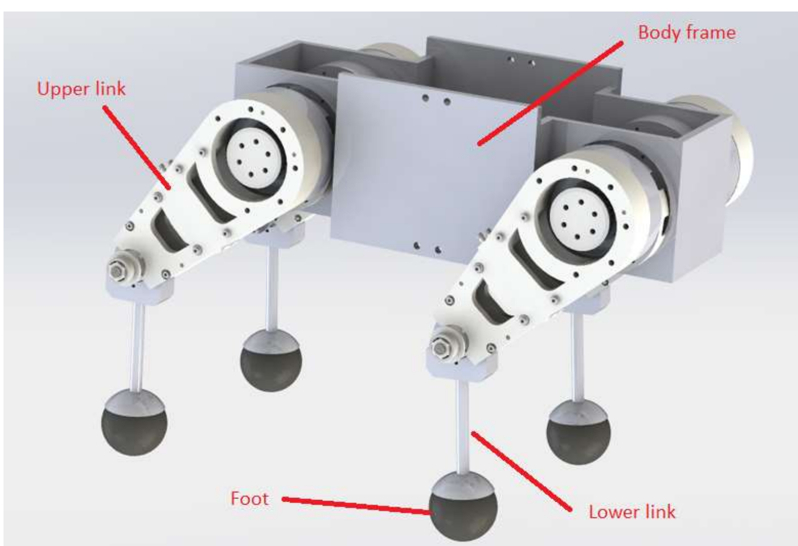


Figure 1. Concept Design Labeled CAD Isometric**.**

The body was based on the selected testing set up. Notice the solid tab with holes on the body that tab will act as a guild rail for the mount to slide on. When the holes of the mount are lined up with the holes of the tab, we can easily attach the test stand to the robot. The open top will allow us to easily access internal electronic components and supply external power. An initial revision of the body frame will be additively manufactured for rapid confirmation of the selected geometry. Since we are operating indoors, weather resistance will not be a concern for initial testing. Later revisions of the body frame should be manufactured from waterjet-cut aluminum and additively manufactured internal components for improved durability.

The internal electronics layout has not been determined, but we have selected a lithium poly battery for the high energy density and long battery life as seen in the weighted decision matrix in Appendix 4.4. Further refinement of the body frame is required before the internal electronics layout can be determined, but we plan on making the body frame from a single sheet of aluminum that is cut and bent into the desired frame geometry.

Figure 2 displays our concept prototype and the accompanying test stand. These images reveal that the method of attaching each leg to the body frame has not been determined. The concept prototype simply press-fits the actuators into holes in the body frame; the final design will use M4 fasteners to attach the hip actuator to the body frame (the actuators utilize M4 fasteners). Our concept prototype made it clear that an optimized leg design will have a solid lower link to reduce its inertia.

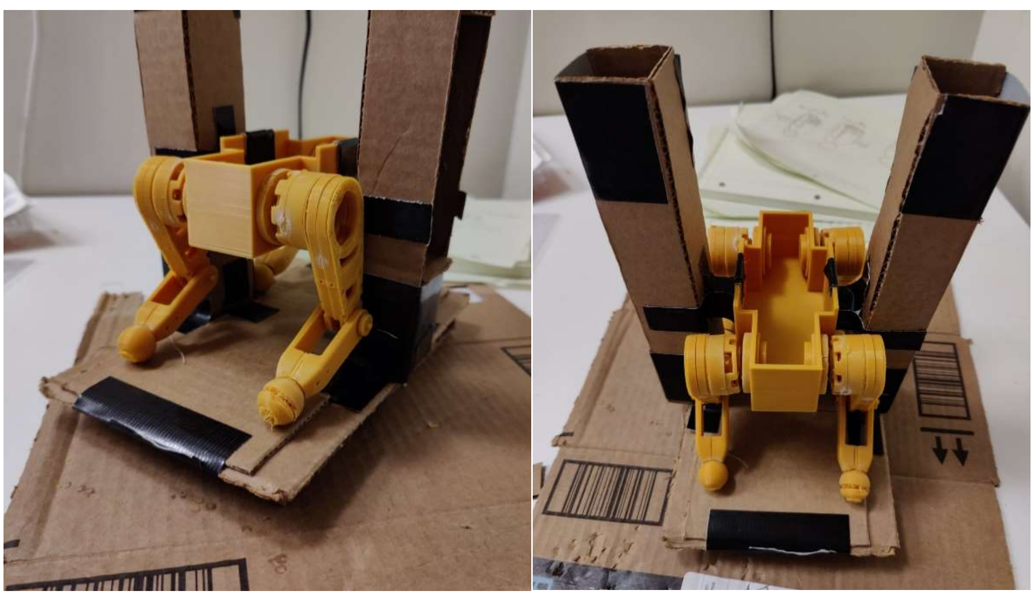


Figure 2. Concept Prototype and Test Stand.

4. Concept Justification

4.1 Design Specifications

The following section outlines our project specifications and describes how our design will satisfy these specifications.

1. Vertical Leap Height – 10 cm

Our target leap height of 10 cm will be achieved with proper tuning of the controller parameters. Preliminary testing yielded leap heights greater than 4-5 cm; thus, further tuning of controller parameters is necessary but certainly achievable.

2. Fatigue Durability – 30 minutes of operation

Our testing day indicates that the interface between the knee pulley and driveshaft is the primary area of fatigue; changing the knee design such that the knee shaft does not experience any torque will alleviate this fatigue issue.

3. Assembly Time – 10 minutes per leg

The original goal of a five-minute assembly time may be unrealistic. However, since the final prototype will not be frequently assembled and disassembled, this rapid assembly is not necessary. A new assembly time of 10 minutes per leg is more reasonable. Currently, the assembly time for the internal electronics of the body frame is unknown, but a goal of 10 minutes is a reasonable initial assumption.

4. Weight Management – 10 kilograms

With a single-leg weight of ~1.33 kg (including the actuators), the minimum weight of the current leg design is 5 kg. Since the battery will also not be of insignificant mass, an initial estimate for the body frame might be 1-3 kg. Thus, a leg that utilizes the current design will weight 7.5 kg. With a redesigned lower link, each leg will have reduced mass of approximately 1.25 kg, for a total weight of 7.5 kg.

5. Center of Mass Position - <0.5 inches from center

To locate the center of mass at the center of the body frame, we should place the battery in the center of the frame because it will be the heaviest internal electronic component.

6. Compilation Time – 5 minutes

While the controller for the quadruped has not been developed, the compilation time for the single leg MATLAB/Simulink controller takes less than one minute to compile. If the compilation time scales linearly with the number of legs (this may be an invalid assumption), then a compilation time of five minutes is reasonable.

7. Total cost of components – <$5,000

The single leg total cost (including earlier revisions) was less than $300, which is $1,200 for all four legs. We may potentially have to buy another 6 actuators if Craig's motor design is delayed. 6 AliExpress actuators will cost $1,800. This leaves $2,000 for the internal electronics, body frame materials, and test stand materials. The total cost of the original test stand was $1,500, which leaves $500 for the internal electronics and body frame materials. The internal electronics excluding of the battery should not be incredibly expensive, and the body frame will also be inexpensive. To ensure that we remain under budget, we must carefully select the new test stand components and internal electronics to minimize cost.

8. Avoid Rolling During Flight – Δt between side impacts < 0.05 sec

To avoid any rolling during a jump the controller will designed to give steady inputs to each leg simultaneously. This will allow each leg to jump at the same time thus not allowing for the creation of a moment.

9. Avoid Flipping During Flight – Δt between front & back impacts < 0.05 sec

To avoid any flipping during a jump the controller will designed to give steady inputs to each leg simultaneously. This will allow each leg to jump at the same time thus not allowing for the creation of a moment resulting in a flip.

10. Leg Response Overcorrection – < 0.03 radians

To avoid leg overcorrection the controller will be designed produce an overshoot of no more than 0.03 radians. To avoid this an integral control will be used to dampen the response of the leg

11. Leg Response Time – < 0.1 seconds

To reduce steady state, position the controller will be designed produce a time constant of no more than 0.025 seconds. To avoid this a proportional control will be used to reduce the time constant and get a faster response.

12. Leg Steady State Position Error – < 0.01 radians

To reduce steady state, position the controller will be designed produce an overshoot of no more than 0.01 radians. To avoid this a proportional control will be used to reduce the steady state error.

4.2 Preliminary Analyses

As mentioned previously in this document, we conducted a testing day for the single-leg prototype on October 30, 2021. Detailed images of the testing day results may be referenced in Appendix 5. The results of these tests motivated a shift in the knee design, namely, to change the knee joint to improve mechanical durability. After constructing our concept prototype, we realized that a lower inertia knee design will simultaneously satisfy this need for improved durability. In this design the knee shaft only facilitates rotation and does not transmit torque. This will reduce the stress on the knee shaft and improve its endurance life. The design change will also reduce the overall inertia of each leg and improve the robot's performance.

4.3 Design Hazards

Our design has few scenarios where the quadruped user is at risk of injury. Since the quadruped will initially be operated on a test stand, the user will be at a safe distance from the robot if any unpredicted motion occurs. Additionally, since the quadruped has a relatively small footprint (~20" L x 10" W x 20" T) the user will only be at risk of injury if they place their extremities close to the quadruped while the motors are initiated. Thus, any time the user wishes to access the robot or test stand, we will ensure that the motors have been de-initiated so any sporadic quadruped movement cannot occur.

Regarding the batteries onboard the quadruped, a power distribution board will be developed by Daniel Munic to ensure that no actuators receive a dangerously high current load during operation.

Appendix 6 contains our design hazard checklist and design hazard table that presents solutions to any potential danger to the user of our quadruped.

4.4 Current Challenges, Concerns, and Unknowns

Regarding the mechanical design of the quadrupedal robot, the main challenges and unknowns relate to the development of the test stand mounts and the durability of the knee joint. Our test stand should allow the robot to pitch and yaw so we may evaluate the quality of our controller. Currently, our test stand is equipped to restrain the motion of the single-leg prototype to a purely vertical motion. We will need to develop a convenient mount design that allows the robot to both rotate and be restrained to planar motion, if desired. The new knee joint and lower link design should improve the quadruped's durability; however, thorough testing of the redesigned leg must occur to verify our design. Also, the quadruped's geometry and cable harness routing are another area of concern for our project. Since each actuator requires its own discrete power cable and data transmission cable, there will be plenty of opportunities for wires to become tangled.

5. Project Management

5.1 Design Process Description

We plan to implement the new leg design and test stand modifications in SolidWorks over winter break, and subsequently make a bill of materials for these assemblies. Upon completion, we will 3D print the body structure, fabricate the metal joints and links, and purchase internal electronic components. After manufacturing, we will use the new test stand to evaluate the new leg design. Controller development will begin once the first leg is assembled; before testing the algorithm on a microcontroller we will use the SpeedGoat (a real-time simulation tool) to verify the controller. Once the whole robot is assembled, we will test the quadrupedal controller. Ideally, once the quadruped controller is functioning testing will transition to be independent of the test stand. Tables 1a, 1b, and 1c show our quarterly objectives and milestones. See Appendix 7 Tables A7.1-7.3 for each table's respective Gantt charts.

Table 3a. Outline of Fall Quarter Objectives and Milestones.

Quarter	Objectives	Milestones
Fall	Design:	Sponsor PDR
	Plan Body	11/19/2021
	Produce Concept Prototype	Present Prototype to Sponsor
	Design Leg to Body Mount	11/19/2021
	Design Test Stand to Body Mount	
	Begin SolidWorks Body Assembly	
	Adapt Test Stand For 8-DOF Hopping	

Table 3b. Outline of Winter Quarter Objectives and Milestones.

Winter	Manufacturing:	Interim Design Review (IDR)
	Create Leg BOM	1/13/2022
	Create Robot BOM	Sponsor IDR
	Order Parts	1/14/2022
	Assemble Single Leg	Present Single Leg Assemble
	Assemble Robot	1/28/2022
	Coding:	Critical Design Review (CDR)
	Code Controllers in C++	2/18/2022
	Testing:	Sponsor CDR
	Single Leg SpeedGoat Testing	2/25/2022
	Single Leg Controller Testing	Manufacture & Test Review
		3/10/2022

Table 3c. Outline of Spring Quarter Objectives and Milestones.

Spring	Coding:	Present Body Assemble
	Code More Controls	4/1/2022
	Testing:	VP Sign-Off
	8-DOF Robot Control Testing	4/26/2022
	Independent Hopping Robot	DVPR Sign-Off
	Project Wrap-Up:	4/30/2022
	Create Expo Report	EXPO
		5/27/2022
		Final Design Review (FDR)
		6/3/2022

5.2 Planned Analyses and Early Tests

Apart from our single-leg testing day (reference in Appendix 5) we plan to conducting fatigue testing of the redesigned single-leg while constructing the quadruped prototype in Winter 2022.

Upon completion of the quadrupedal prototype, we will begin the testing and refinement of our quadrupedal controller. The anticipated start date for this testing is the week before our Critical Design Review and continued testing of the controller will endure throughout Spring 2022. Reference Appendix 7 Table A7.2 and A7.3 for more detailed plans regarding testing of the quadrupedal prototype.

5.3 Planned Purchases

Currently there are no planned purchases for components. Our goal is to have a Bill of Materials complete by the beginning of Winter 2022, so we may order the necessary parts and begin manufacturing early in Winter 2022. We will request to move our CDR date forward to accommodate this early start. The pulleys and timing belts have the longest lead times (~2 weeks) and thus these components may be ordered earlier than the rest of the materials, since we know exactly what timing belts and pulleys we want to use and their quantities. Reference Appendix 7 Table A7.2 for detailed dates regarding material purchasing.

5.4 Preliminary Construction and Final Design Testing

With the materials ordered early in Winter 2022, our goal for the assembly date of the final design is the end of January or beginning of February. With our quadrupedal robot assembled before the second week of February, we will have time to conduct initial testing before our Critical Design Review. Having a fully assembled quadruped by the middle of Winter 2022 will give us ample time for controller development and refinement before our Final Design Review.

We will construct the quadrupedal test stand in tandem with the quadrupedal prototype itself, with a completion date of January 28, 2021. Reference Appendix 7 Table A7.2 and A7.3 for exact dates of preliminary constructing and testing of our final design.

6. Conclusion

This document outlines our concept development process, including our ideation and subsequent refinement of those ideas to arrive at a system-level design. An overview of our chosen concept design and its related functions, materials, and manufacturing processes was given. To justify our concept design, we addressed the engineering specifications that we defined in our Scope of Work document, and how our chosen concept design satisfies those requirements.

7. References

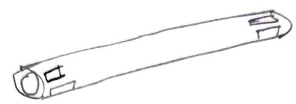
[1] Jarema, Radek. "Batteries - Choose the Right Power Source for Your Robot." *Medium*, Husarion Blog, 13 Apr. 2018, medium.com/husarion-blog/batteries-choose-the-right-power-source-for-your-robot-5417a3ec19ca.

[2] K, Hai Prasaath. "Choosing Batteries for Robots." *Engineers Garage*, 25 Feb. 2021, www.engineersgarage.com/choosing-battery-for-robots/.

8. Appendices

8.1 Appendix 1: Ideation Sketches

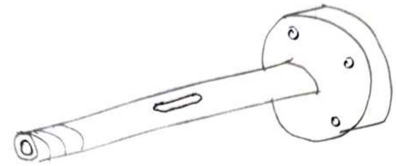
Separate knee shaft (steel) with splines



This idea is similar to the datum design, except the knee hub and shaft are not welded together. Instead, torque transmission will occur via splines. Additionally, this shaft will be made from steel, instead of aluminum. During our team's fatigue testing day this weekend, the aluminum shaft was galled by the pulley, which resulted in the pulley "sticking" to the aluminum shaft and proved to be extremely troublesome for assembly/disassembly. By making the shaft out of steel, this issue will no longer occur. To reduce the mass of the shaft, we could bore into the center to remove excess steel.

Figure A1.1. Knee Joint Ideation Sketch and Description 1

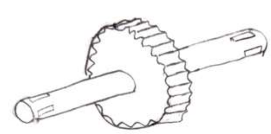
Solid piece/part with shaft & hub (steel)



This idea is very similar to the datum, except it will be made from steel instead of aluminum. During our testing day, our aluminum shaft saw significant galling, which led to problems with the assembly/disassembly process. By making the shaft & hub out of steel this galling will not occur. Additionally, this part will be machined from one solid steel cylinder. While this may increase material cost, it will eliminate the need for any welding, and reduce the number of keyways that need to be machined in the shaft when compared to the other two ideas.

Figure A1.2. Knee Joint Ideation Sketch and Description 2

Solid Piece/Part with pulley and shaft



This idea changes the assembly method of the knee joint. With this design, the shaft and pulley are 1 solid part (possibly via welding; press fit could work too). The advantage of this is two-fold: firstly, the assembly process will be improved because the knee hub is no longer permanently fastened to the knee shaft. Instead, the torque will be transferred from the shaft to the knee via splines w/ keys. The second advantage is that there is no longer such a precise shaft & hole tolerance to allow for repeated assembly & disassembly of the shaft & pulley.

Figure A1.3. Knee Joint Ideation Sketch and Description 3

Guide Rail Design Options: Having guide rails makes mounting easier. The threads are easily assessable from the top or bottom of the robot. The guide rails could hold the robot still while during mounting. These designs require the robot's side panels to be extended to allow room for holes. The concepts that mesh well with guide rails are the concentric cylinder Figure A1.4 Left and the ordinary mount Figure A1.4 Right. The major difference is that concentric cylinder allows for more motion and an ordinary mount cost less and would be easier to manufacture. These designs rely on the preexisting linear bearing on the test stand.

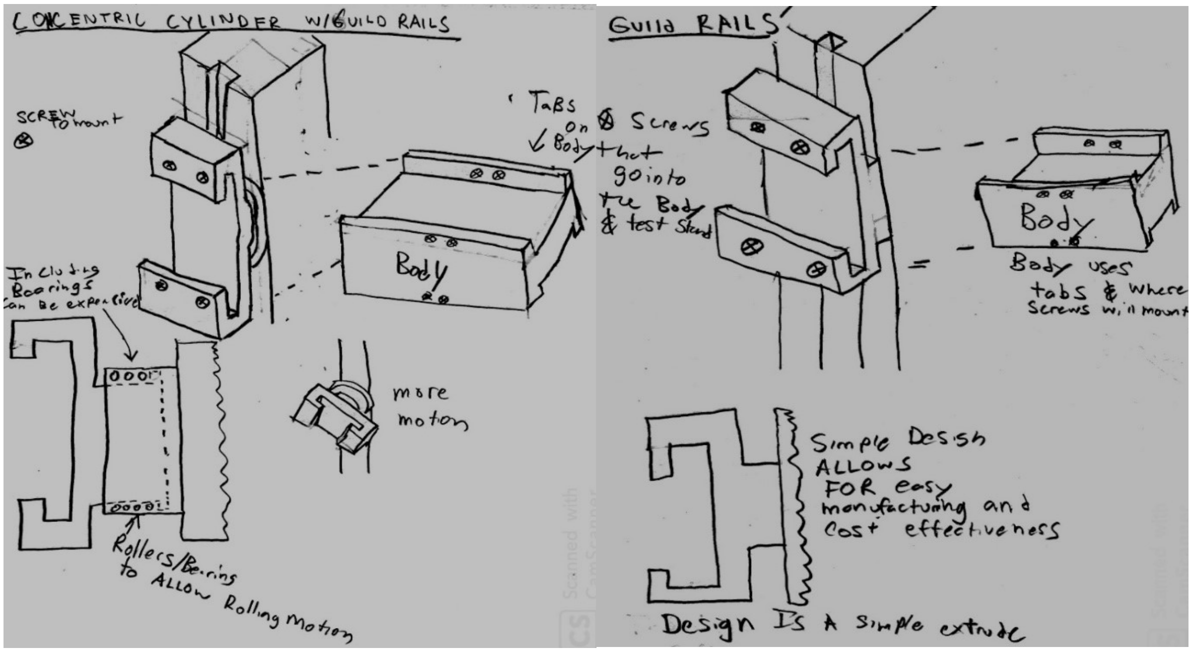


Figure A1.4. Test Mount Ideation Sketches, Right: Concentric Cylinders, Left: Rigid Mount.

Mounting Tabs: Mounting tabs are just like guild rails but instead of fastening screws from the side one would fasten directly into the robot. This method could make assemble a bit more challenging but will simplify cost and manufacturing.

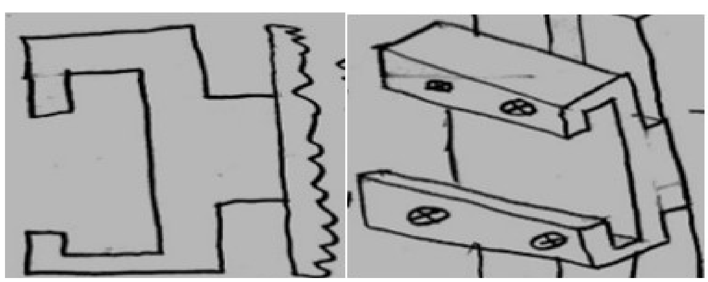


Figure A1.4. Test Mount Ideation Sketches, Mounting Tabs.

Harness: The harness design is like a bungee cord that connects a leather strap on the robot to test stand frame. The bungee cord dampens impulses and is short enough for the body not to hit the ground and long enough to let the leg touch the test stand. Having a harness does not have any constraints on motion. This kind of testing is the final step before jumping without a test stand.

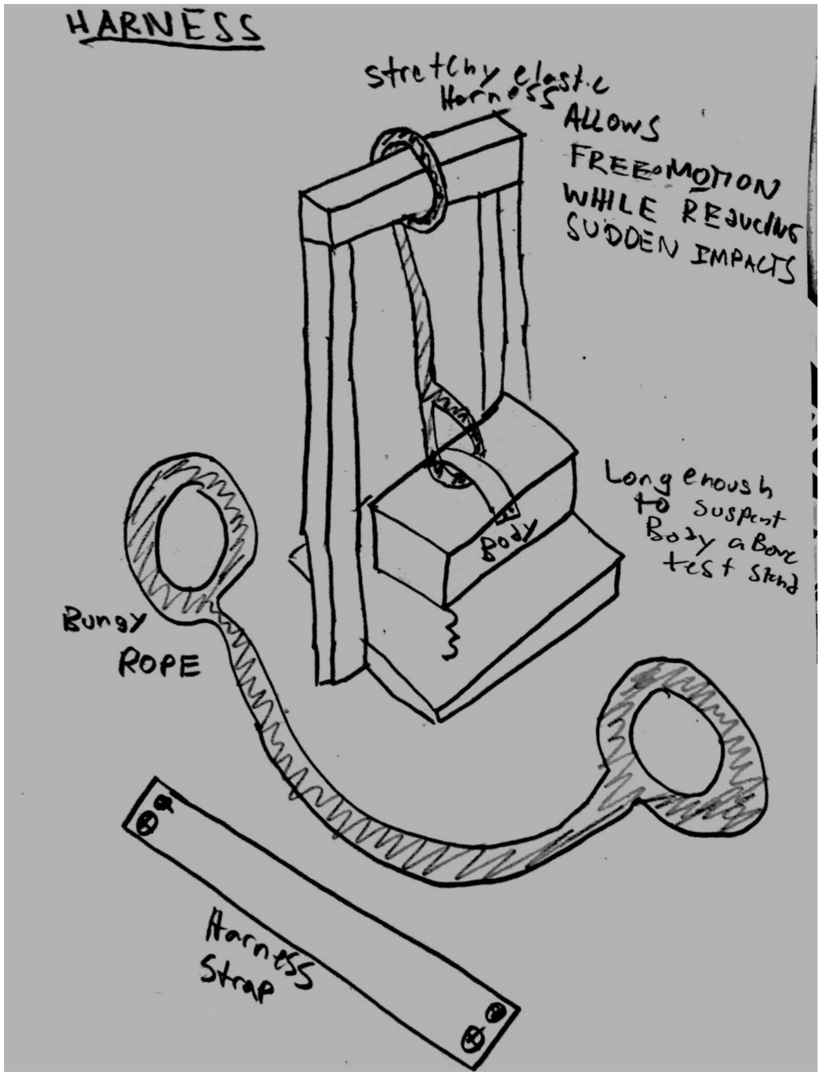


Figure A1.5. Test Mount Ideation Sketch, Harness.

8.2 Appendix 2: Ideation Model Pictures

Figure A2.1. Clayton Ideation Model 1 – Low Inertia Calf

Figure A2.2. Clayton Ideation Model 2 – Knee hub design using splines

Figure A2.3. Clayton Ideation Model 3 – Driveshaft design with splines

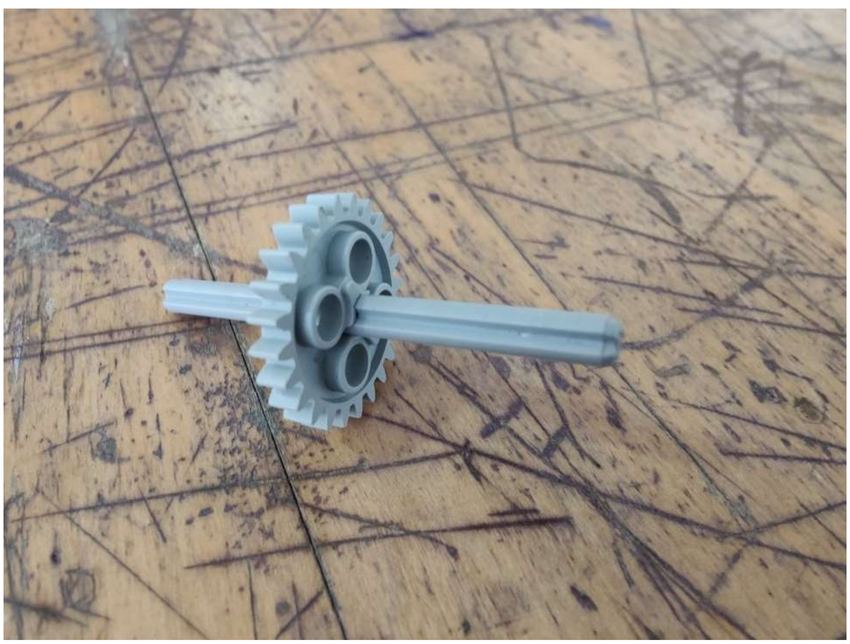


Figure A2.4. Clayton Ideation Model 4 – Permanently fixing the knee pulley to the driveshaft

Figure A2.5. Clayton Ideation Model 5 – Leg design with calf link inside of thigh link

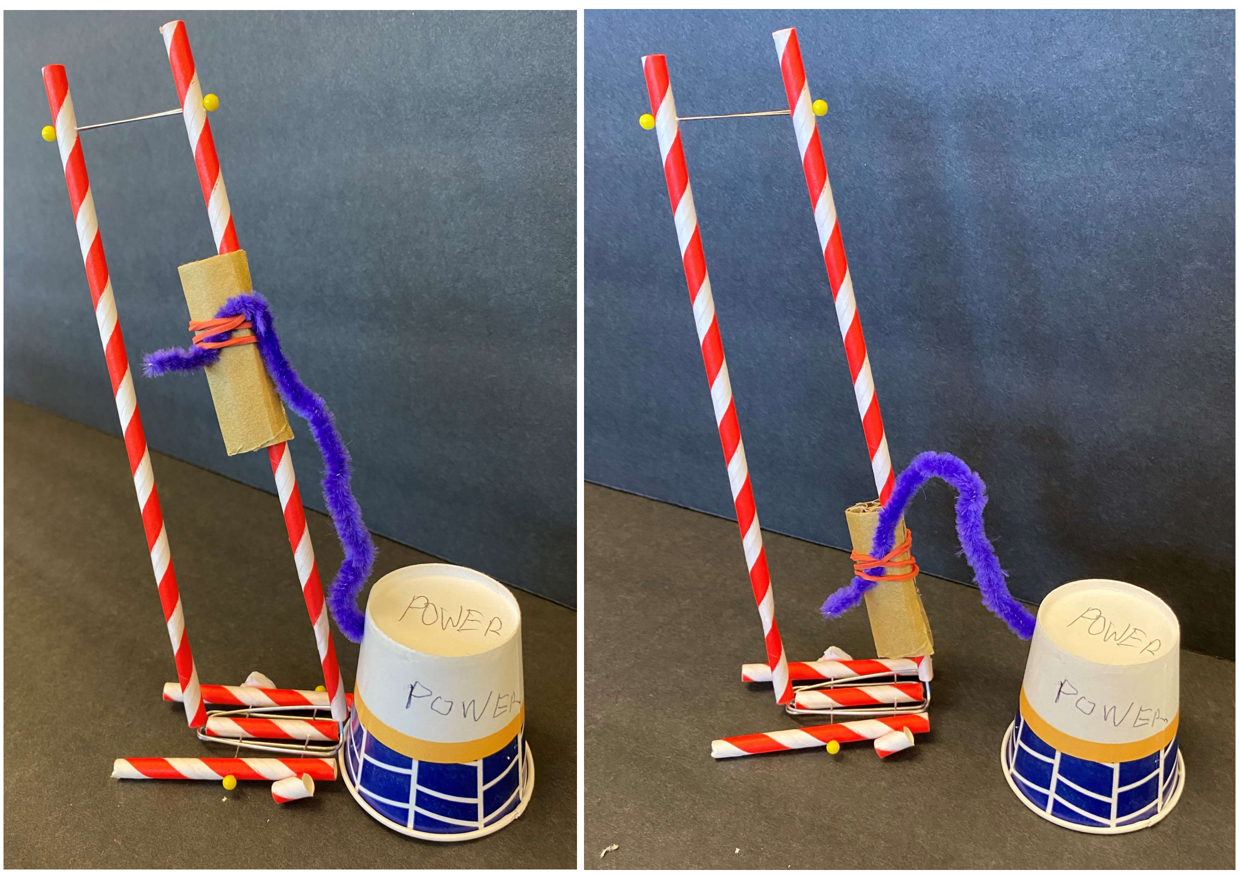


Figure A2.6. John Ideation Model 1 – Test Stand Two Linear Sliders Power Supplied from Side

Figure A2.7. John Ideation Model 2 – Test Stand Two Linear Sliders Power Supplied from Top

Figure A2.8. John Ideation Model 3 – Test Stand Two Linear Sliders Power Supplied from Side

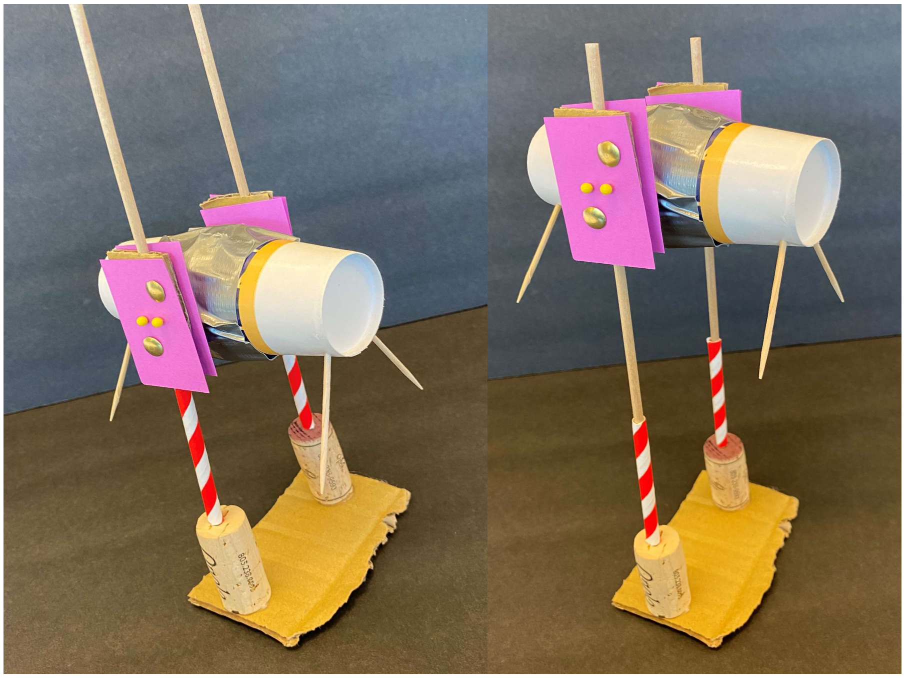


Figure A2.9. John Ideation Model 4 – Test stand With Two Linear Sliders (Vertical Motion only)

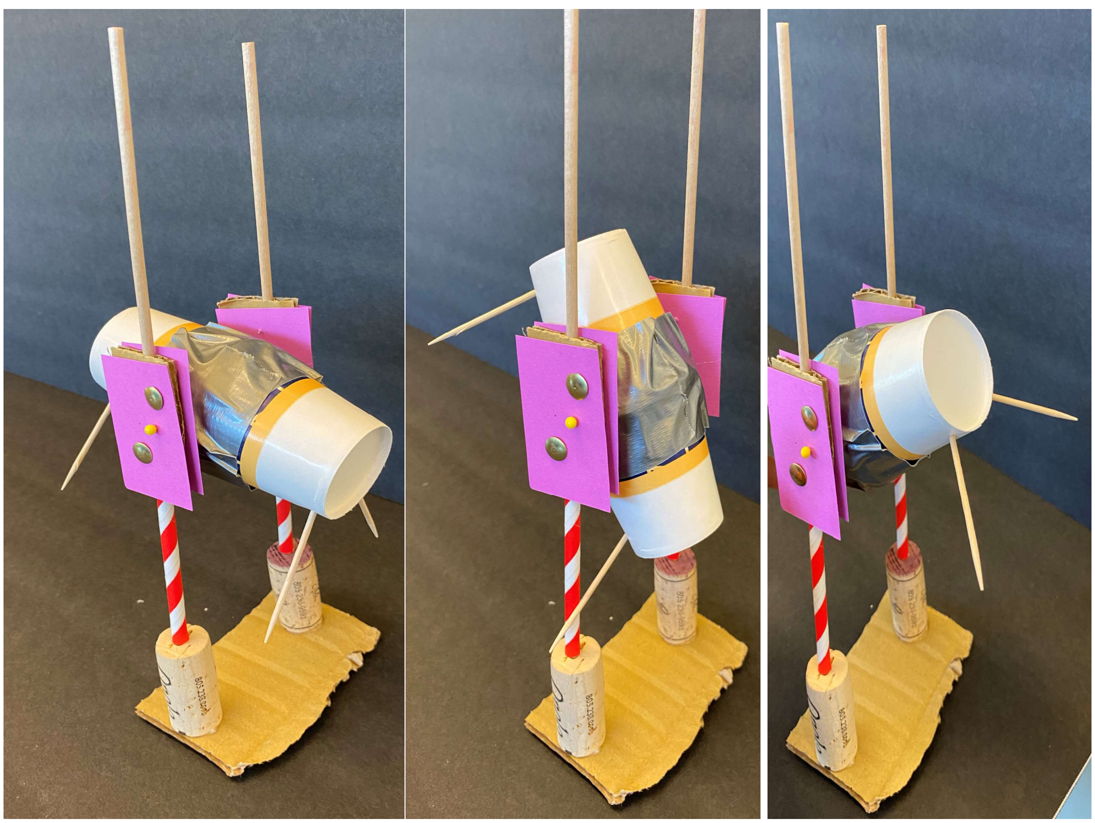


Figure A2.10. John Ideation Model 5 – Slider Connecting Robot to Test Stand (Vertical Motion and Pitch)

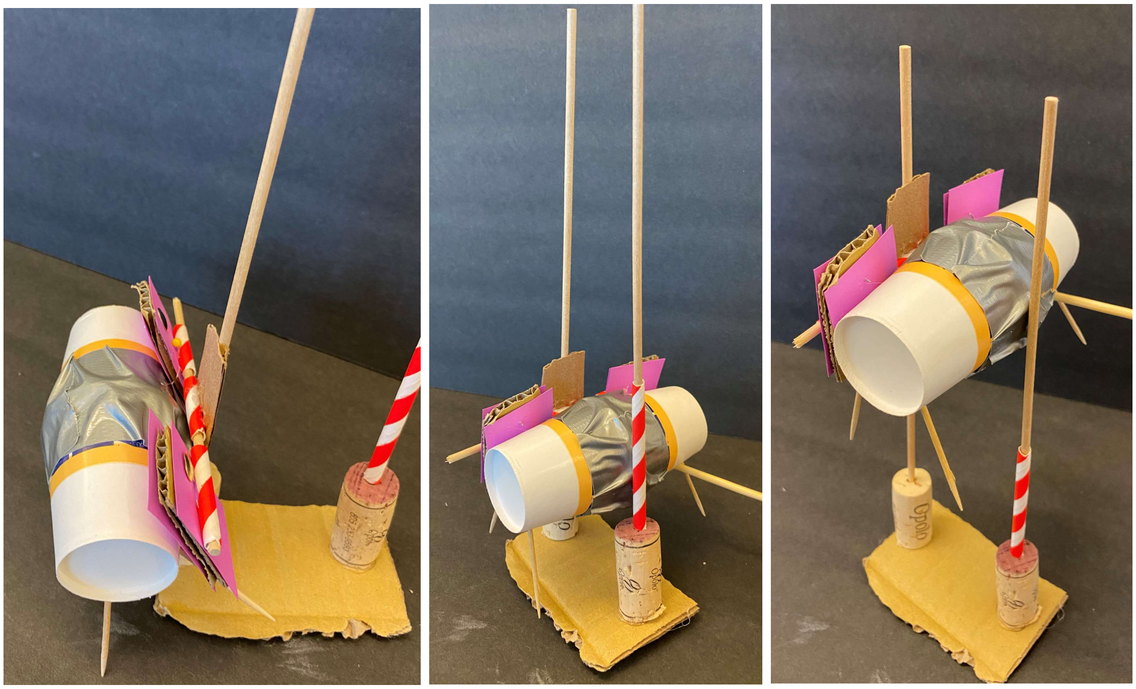


Figure A2.11. John Ideation Model 7 – Slider Connecting Robot to Test Stand (Vertical Motion and Roll)

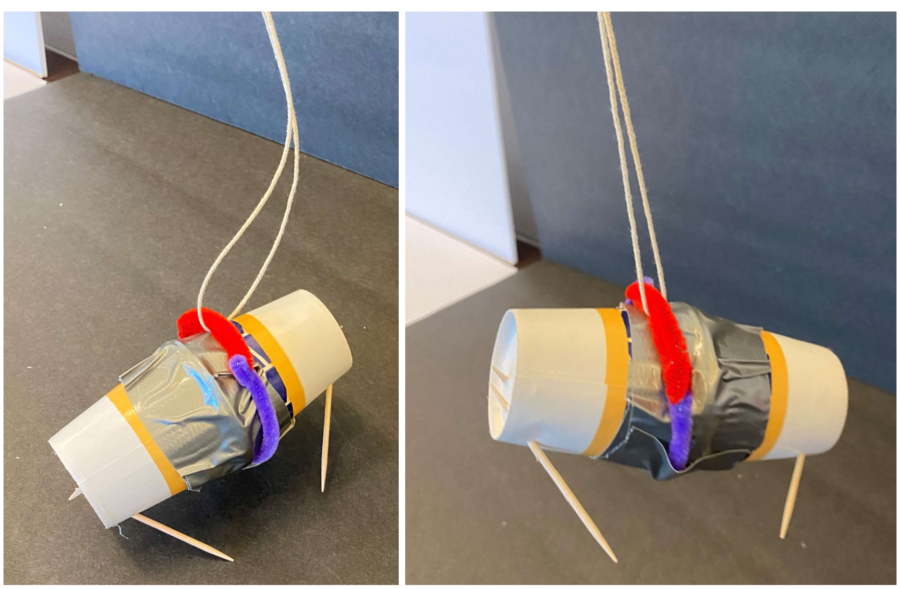


Figure A2.12. John Ideation Model 8 – Harness Connecting Robot to Test Stand (All Motions)

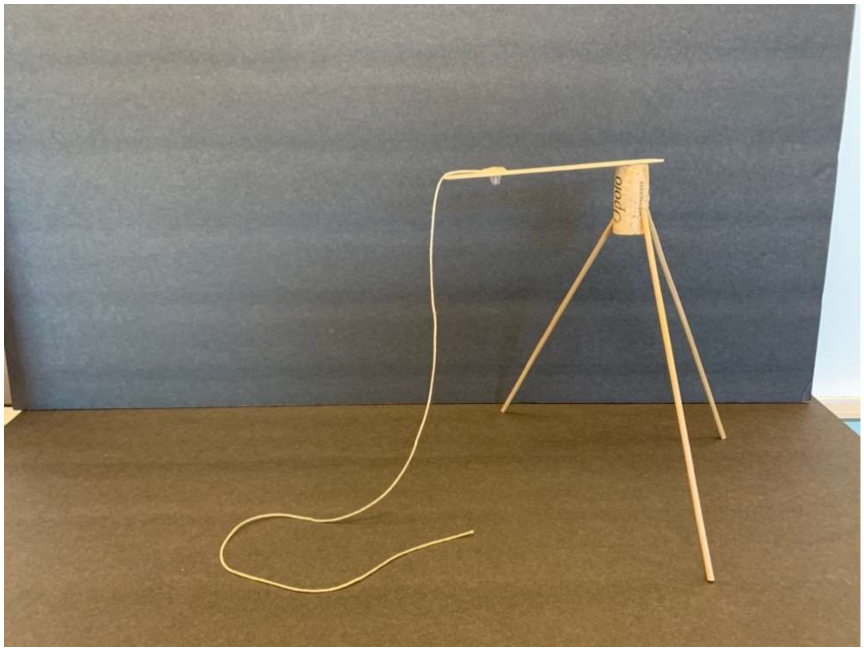


Figure A2.13. Tyler Ideation Model 1 – Test Stand for full Range of Motion

Figure A2.14. Tyler Ideation Model 2 – Full 8DOF Robot with Body and Leg Wiring

Figure A2.15. Tyler Ideation Model 3– Leg for 8DOF Robot with Torque Transmitter

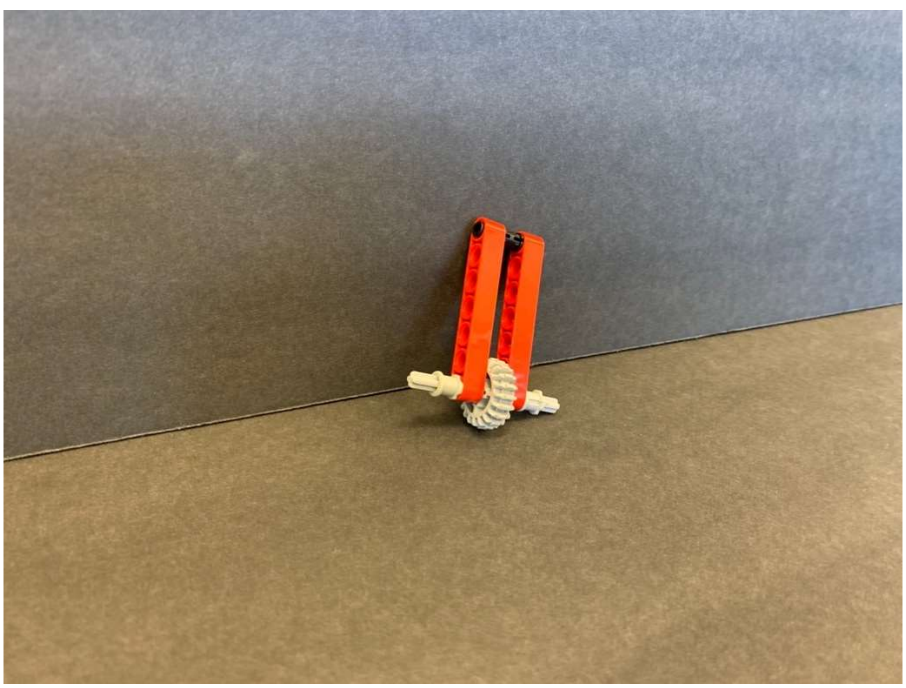


Figure A2.16. Tyler Ideation Model 4– Knee Torque Transmiter with Splines

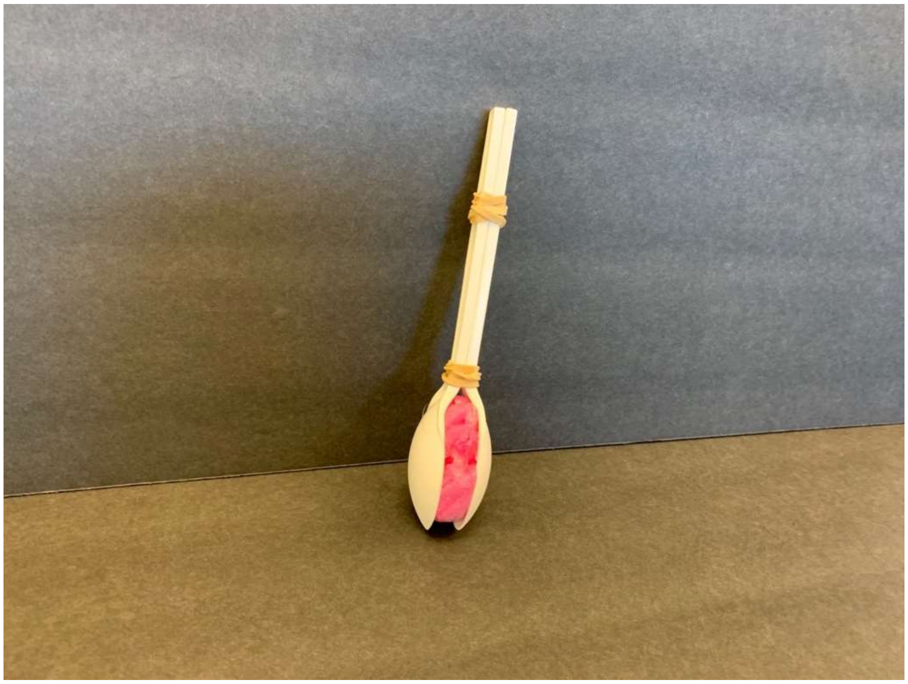


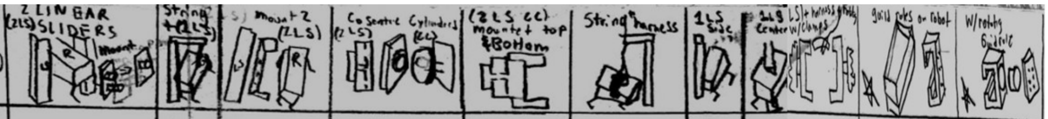
Figure A2.17. Tyler Ideation Model 5– Foot Attachment for Leg

8.3 Appendix 3: Pugh Matrices

Table A3.1. Knee Joint Pugh Matrix

Function: Knee Joint	Datum: Current prototype idea	Splines w/ sep pulley	Solid piece/part	Splines w/ attached pulley	Slot in end of	Square/ rectangular slot
Low Inertia	S	–	–	S	–	–
Mechanical Durability	S	+	+	+	–	–
Cost	S	–	–	=	–	–
Manufactuable	S	–	+	–	–	–
Ease of Assembly	S	+	S	+	+	+
Teachable to freshman	S	–	+	–	S	S

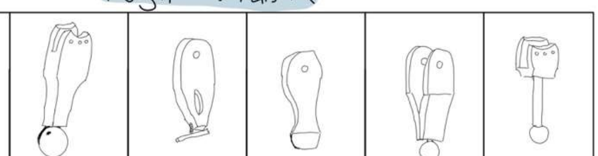
Table A3.2. Test Stand Pugh Matrix



MOUNTING ROBOT TO Test STAND	2 LINEAR SLIDERS (2LS)	String + (2LS)	mount 2 (2LS)	Co-centric Cylinders (2LS) (CC)	(2LS CC) mounted top & Bottom	String harness	1LS Side	1LS Center	LS + harness w/ clamps	guide rails on robot	W/ rotating guide
EASE OF ASSEMBLY (1)	S	+	+	S	+	+	+	+	-	+	+
COST (2)	S	+	+	-	-	+	+	+	-	+	-
FUNCTIONAL TEST STAND (3)	S	-	S	+	+	-	-	S	+	S	+
MODULARITY / PORTABLE (4)	S	S	S	S	S	+	S	S	S	S	S
STABLE FLIGHT PHASE (6)	S	-	S	S	S	S	-	-	S	-	S
Σ +	0	2	2	1	2	2	2	2	1	2	2
Σ -	0	2	1	-1	-1	-2	-2	-2	2	1	1
TOTAL	0	0	1	0	4	0	0	0	-1	1	1

Table A3.3. Lower Link Pugh Matrix

Pugh Matrix

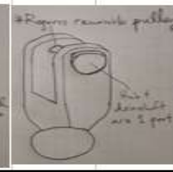
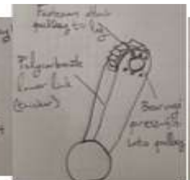
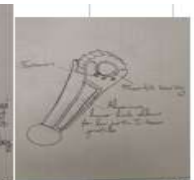


Idea / Wants/Need	Current Calf	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5
Ease of Assembly	S	+	-	+	S	S
Mechanical Durability	S	+	+	+	-	+
Cost	S	S	-	+	S	+
Manufacturable	S	-	-	+	S	+
Teachable	S	S	S	S	+	+

8.4 Appendix 4: Weighted Design Matrices

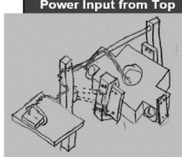
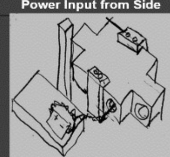
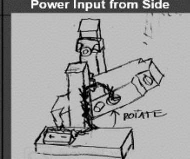
Table A4.1. Lower Leg and Knee Joint Weighted Decision Matrix

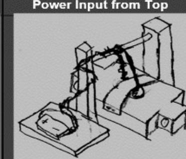
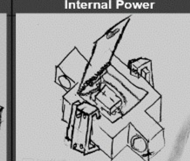


Criteria	Weight (%)	Splines with Separate Pulley; Forked Lower Link		Splines with attached Pulley; Forked Lower Link		Solid Shaft and Hub; Forked Lower Link		No driveshaft; Pulley attached to plastic lower link		No driveshaft; Pulley attached to aluminum lower link	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Low Inertia	15.25%	3	6.1017	3.6	7.9322	4.2	9.7627	4.2	9.7627	5.4	13.4237
Mech. Durability	13.56%	3	5.4237	3	5.4237	3.6	7.0508	4.2	8.6780	4.8	10.3051
Cost	18.64%	3.6	9.6949	3.6	9.6949	4.8	14.1695	4.2	11.9322	4.2	11.9322
Manufacturable	15.25%	1.2	0.6102	1.2	0.6102	3.6	7.9322	3.6	7.9322	3	6.1017
Ease of Assembly	18.64%	3.6	9.6949	4.2	11.9322	1.8	2.9831	3.6	9.6949	3.6	9.6949
Teachable to Freshman	18.64%	4.8	14.1695	4.8	14.1695	4.8	14.1695	4.8	14.1695	4.8	14.1695
Totals:	100.00%		45.7		49.8		56.1		62.2		65.6

Table A4.2. Testing Set Up Weighted Decision Matrix

Criteria	Weight (%)	#1 Guild Railed Mounts; Power Input from Top		#2 Tabbed Mounts; Power Input from Side		#3 Rotating Mount; Power Input from Side		#4 Support Harness; Power Input from Top		#5 Guild Railed Mounts; Internal Power	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Ease Of Assembly (Mount to Robot)	9.00%	2	6.75	4	2.25	3	4.50	2	6.75	1	9.00
Orginazation	9.00%	3	4.50	2	6.75	2	6.75	2	6.75	1	9.00
Freedom of Motion	16.00%	5.5	10.29	4	6.86	2	2.29	1.5	1.14	7	13.71
Allows Stable Flight Phase Testing	16.00%	2	3.20	2	3.20	5	12.80	6	16.00	2	3.20
Manufacturability	16.00%	7	16.00	2.5	4.00	2.5	4.00	5.5	12.00	3	5.33
Mobility/Portable	7.00%	1	0.00	3	1.56	3	1.56	3	1.56	8	5.44
Variety of Testing Motions	11.00%	1	0.00	1	0.00	3	7.33	1.5	1.83	1	0.00
Cost	16.00%	7	10.67	5	16.00	11	0.00	9	5.33	9	5.33
Totals:	100.00%		51.40		40.61		39.22		51.37		51.03

Table A4.3. Battery Weighted Decision Matrix




Criteria	Weight (%)	Alkaline		NiMH		Lithium-Ion (LiCoO2)		Lithium-Poly (LiMn2O4)		Lithium-Poly (LiFePO4)	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Cost	7.00%	9	0.6300	3	0.2100	6	0.4200	7	0.4900	7	0.4900
Weight	11.00%	4	0.4400	5	0.5500	8	0.8800	9	0.9900	9	0.9900
Size/Shape	14.00%	3	0.4200	6	0.8400	9	1.2600	8	1.1200	8	1.1200
Battery Life	18.00%	3	0.4200	7	1.2600	9	1.6200	9	1.6200	9	1.6200
Discharge Current	21.00%	3	0.4200	4	0.8400	5	1.0500	9	1.8900	6	1.2600
Ease of Charging	18.00%	3	0.4200	5	0.9000	6	1.0800	6	1.0800	6	1.0800
Safety	11.00%	3	0.4200	9	0.9900	7	0.7700	7	0.7700	9	0.9900
Total	100.00%		3.17		5.59		7.08		7.96		7.55

8.5 Appendix 5: Preliminary Analysis and Testing

We conducted a testing day on October 30, 2021 to assess the fatigue durability of our design, and subsequently expoes and areas of weakness within the design. We subjected the single-leg prototype that was developed over the sumer to ~1,000 cycles and simultaneously refined our MATLAB/Simulink controller parameters such that the leg was able to exected a repeated jump for an arbitrary amount of cycles. Upon the completion of our testing process, we observed that the driveshaft experienced signifciant galling from the knee pulley's setscrews, which prevented disassembly of the knee joint and thus an entire half of the single-leg. Figure A5.1 displays the galling of the driveshaft from the setscrew pressure, and Figure A5.2 displays the galling of the key from the setscrew pressure.

Figure A5. 1. Close-up of driveshaft surface galling due to setscrew pressure.

Figure A5.2. Close-up of key surface galling due to setscrew pressure.

8.6 Appendix 6: Design Hazard Checklist

Design Hazard Checklist

Y	N	
	✔	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
✔		2. Can any part of the design undergo high accelerations/decelerations? – relatively large forces.
✔		3. Will the system have any large moving masses or large forces? - a potentially broken robot.
	✔	4. Will the system produce a projectile?
	✔	5. Would it be possible for the system to fall under gravity creating injury?
	✔	6. Will a user be exposed to overhanging weights as part of the design?
	✔	7. Will the system have any sharp edges?
✔		8. Will any part of the electrical systems not be grounded? - battery
	✔	9. Will there be any large batteries or electrical voltage in the system above 40 V?
✔		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	✔	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	✔	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	✔	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✔	14. Can the system generate high levels of noise?
	✔	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
✔		16. Is it possible for the system to be used in an unsafe manner? - In theory, though pretty much any system can be unsafe if one tries hard enough
	✔	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Table A6.1. Design Hazard Plan

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Rapid leg acceleration during jumping motion	Operate the leg in an open space; ensure all operators are a safe distance from the test stand; de-initiate motors before attempting to access quadruped	1/03/21	TBD
Large GRF to launch quadruped	Use a strong material for the test stand base; soft material for the quadruped foot	9/20/21	TBD
Non-grounded battery	Battery will be mounted within body frame of quadruped and inaccessible during operation.	1/03/21	TBD
Battery stored energy	Design a power distribution board to ensure that motors are not given an excessive current load.	2/1/21	TBD

8.7 Appendix 7: Gantt Chart

Table A7.1. Fall Term Gantt Chart

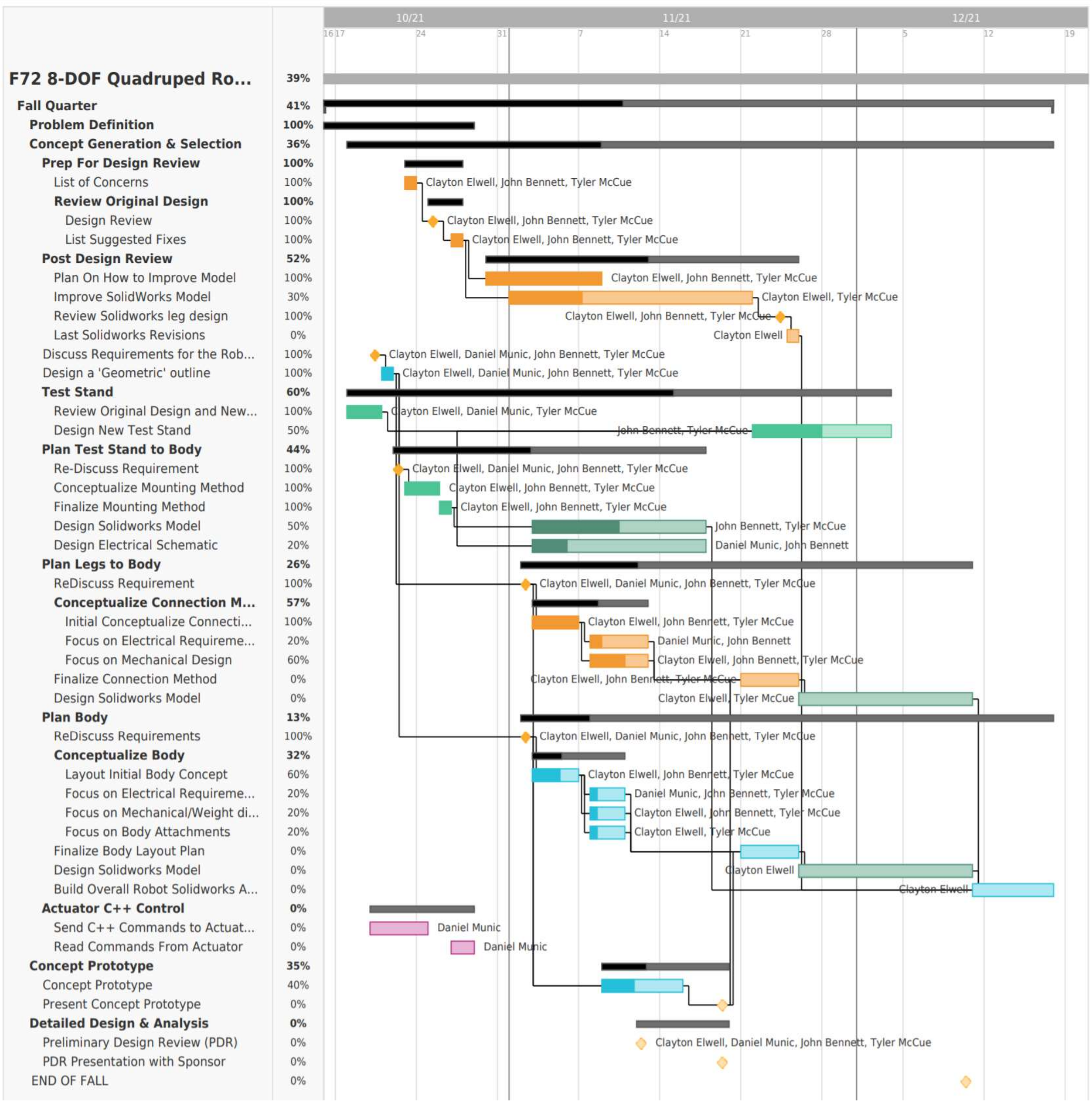


Table A7.2. Winter Term Gantt Chart

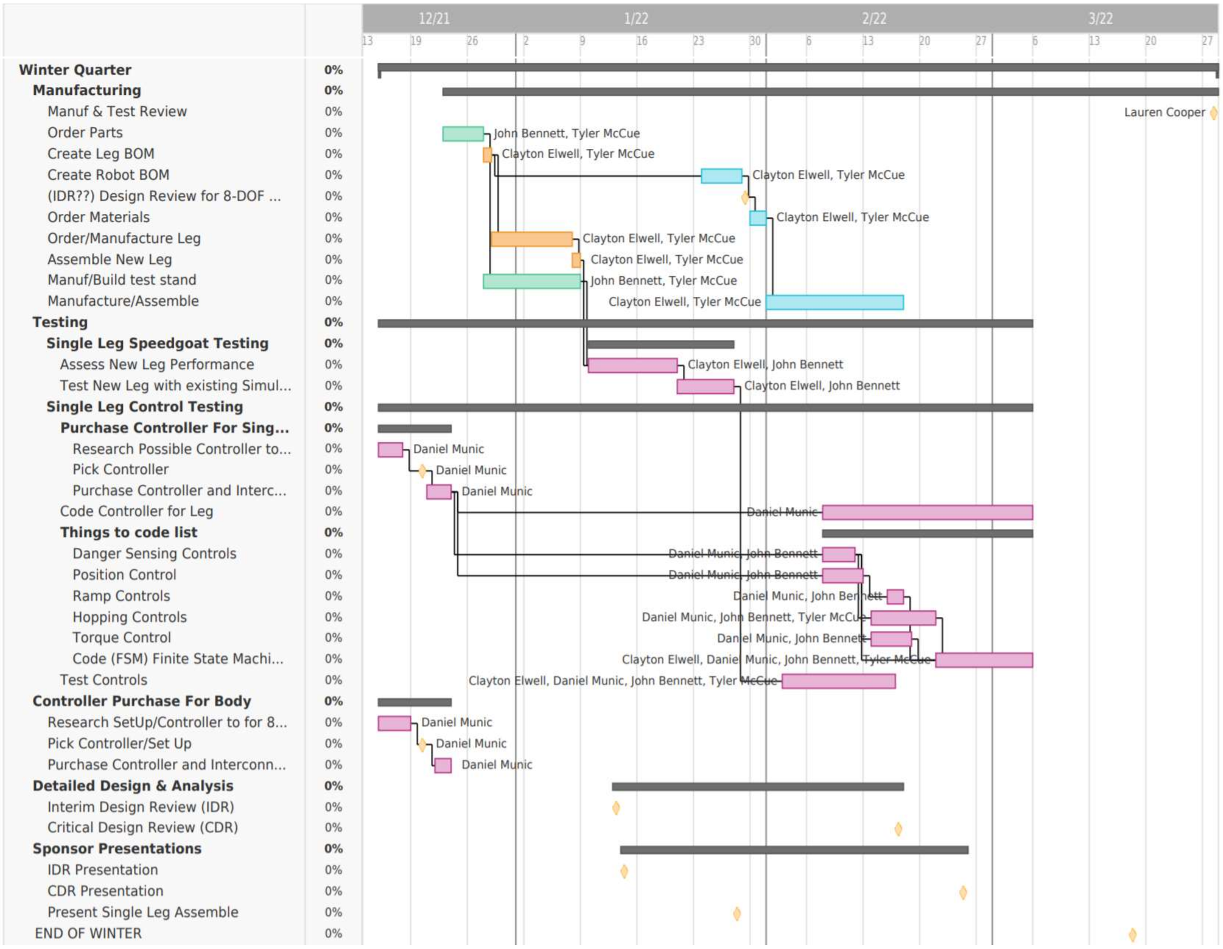
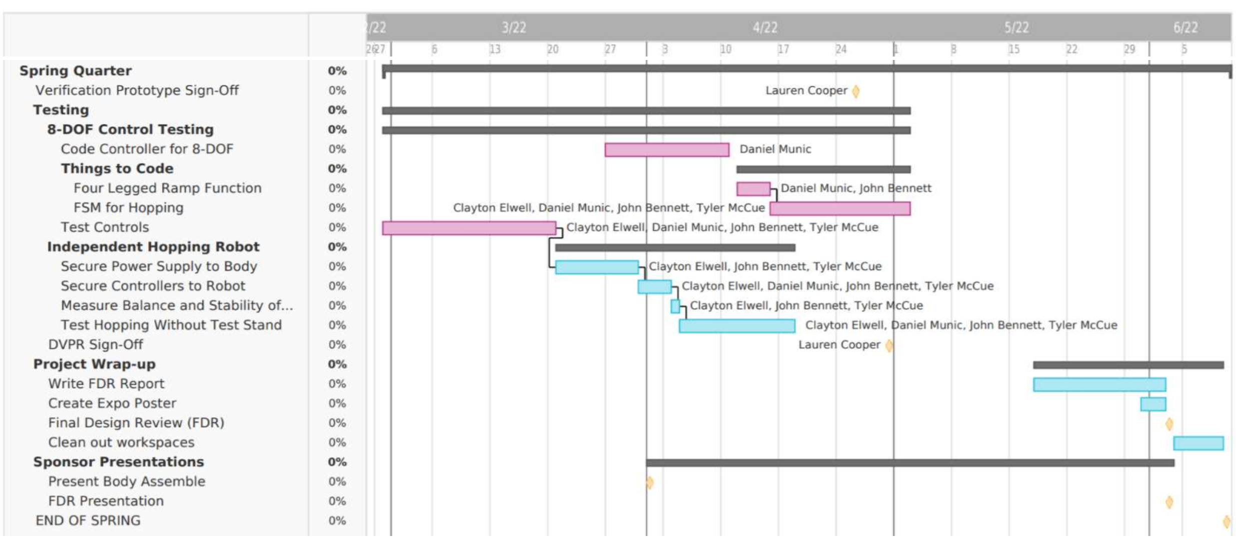


Table A7.3. Spring Term Gantt Chart



8 DOF Quadrupedal Hopping Robot

Critical Design Review

February 10, 2022

Winter 2022 ME 429-07 Group F72

The B.R.U.C.E. Bot Engineers

Tyler McCue Daniel Munic

Clayton Elwell John Bennett

8dofseniorproject@gmail.com

Prepared for Dr. Siyuan Xing and Charlie Refvem

sixing@calpoly.edu crefvem@calpoly.edu

Department of Mechanical Engineering

California Polytechnic State University, San Luis Obispo

Abstract

California Polytechnic State University does not offer lower division robotics courses, which prevents underclassmen from accessing a structured learning environment that focuses on the field of robotics. Our senior project aims to prototype an eight degree of freedom quadrupedal robot, and a modular test stand, that will be a platform for future Cal Poly students to refine; both the robot's mechanical design and control algorithm that it uses. In addition to giving future Cal Poly students exposure to robotic design and control, the robot will bring awareness to our sponsors' (Dr. Siyuan Xing and Charlie Refvem) research group – Cal Poly Legged Robots. The quadruped will include adequate assembly instructions and controller documentation so that underclassmen at Cal Poly may learn from the project and explore the field of robotics with a more structured curriculum.

This document presents the details of our quadrupedal robot design and explains how it will function. It proceeds to outline our design specifications, and subsequently highlights the choices made and tests performed to satisfy these specifications. After outlining the justification for our design, the document explains the process of fabricating and assembling the quadrupedal robot and test stand, in addition to the procurement of materials. The report proceeds to describes our planned tests to evaluate the quadruped's ability to satisfy our specifications. Lastly, the key next steps are identified and a request for approval from our sponsor to begin ordering parts and manufacturing the verification prototype and test stand is made.

Table of Contents

1. Introduction

1.1 Team

Dr. Siyuan Xing and Charlie Refvem, professors in the mechanical engineering department at Cal Poly are interested in developing an 8-DOF Quadruped. Dr. Xing and Charlie have been coordinating projects for the Cal Poly Legged Robots research group. Dr. Xing proposed the fall F72 senior project to build upon the 2 DOF robotic leg summer research. The team consists of three mechanical engineers, Clayton Elwell, John Bennett, Tyler McCue, and one Computer Engineer, Daniel Munic.

Clayton initially took interest in Dr. Xing's quadrupedal robot research at the beginning of Spring quarter 2021. Throughout the duration of Spring 2021, he developed a SolidWorks model of a single robotic leg, which he manufactured and developed a controller for during Summer 2021 with the assistance of John Bennett. This single-leg prototype was a precursor to the quadruped that is the goal of this senior project.

John Bennett's interest in controls, mechatronics, and mechanical design drew him to the project. Building an 8-DOF robot provides exciting challenges and requires a variety of engineering skills.

Tyler was drawn in due to the challenge of the project. With mechanical design, coding, and controls being an important aspect of the quadruped, this project was a gateway into the rigorous field of robotics.

Daniel was interested in the project due to the control system and electrical design complexity of the project. Building those systems from scratch is a difficult but attractive way to learn the embedded systems side of robotics.

1.2 Design Challenge

The design challenge for this senior project is to develop a prototypical model of a quadrupedal robot, which will be used to expose underclassmen at Cal Poly to the process of robotic mechanical design and the development of robotic control algorithms. The goal for this project is to manufacture the prototypical quadruped and subsequently develop a controller that commands it to execute a vertical hopping motion. To facilitate this dynamic motion, our team will also develop a modular test stand that provides external power to the quadruped. Upon completion of the quadruped prototype and test stand, proper documentation and assembly guidelines must be created so that future Cal Poly students may understand the technical details of our project and continue to improve upon the results of our senior project.

1.3 Major Design Changes

There have been major design updates to the test stand, body frame, and leg designs since PDR. We developed a SOLIDWORKS model for the complete system, and upon creation of this model realized that the vertical struts that guide the motion of the robot should be moved to the front and back panels of the quadruped, rather than fastening to the side panels of the body frame. This will ensure the test stand geometry and quadruped motion do not interfere and allow us to evaluate the robot's tendency to roll.

The body frame design has seen significant development since PDR. We have developed an initial electronics layout in our SOLIDWORKS model, but still need to refine the cable harness layout and the specific wires/connectors needed for certain components. This issue will be fully fleshed out during the process of manufacturing and assembling the prototype; the necessary components are usually available with short lead times and thus not undesirably delay our testing process. Additionally, since our initial tests will occur with a single leg, we will have additional time to configure the quadruped's internal electronics layout. A detailed design of the body frame structure has been developed with manufacturing simplicity in mind; it includes the necessary holes to allow the wire harness to connect to the actuators while relieving strain from connectors.

The lower link geometry has been reconfigured to sit inside of the upper link, rather than forking around the upper link. The pulley will be attached to the lower link, rather than the upper link. This essentially turns the knee shaft into a pin, which will eliminate the necessity to transmit torque through it and ultimately reduce the wear that the knee shaft will experience. The upper link has been minorly adjusted to accommodate the new lower link geometry. Additionally, we redesigned the lower link with manufacturing in mind, and significantly reduced the complexity of the manufacturing processes required to manufacture the lower link.

1.3 Report Overview

This document outlines our detailed design and prototype's functionality, and subsequently identifies the analysis and tests we have conducted to justify the current design. The manufacturing plan for our quadruped and test stand is outlined, in addition to assembly instructions. Procurement for necessary materials is also highlighted. A design verification plan is then presented, in the form of tests that will evaluate the specifications determined in Fall 2021.

2. System Design

This section discusses the final design of the 8-DOF hopping robot and each subsystem. It also discusses the specific parts and materials chosen and breaks down the total cost.

2.1 Final Design

Our final selected design for 8-degree of freedom hopping robot. Our design was developed by focusing on making the design manufacturable, safe, and lightweight. This design is comprised of several subsystems that will work together to create controlled hopping; these includes the legs, body frame, and test stand assemblies. The complete system is displayed in Figure 1. The legs are mounted to the body frame, which holds various electrical components that power the actuators and control the robot's motion. The test stand will be attached to the body frame from the front and back panels to ensure that the test stand will not interfere with the legs dynamic motion. The body frame's motion is constrained by the test stand such that it may roll and vertically translate. The test stand also provides a level surface that will grip well with the robot's TPU feet. This set up will be used to test and subsequently optimize our hopping controller in a safe and efficient manner.

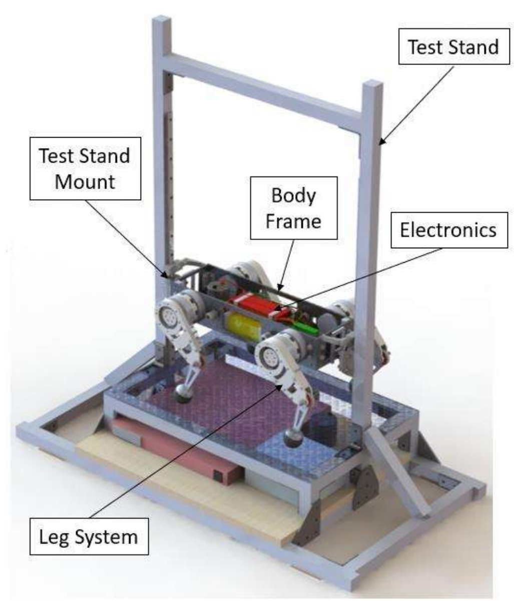


Figure 1: Current system design and test stand.

2.2 Subsystems and Components

2.2.1 Leg

The leg is made from a mixture of 3D printed materials and aluminum. There are two motors attached to the thigh link by a 3D printed adapter, as seen in Figure 2. The thigh is attached by fasteners directly onto the motor. A pulley adapter is also then fastened directly with the pulley attached to the adapter. The thigh also consists of a belt tensioner created with 2 bearings and bolts that allow the belt to be tightened as needed. The knee joint receives torque directly from the belt and rotates around the knee pin which is comprised of a simple nut and bolt. This is also where the second pulley is located with a bearing in the middle. The lower link, made from two 1/8th in. thick aluminum parts, fastens right onto the knee pulley accompanied by the foot at the very bottom.

Detailed drawings for the leg's aluminum calf and 3D printed components may be referenced in Appendix J. The cost for the materials and motors may be referenced in Appendix D.

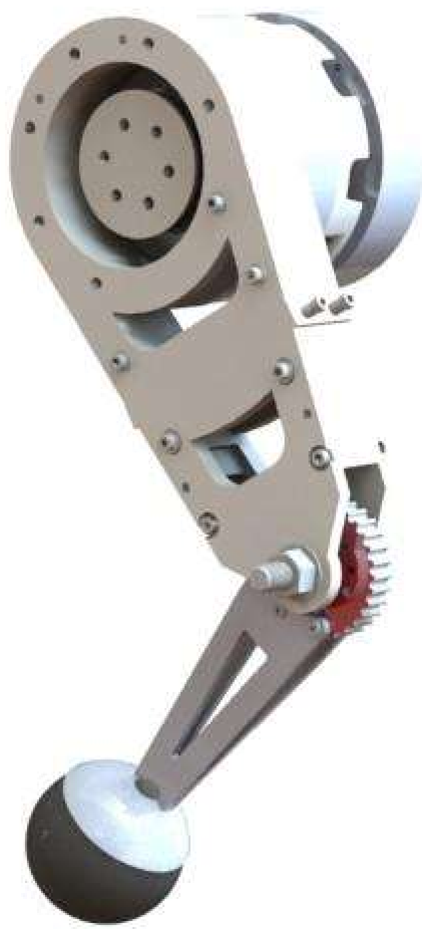


Figure 2: Redesigned leg with aluminum lower link.

2.2.2 Body Frame

The body frame is made from quarter-inch aluminum panels that are waterjet to include the desired holes for attaching the actuators to the robot, allowing wires to pass through, connecting the panels together, and minimizing the weight of the frame. The chassis panels are connected by four L-brackets that may be seen in Figure 3. The L-brackets are 1/8th inch thick aluminum; 1/4-20 fasteners are used in the L-brackets. The internal electronics layout has not been finalized, but we know that the components will include two 13.6 V 8.6 Ah batteries in series in addition to a battery management system (BMS), capacitor for maintaining current, relays for managing power to the actuators, fuses for emergency actuator protection, and a power distribution board (PDB) with an STM brand microcontroller mounted on the PDB's headers to step the 24 V battery output down to 3.3V which is used for data transmission via CAN protocol. The internal electronics packaging will be 3D printed for rapid iteration and affordability. The packages for the electronics will be secured to 14-gauge aluminum panels that will be waterjet. These panels will fasten to 3D printed adapters, which subsequently attach to the chassis via M3 socket-head cap screws. Cable glands allow the internal wiring to pass through the walls of the chassis to the actuators, and simultaneously provide strain relief for the harness.

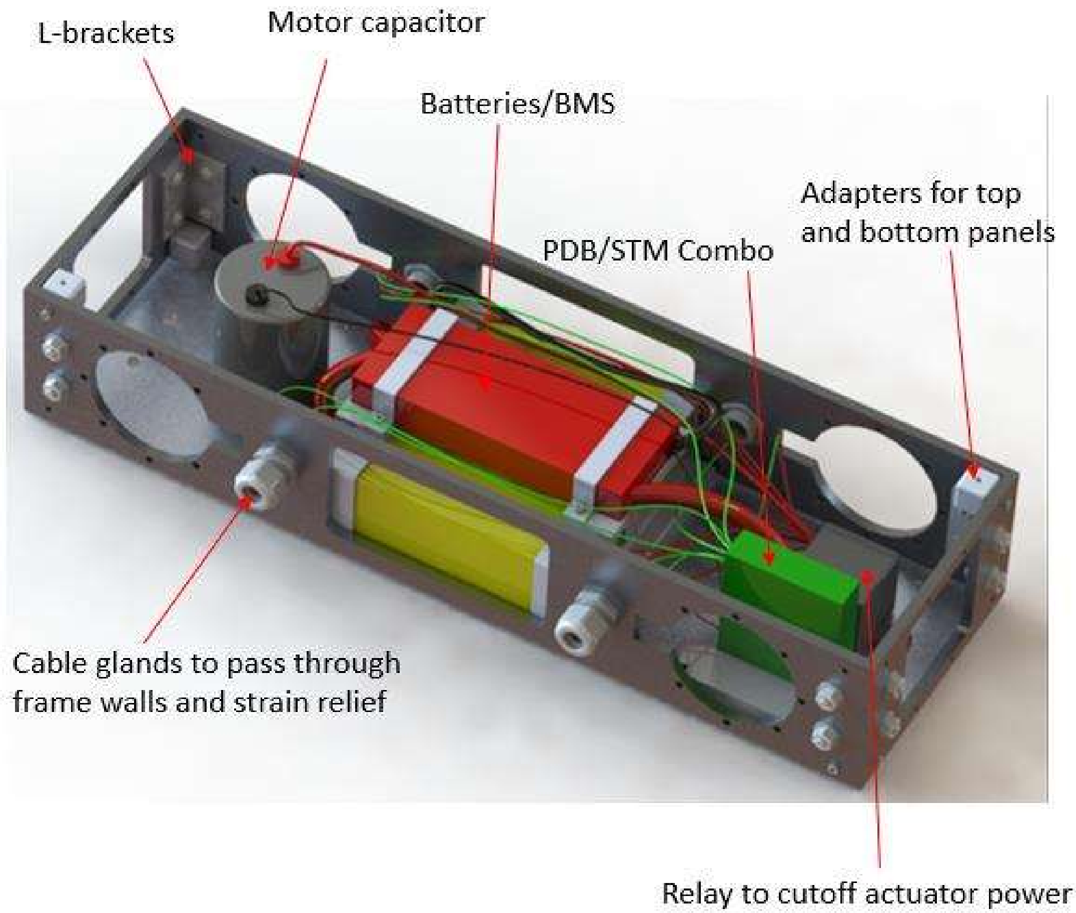


Figure 3: Body frame design and initial electronics layout revision.

Detailed drawings for the body frame's aluminum and 3D printed components may be referenced in Appendix D. The cost for the chassis materials and internal electronics may be referenced in Appendix J. Reference wiring diagrams for our initial/summer testing in Appendix B.

2.2.3 Test Stand

The test stand is designed to provide a safe place to facilitate all planned quadrupedal testing. The test stand frame is made of 1.5"x1.5" slotted 80/20 and is held together by 80/20 brackets. To make the test stand more modular, the frame width is designed to be 24.5”, which is wide enough to fit through doors. To make the test stand more mobile, caster wheels were added. The caster wheels have a gear inside to raise and lower the wheels, allowing the test stand to be stationary for testing. The quadrupedal robot needs a lot of room for testing, and we were given a lot of massive external electronics. To increase organization, we chose to raise the jumping platform so we can store all our larger external electronics. The key electronic components are 24V DC power supply (PS), Speedgoat (SG), Motor capacitor (C). The jumping platform is a .25” polycarbonate plate that will be water jetted to fit and fasten to the test stand. Having a polycarbonate plate provides a flat and grippy surface for the robot to bounce. Also being able to see the electronics under the jumping platform will be a convenient way to examine testing set-ups. When testing with external power, the harness is fed over the upper bar through the top of the robot. See Figure 4 for the test stand layout.

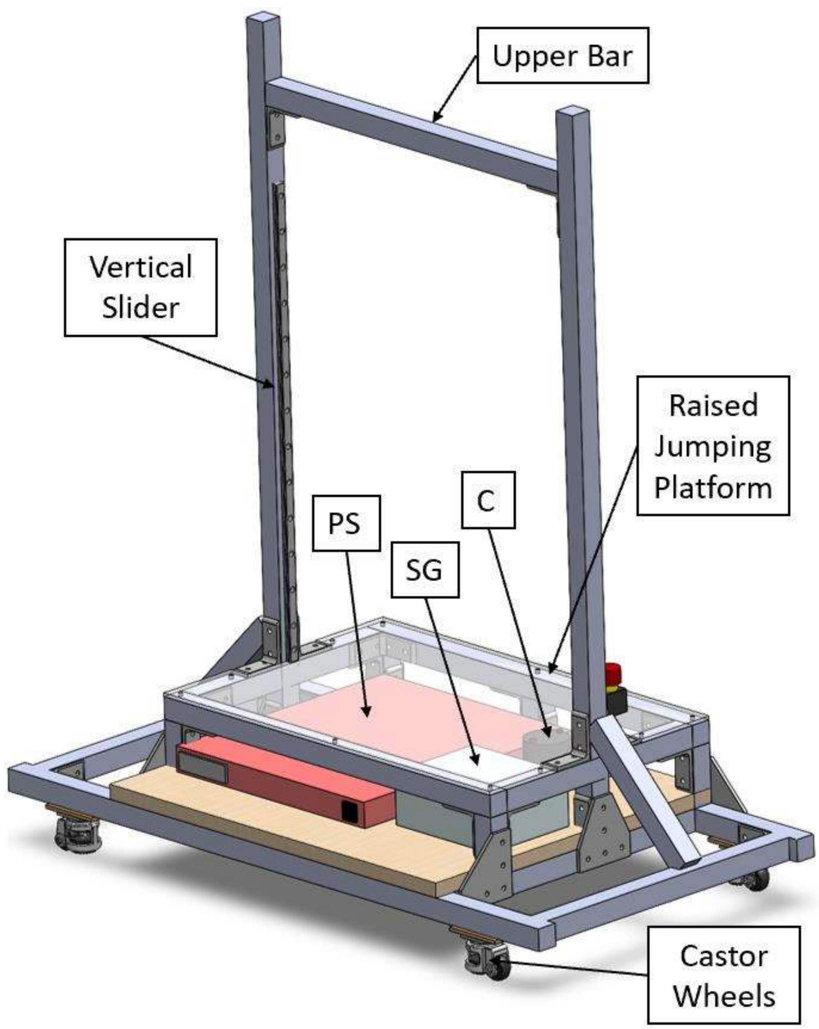


Figure 4: Modular test stand design for quadrupedal robot.

Detailed drawings for the test stand mount and test stand components may be referenced in Appendix J. The cost for each assembly part materials and internal electronics may be referenced in Appendix D.

The test stand mount will be connected to the vertical sliders on test stands and the end frames on the body frame. The test stand mount is designed to be simple to manufacture and assemble. It is made up of three water jet .25" aluminum plates, a .5" diameter shaft, and a purchased ball bearing mount. The plate to the far left is the body mount plate, which is welded to the shaft, to its right is the mount plate for the purchased ball bearing mount and finally the third plat is to allow space for the purchased ball bearing mounts fasteners. This is all simply held together by fasteners. The function of the test stand mount is to allow testing of both vertical translation and rolling motions. Ball bearing carriage allows vertical translation along guide rails and the .5" shaft with ball bearing mounts allow rotation. The test stand mount is held together by fasteners. See Figure 5 for the test stand mounts design.

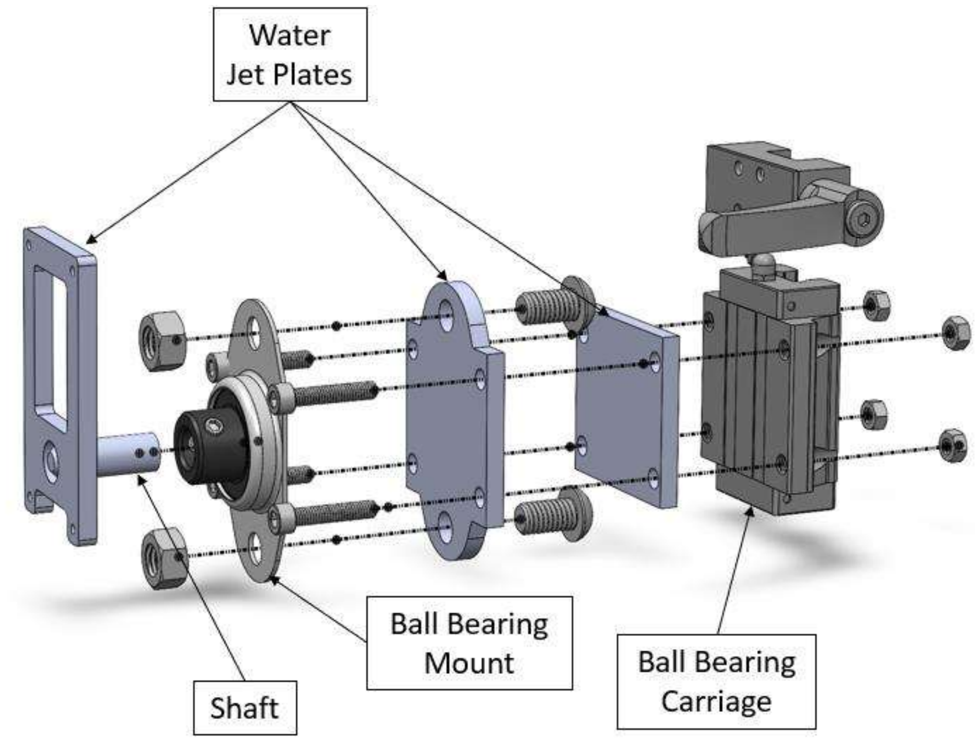


Figure 5: Test stand mount design that connects from vertical test stand struts to quadruped body frame.

2.2.4 Electronics

The final electronics design (Figure 6) includes eight actuators and fuses, the relay, motor capacitor, power distribution board, battery, and battery management system. One fuse (amperage rating not yet known, needs testing) will be connected to each actuator. The relay will be connected to the actuator in parallel with a resistor (100ohm) to prevent inrush current damage. The motor capacitor (100mF) will be in parallel with the actuators with a bleeding resistor (100ohm) in series with it. The power distribution board will contain all protection circuitry and connectors for the microcontroller. The battery (24V) will supply power to all components with the battery management system board between the battery and the components to prevent damage to the battery.

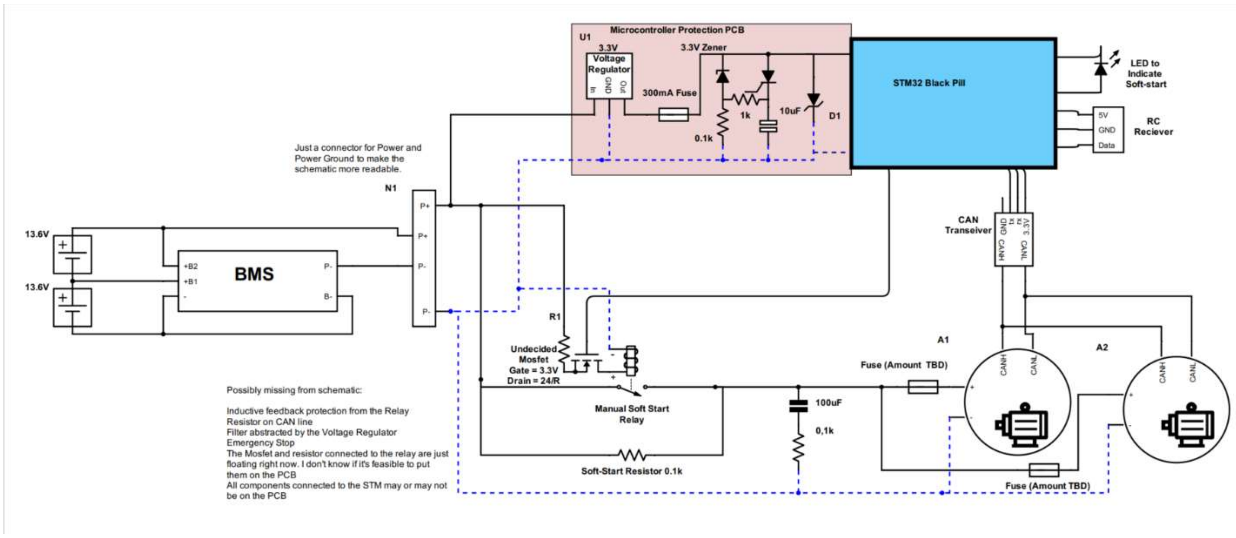


Figure 6: System electronics layout; two actuators included for brevity.

The microcontroller (stm32 black pill) will run autonomously and be connected by headers onto the power distribution board. This microcontroller will send CAN (Controller Area Network) messages to the actuators through a CAN transceiver, which will be daisy chained through many actuators so each motor can receive the same signal from a single CAN bus. The microcontroller will also control the motor soft-start by activating the relay. The robot will take input through a remote control connected to the microcontroller.

2.2.5 Controller development

We have begun initial efforts to communicate with the motors via a Nucleo and C++ code and intend on beginning the testing process with a single leg to ensure the conversion of our MATLAB/Simulink controller to C++ was successful. Currently our controller utilizes position control during the flight phase, and impedance (torque) control during the ground phase. The state machine switches back and forth between the flight and ground phase was implemented during Summer 2021 using the Stateflow MATLAB toolbox. Additionally, the CAN communication done via the Speedgoat utilized the IO691 CAN I/O Module that is provided by MATLAB. A collision detector was also developed out of the necessity to recognize when the leg is in the air or in contact with the ground. Reference Appendix C for images of our Simulink closed-loop controller and finite state machine that controls the hybrid system.

2.4 Cost Analysis Summary

Most of our budget is going towards the actuators used to drive the legs of our robot. As seen in Table 1, of our $5,000 budget, $2,400 is going towards these actuators. The next most expensive components of our system are the test stand structural elements and the ball bearing carriage and subsequent guide rail for the carriage. For a more detailed breakdown of our budget and system costs reference the project budget and iBOM in Appendix J. We decided to submit a Winter proposal to CP Connect to ensure that our budget is sufficient for our project's needs.

Table 1: Cost breakdown by subsystem.

Components/Subsystems	Approximate Cost
Upper Link	$ 183.84
Lower Link	$ 103.00
Body Frame Structure	$ 18.30
Battery	$ 250.00
Actuators	$ 2,400.00
Other Components	$ 100.88
Test Stand Mount Assembly	$ 90.81
Test Stand Frame	$ 401.78
Guild Rail Parts	$ 694.35
Total Cost	$ 4,242.96

3. Design Justification

3.1 Design Specification Justification and Analysis

The following section outlines justifications to why our design will satisfy project specifications, and highlights what we learned from our structural prototype. For our structural prototype we manufactured a redesigned leg, with the lower link manufactured from PLA instead of waterjet from aluminum. In addition, we manufactured our initial test stand mount design, with the housing made from PLA instead of aluminum. Lastly, we manufactured a rough prototype of the chassis from waterjet steel and 3D printed components to verify our manufacturing plan and develop and understand for the scale of the quadruped verification prototype. Figure 7 displays our redesigned leg structural prototype.

Figure 7: Redesigned leg with 3D printed lower link instead of waterjet aluminum link.

We confirmed that our design is easily assembled, and that the tolerances of the different bearings and shafts were agreeable. We also confirmed that there is very little clearance between the upper and lower link in the knee joint, and thus must use ultra-low-profile machine screws to fasten the lower links to the knee pulley.

Figure 8 displays our initial test stand mount design. We intended to make the test stand mount from aluminum and fabricate a custom housing but could not devise a design that satisfied our requirements and was simple to manufacture. Thus, we decided to opt for a pre-purchased two-hole flange bearing. This will reduce the manufacturing processes for the test stand mount to using the waterjet to cut aluminum.

Figure 8: Initial test stand mount design with 3D printed bearing housing.

Our final structural prototype component is the chassis. We purchased cheap steel sheet metal from Home Depot to test how feasible it was to waterjet the various holes that are needed for fastening and wire routing. As seen in Figure 9, the waterjet holes are more than acceptable, and confirm that the entire chassis may be waterjet, which drastically simplifies the manufacturing processes for the chassis.

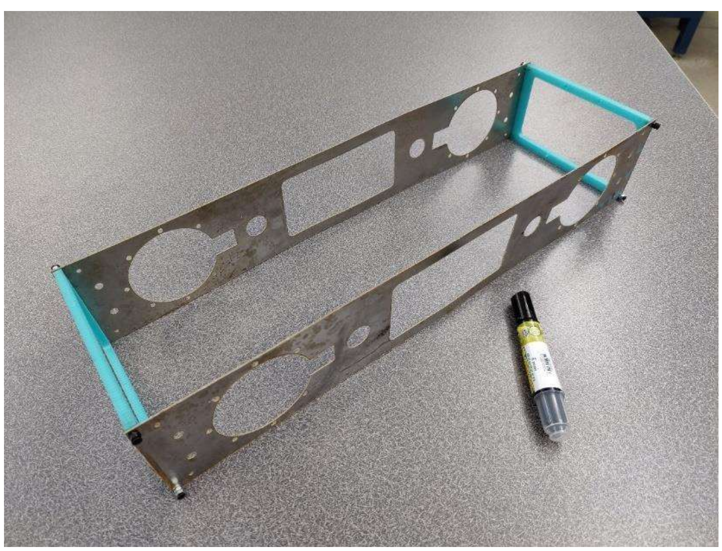


Figure 9: Body frame chassis made from waterjet aluminum and 3D printed components. M3 socket head cap screws and heat-set inserts are used instead of the L-brackets for manufacturing simplicity.

1. Vertical Leap Height – 10 cm

To assess that our robot can achieve the minimum height of 10 cm we performed a preliminary calculation based on motor voltage and current, the electrical to mechanical efficiency [9909] and the maximum mass of the robot. We also made major simplifying assumption being that the power distribution of energy pushing the foot of the ground in a hop is a half sin wave and the leg is a single rigid mass in the same configuration in our finial and initial states. Finally, we were able to determine jump time, .04 seconds from summer single leg testing. Based on this calculation we found the robot should be able to achieve a jump height of 21cm. Reference the vertical leap height hand calculations in Appendix E. This indicates that we do not need to change our design, 10kg is a safe weight to still achieve the 10cm jump. To achieve optimal jump controls, need to be developed to maximize energy pushing the robot up.

2. Fatigue and Durability – 30 minutes of operation

To ensure our robot can operate for an extended period we chose to select more durable materials than our original single leg prototype, specifically aluminum and steel. Our original prototype experienced unnecessary fatigue at the knee joint, so our redesigned knee does not use the knee shaft for torque transmission and should eliminate the surface galling seen in the original prototype. An FEA simulation was also performed half of the lower link. The stresses found were a 10^{th} of yield strength. So, with other factors such as dampening effects from the foot and motor along with the assumption that the robot will land on at least two feet at a time, gave us adequate justification to continue with the design. Reference Appendix F for an image of the lower link FEA analysis.

3. Assembly Time – 10 minutes per leg

The assembly time of the leg will be evaluated when we assemble the first functional prototype of our single leg. When assembling the structural prototype, which is nearly identical to functional prototype, we found that the assembly time totaled less than 10 minutes, which is a good indicator for the functional prototype. However, we are quite familiar with the leg design at this point. Thus, to evaluate the actual assembly time we will give the leg components and a set of instructions to someone who is less familiar with the system and ask them to assemble it.

4. Weight Management – 10 kilograms

The current mass for the single leg is ~1.25 kg. The mass of the batteries and BMS is 2.5 kg. The mass of the aluminum body chassis is 1.5 kg. This leaves 1 kg available for the internal electronics and fasteners; this is a low margin of error for the remaining electronics, and we may consider downsizing to smaller batteries if we exceed the 10kg weight requirement for the quadruped.

5. Center of Mass (COM) Position **-** <0.5 inches from center

We placed the batteries and BMS in the center of the frame because they will be the heaviest internal electronic components. Since the final internal electronics layout has yet to be confirmed, the location of smaller electronics is in-development and subject to change. However, since the weight of the other electronics is small compared to that of the battery, BMS, and body frame they should not significantly impact the overall COM location.

6. Compilation Time – 5 minutes

We chose to code our microcontroller in C++ since C++ is known for having faster computing times when compared to MATLAB/Simulink. C++ is also the industry standard for mechatronic systems and robotics, and thus we will attain applicable skills by writing the control algorithm using C++.

7. Total cost of components – <$5,000

Based on the iBOM document we are currently spending $4,458 of the $5,000 allotted to us by Dr. Xing. While we do not anticipate exceeding the $5,000 budget, we have submitted a grant proposal to CP Connect out of an abundance of caution. Our grant approval is pending.

8. Avoid Rolling During Flight – Δt between side impacts < 0.05 sec

To avoid any rolling during a jump a rotating test mount has been selected this allows fine tuning of controller parameters to create a balanced impact. The controller will also be designed to give steady inputs to each leg simultaneously. This will allow each leg to jump and land at the same time thus not allowing for the creation of a moment.

9. Leg Response Overcorrection – < 0.03 radians / Leg Response Time – < 0.1 seconds / Leg Steady State Position Error – < 0.01 radians

Having a proportional and integral control will give us control of the leg response characteristics. Like overshoot, steady state error, and response time. Plenty of testing days are required to optimize the controller.

3.2 Design Hazards (Safety, Maintenance, and Repair Considerations)

Our design has few scenarios where the quadruped user is at risk of injury. Since the quadruped will initially be operated on a test stand, the user will be at a safe distance from the robot if any unpredicted motion occurs. Additionally, since the quadruped has a relatively small footprint (~20" L x 10" W x 20" T) the user will only be at risk of injury if they place their extremities close to the quadruped while the motors are initiated. Thus, any time the user wishes to access the robot or test stand, we will ensure that the motors have been de-initiated so any sporadic quadruped movement cannot occur.

The high current levels pulled by the motors can cause a large amount of heat to be generated from constant use. Large wire gauge and short wires should be used for high current lines to prevent those lines from heating up too much (which could be a fire hazard). A short circuit could also start a fire; however, our cables will be insulated and use connectors so a short is unlikely. There is negligible risk of electrocution because the current only spikes for a brief time (a few milliseconds) and the low voltage (24V) makes electrical shocks to humans unlikely. The current spikes only happen when the robot is jumping, which means the user should be a safe distance away regardless.

Appendix G contains our Design Hazard Checklist and design hazard table that presents solutions to any potential danger to the user of our quadruped. Appendix H contains our failure modes effects and analysis.

3.3 Current Challenges, Concerns, and Unknowns

The most prominent unknown in our system design is the final internal electronics layout. We are in the process of finalizing the necessary electronics for the final prototype, and simultaneously must ensure that these electronics are packaged in such a way to centralize the body frame's center of mass. This unknown will not impede our initial testing, which will focus on communicating with the actuators via a Nucleo and CAN transceiver, and subsequently testing our single leg controller to ensure that we have properly converted it from MATLAB/Simulink to C++. We will finalize the internal electronics layout as we conduct testing of the single leg and later the quadruped with an external power supply. Since the body frame is waterjet, we may easily add additional holes to the chassis panels if a new cable harness route is developed.

Another concern is the jumping platform width. Currently a vertical leg touches 2.5 inches from the edge of the jumping platform. If the robot rolls too far in each direction and the leg extends fully there is risk of the robot leg missing the testing platform. We need to determine if 2.5 inches is enough room to avoid having the leg missing the testing platform and what we will do if that is a concern. One option is to leave the entire test stand assembly as is but water jet the polycarbonate plate so that it over hangs the test platforms frame.

4. Manufacturing Plan

Reference Appendix A for our Gantt chart which contains a detailed outline of our intended manufacturing and assembly dates.

4.1 Material Procurement

Purchasing will be done through our sponsor Dr. Siyuan Xing. Raw materials such as aluminum and steel will be purchased from B&B Steel located in Santa Maria, with a few purchases made at Home Depot. Fasteners will be purchased from Fastenal and Amazon. The pulleys will be purchased from Misumi, and their corresponding timing belts from Royal Supply. Bearings and other such small parts will be purchased from Amazon. Custom parts compatible with 80/20 will be purchased from McMaster. Electronic components will be purchased from Amazon, HobbyKing, Digikey, and AliExpress. Reference Appendix D for our iBOM and Project Budget.

4.2 Manufacturing Plan

4.2.1 Robot Leg

The robot leg can be broken apart into two main components the upper and lower links, or thigh and calf. The upper link houses the two actuators which control the hip and knee actuation, along with a timing belt, two bearings, a pulley, adapters for the pulley and hip, and corresponding fasteners. The lower link is a much simpler design containing, a modified pulley, bearing, calf links, and a spherical foot. A full list of components can be found in the iBOM found in Appendix D.

All the custom parts within the upper link are 3D printed save the pulley; however, all that needs to be modified with the pulley is the overall width of it, specifically it should be faced down to a 10 mm width. This operation will be done on a lathe. The belt tensioner shafts will be cut to size from 6 mm OD aluminum rod stock, and a 3 mm long step on either side will be turned to 4 mm OD with a lathe. Two R696 bearings will be press fit or permanently fastened to the 6mm step. The rest of the parts will be 3D printed with PLA. The hip-pulley adapters are by far the most complex part of this design to manufacture, but we already had four manufactured this summer, which is enough for a quadruped.

For the lower link, the pulley again will be modified and turned down to the appropriate length, however the inner hole will be reamed to a 7/8" ID to accommodate the R6 knee bearing as well as adding three #6-32 holes along the radius of the pulley to attach the calf link; these holes will be tapped from both sides to allow the use of right-hand screws on either side. The calf link will be made from an aluminum sheet that will be cut with a water jet and then bent accordingly. Finally, the spherical foot will be 3D printed using a dual extrusion FDM printer.

One R6 bearing will be press fit into the reamed knee pulley hole. To ensure that the bearing is centered in the knee pulley, use the 3D printed jig that mates with the pulley's inner diameter.

4.2.2 Robot Frame

The body frame of the quadruped will be nearly entirely waterjet and 3D printed, aside from the L-brackets that attach the body frame panels together. The L-brackets will be made from 1/8th inch aluminum and are cut to a 2-inch length from angle stock with an angle grinder. 0.25" clearance holes will be match-drilled based on the body frame holes with a drill press, and a scotchbrite wheel will be used for deburring. The body frame panels will be waterjet from quarter-inch thick aluminum; the top and bottom panels, which support the internal electronics, will be waterjet from 16-gauge (0.0598" thick) aluminum. The fixtures that secure the battery, BMS, capacitor, relay, and PDB to the aluminum panels will all be 3D printed. The adapters that connect the top and bottom panels to the quadruped frame will also be 3D printed and have M3 heat-set inserts pressed in with a soldering iron.

4.2.3 Test Stand Mount

The materials chosen for the test stand mount plates will be a 0.25" aluminum plate which will be repurposed body frame scraps, The 0.5-inch aluminum shaft will be bought online from metals depot. The two-bolt flanged mount will be purchased from McMaster-Carr. There are three plates in the test stand mount design, body mount, mount plate, spacer plate. All these plates will be cut with the water jet according to DXF files. Once cut check clearance holes and drill out holes that are too small. The .5" aluminum shaft will be cut with the circular saw to the length 1.4". Then a .13" chamfer will be added by a lathe. To make the body mount-shaft place the shaft (the side with the chamfer) in the .5-inch hole in the body mount. Then add a fillet weld to the shaft to the body mount plate, where the shaft and body mount meet at 90 degrees. Then add a bevel weld around the chamfered edge of the shaft.

4.2.4 Test Stand Frame

We plan on reusing components from the single leg test stand assembly and cutting them to lengths we can use. The 8020s will be purchased at custom lengths from the 80/20 online store. The test stand frames brackets, guild rails, linear sliders and jumping platform will be purchased from McMaster. To manufacture, first dismantle old single leg test stand assembly we should be left with two 11" diagonals, three 48", three 24.5", three 12", three 9" 80/20 pieces, twelve corner brackets and one T bracket. All other parts are bought at correct lengths. Then with the Circular Saw cut the extra 12" pieces into three 7.5" 80/20 pieces and three 4" 80/20 pieces. Then cut the two extra 9" pieces into a two 4-inch pieces and one 7.5" piece. Finally cut the 24.5" pieces down to three 21.5" pieces. The jumping platform will be water jet from the 30"x30"x.25" polycarbonate plate, according to the DXF file for jumping platform. The clearance holes will need to be checked and widen if too small. The last part that needs to be manufactured is the wood base, which will not be manufactured until after the test stand base is assembled. We will use the sketched outline from test stand base to cut the wood base's outer profile with the Table Saw. Then we will use the jig saw to cut out slots for the 80/20s to sit. Finally, a check if the wood base fits in the test stand frame and make additional cuts if needed.

4.3 Assembly Plan

4.3.1 Robot Leg

Once the fabrication of all parts has commenced, assembly of the leg can begin. The upper link will be assembled first with both actuators being fastened together using the 3D printed adapter. Next the pulley with pulley adapter will be attached with three 12 mm M4 FHCS and six 20 mm M4 SHCS. The upper link is constructed by placing the two belt tensioner bearings and timing belt in the belt tensioner slots of one half of the upper link. The user then carefully places the other half of the upper link to enclose the timing belt, ensuring that the belt tensioner bearings enter the belt tensioner slots on this half too. Next, the user slides the 0.75" 3/8 machine screw into the upper link knee holes and into the knee bearing inner race. Preload the knee bearing by adding a nut and washer to the machine screw. Add the remaining 35mm long M3 fasteners to the upper link and install the 20 mm M3 belt tensioner screws. Now one may attach the lower link to the knee pulley with the 0.25" #6-32 machine screws. The rubber food is permanently adhered to the lower link with epoxy.

4.3.2 Robot Frame

First one should connect the four quarter-inch thick body panels together using the L-brackets. Fasten together with ¼-20 socket cap screws. Non-permanent Loctite should be used to ensure that the body frame fasteners do not come loose during operation. The adapters that attach the top and bottom panels should then be installed; this gives the user the opportunity to ensure that the thicker body frame panels are aligned properly. Then begin fastening the various electronic components to the top and bottom panels, starting with the PDB. Follow with the batteries and BMS, and then the relays and capacitor. Once the electronics have been installed on the top or bottom panel, configure the wire harness that goes between the various electronics, but not the harness that feeds power and data transmission to the actuators. Install the four cable glands in the 0.5" diameter holes on the left and right body panels, and then fasten the panel with the electronics to the adapters between the body frame and the electronics panel. Fasten the hip and knee actuators to the body frame, with both actuators connected via the hip-knee actuator adapter. Now one may configure the CAN and power cables between the relay and actuators, and PDB and actuators, respectively. With the entire electronics harness installed, one may now fasten the remaining bottom panel to the body frame and enclose the internal electronics.

4.3.3 Test Stand Mount

Once all the test stand mount parts have been manufactured it is time to begin assembly. First fasten mount backing plate to the two-bolt flange mount with the 7/16" bolts. Then, align the ball bearing carriage with the space plate then the mount backing plate and fasten them together with 30mm M6x1 fastener. Finally, insert the shaft in the two-bolt flange and insert the set screws so that the shaft isn't rubbing against the mount backing plate.

4.3.4 Test Stand Frame

Once the 80/20s are cut we will begin assembling the base level of the test stand. Before assembling be sure to include additional slider end nuts on the 80/20s meant for future steps. Make sure to add 4 nuts on the top and 6 on the outside of the 2nd and 4th 21.5" 80/20 and 1 on the top of the outside bars for future assembly. Then we can construct the base of the test stand by attaching the five 21.5" 80/20 between two 48" 80/20s. One Corner bracket per connection (10 corner brackets) for the base. Then place both linear sliders on the second 2nd and 4th bars facing each other and locate the bar with two corner brackets one 11" diagonal and one T bracket. Do not fasten but use to locate. Only fasten the 11" diagonal to the linear slider. Using the 4", 7.5" and 29.5" 80/20s and brackets (11 corner brackets total). Assemble both sides of the Jumping Platform frame of the robot. Add three extra fasteners to each 29.5" 80/20 for fastening to the jumping platform. Then use the jumping platform frame to locate the desired location of linear sliders on the bar. Then fasten them in place. secure the 26.5" 80/20 to the top of the linear sliders with 2 corner brackets. Use the current configuration of the test stand to sketch out the desired shape of the wood base to avoid contact with vertical rails. This sketch will be used to manufacture the wood base. Once the wood base is complete add the wood base to the assembly. Add both sides of the jumping platform frame to the base. Fasten and secure frame with base with three corner brackets and four L Brackets. Make sure to add an extra fastener on the 7.5" sections for fastening to the jumping platform. Finally, attach and secure jumping platform.

4.3.5 Full System Assembly

Fasten the four hip actuators with the leg fully assembled to the chassis with seven 12 mm M4 SHCS per leg. With the quadruped fully assembled, attach the front and back body frame panels to the test stand mount. Ensure that the guide rail handbrake is set at a height such that the quadruped body frame does not "bottom out" when power is not supplied to the actuators.

5. Design Verification Plan

5.1 Evaluation Plan for Testing Design Specifications

The following section outlines how we will test and evaluate our project specifications.

1. Vertical Leap Height – 10 cm

To measure vertical leap height, we plan on measuring the height that the ball bearing carriage is displaced when the quadruped is executing a vertical hopping motion. We will need access to a 24V power supply for initial quadruped testing, in addition to a large open space for safe testing.

2. Fatigue Durability – >1000 cycles

Cycle the quadrupedal robot and single leg redesign through >1000 cycles. Evaluate and inspect if any fatigue or wear has occurred at any points of the robot. Specifically inspect the knee joint in the leg, and the brackets/fasteners on the body frame. We will need access to 24V power and a large open space.

3. Assembly Time – 10 minutes per leg

Assemble the quadruped (excluding the test stand). This includes the legs, body frame, and setting up the various cable harnesses and installing necessary electronic components. We will be assembling the leg in the mechatronics lab.

4. Weight Management – 10 kilograms

Measure the total weight of the quadrupedal robot when fully assembled. We will need access to a large scale or spring scale

5. Center of Mass Position **-** <0.5 inches from center

Examine the behavior of the quadruped during flight; does it roll to the left or right? If so, the COM is poorly located. To measure the robot's tendency to pitch, we may examine the COM of the body frame/internal electronics in SOLIDWORKS and verify the numerical values with hand calculations of the COM location.

6. Compilation Time – 5 minutes

Record the amount of time it takes for the controller to run once compilation begins.

7. Total cost of components – <$5,000

Total the cost of the components for quadruped and test stand.

8. Avoid Rolling During Flight – Δt between side impacts < 0.05 sec

Examine the quadruped's tendency roll during flight (film the flight of the robot too); if the left and right-side legs of the quadruped do not impact at the same time, then the robot has rolled. Testing will occur in the mechatronics lab; we will need access to a 24V power supply for initial testing.

9. Leg Response Overcorrection – < 0.03 radians / Leg Steady State Position Error – < 0.01 radians

Observe the steady state error of the angular position of the leg upon landing after a jump. Angular position will be inspected on a plot of angular position versus time with data collected from the motor encoders.

10. Leg Response Time – < 0.1 seconds

Observe the time required for the leg to move from fully extended (immediately after liftoff) to the desired landing angle. Angular position versus time plot will be inspected to determine these values.

We will collect numerical data for the tests that evaluate the controller's functionality. From this numerical data, we will perform uncertainty analysis that allows us to assess the validity of our data and if it accurately represents the actual motion of the quadruped. We will ask our sponsors if there is any data that has the potential to carry high uncertainty and perform subsequent analysis to determine what that uncertainty is. All testing will occur in ME 119-118 or 119-116, and the required equipment will all be held on the modular test stand we use, other than a development computer.

5.2 Planned Tests

This project is heavily dependent on testing in addition to fabricating the quadruped. We need to fine tune our code and controller to produce an optimal hopping gait. The days we have decided on testing our design specifications are listed in Table 2. See Appendix I which outlines our design verification plan and intended testing dates.

Table 2: Planned Test Dates.

Test #	Design Specification	Planned Test Date
1	Vertical leap height	3/22/2022
2	Fatigue durability	3/22/2022
3	Assembly time	3/21/2022
4	Weight management	3/21/2022
5	Center of mass location	3/21/2022
6	Compilation time	4/20/2022
7	Total cost of components	2/24/2022
8	Avoid rolling during flight	4/1/2022
9	Leg response overcorrection / steady state error	4/2/2022
10	Leg response time	4/3/2022

6. Conclusion

This document outlines our detailed design and prototype's functionality, and subsequently identifies the analysis and tests we have conducted to justify the current design. The manufacturing plan for our quadruped and test stand is outlined, in addition to assembly instructions. Procurement for necessary materials is also highlighted. A design verification plan is then presented, in the form of tests that will evaluate the specifications determined in Fall 2021. Upon our sponsors approval, the next steps include ordering the parts to manufacture a single leg prototype, beginning single leg testing with the Nucleo, and finalizing the internal electronics layout for the verification prototype.

References

[1] Seok, Sangok, et al. "Design Principles for Energy-Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot." *Design Principles for Energy-Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot*, Institute of Electrical and Electronics Engineers (IEEE), 1 June 2015, https://dspace.mit.edu/handle/1721.1/108096.

Appendices

Appendix A: Gantt Chart

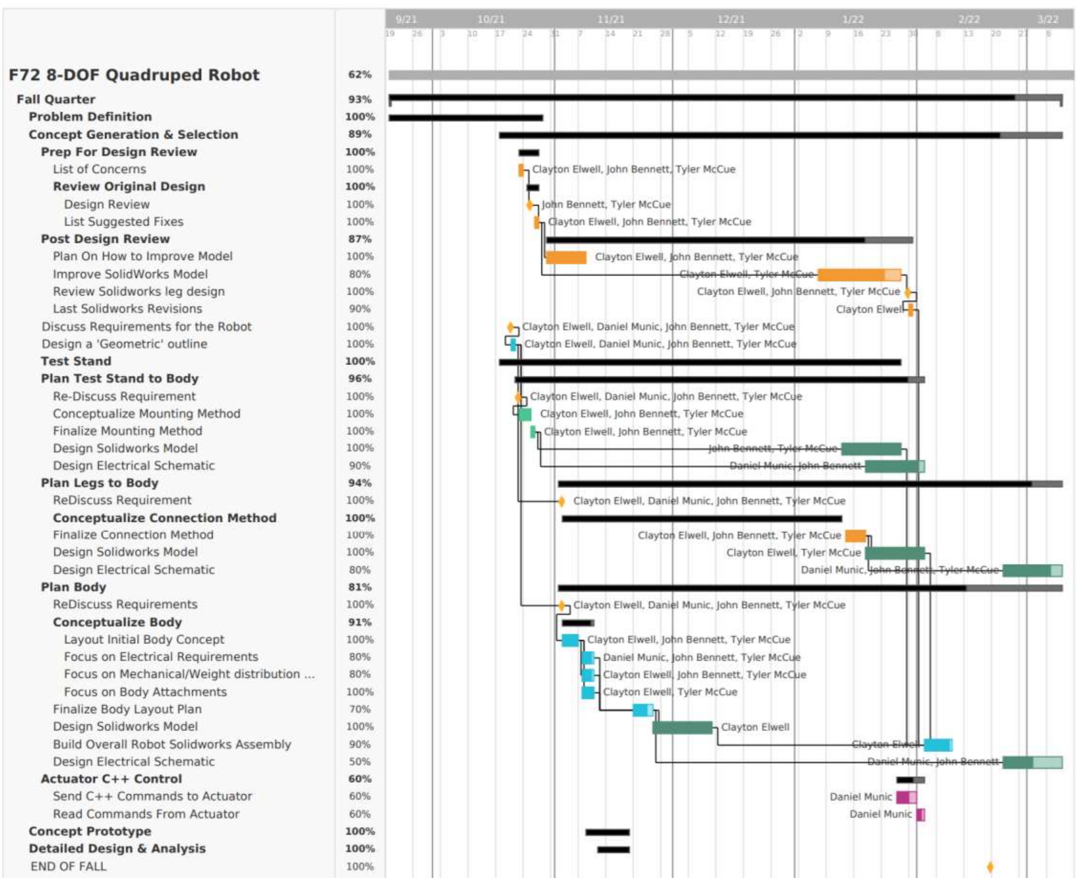


Table J.1. Fall Term Gantt Chart

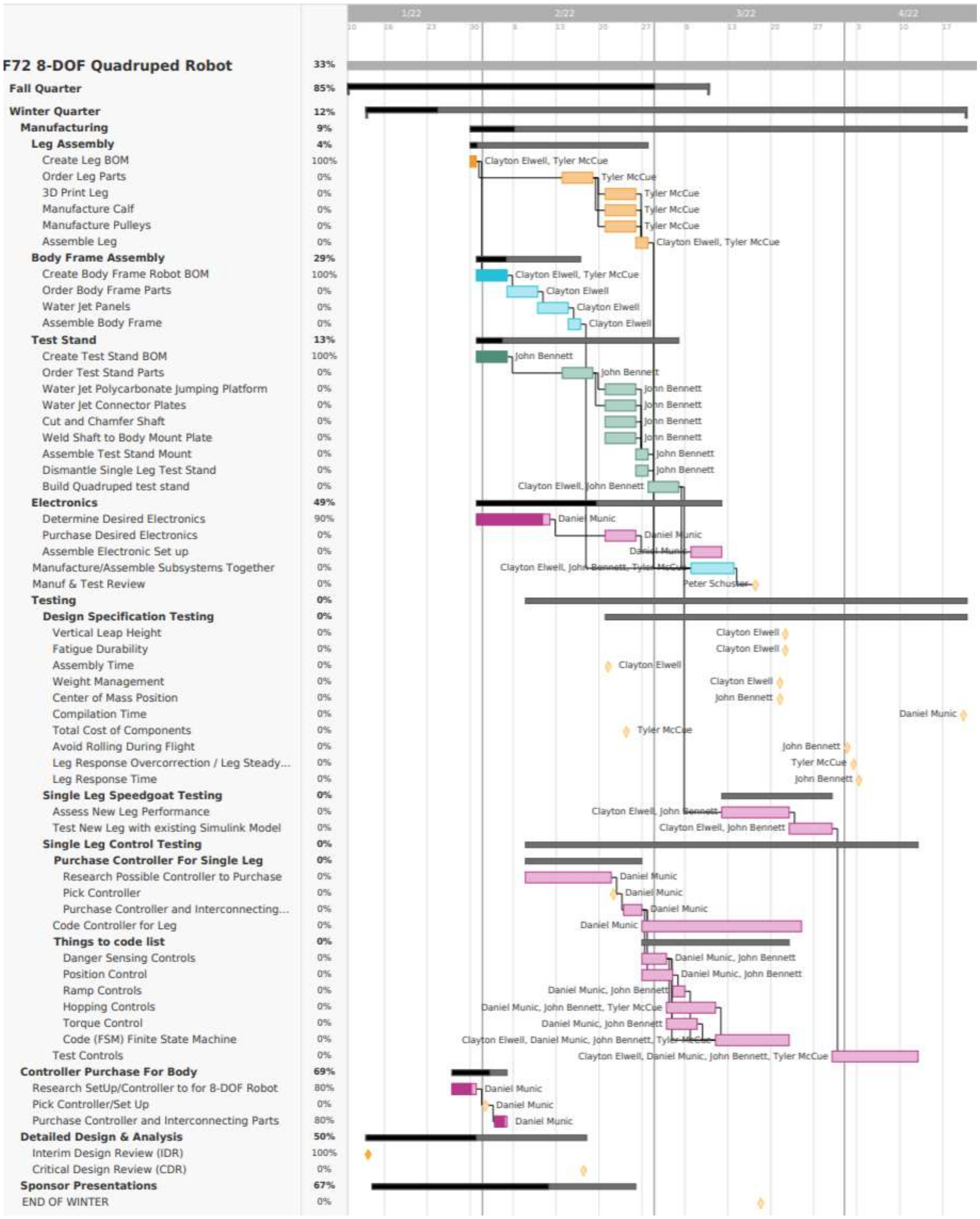
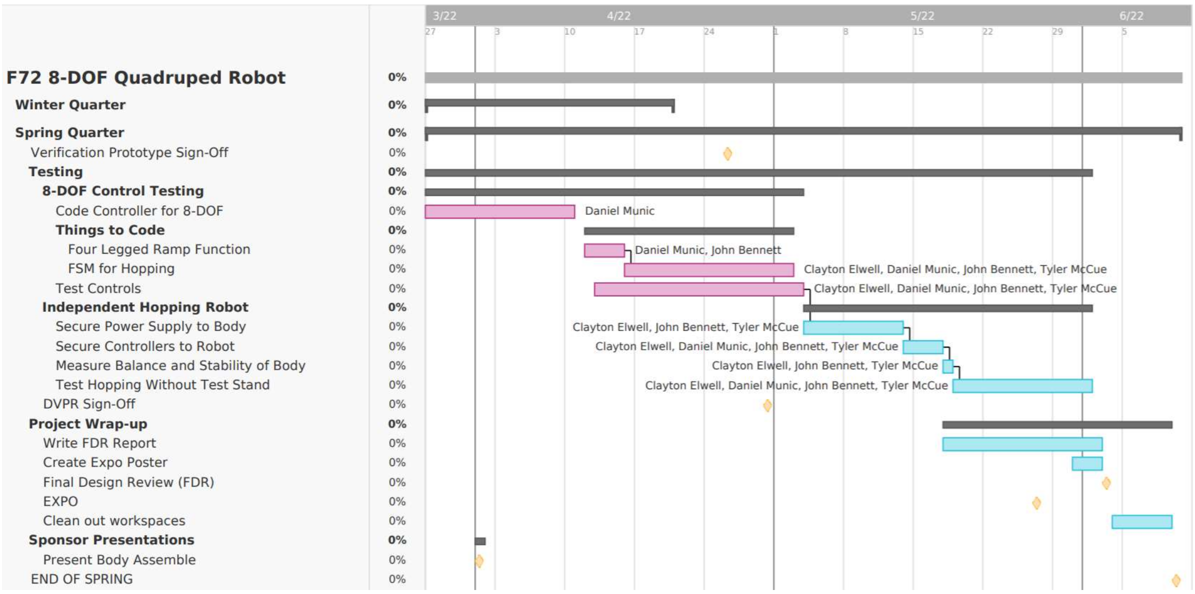


Table J.2. Winter Term Gantt Chart

Table J.3. Spring Term Gantt Chart



Appendix B: Wiring diagrams

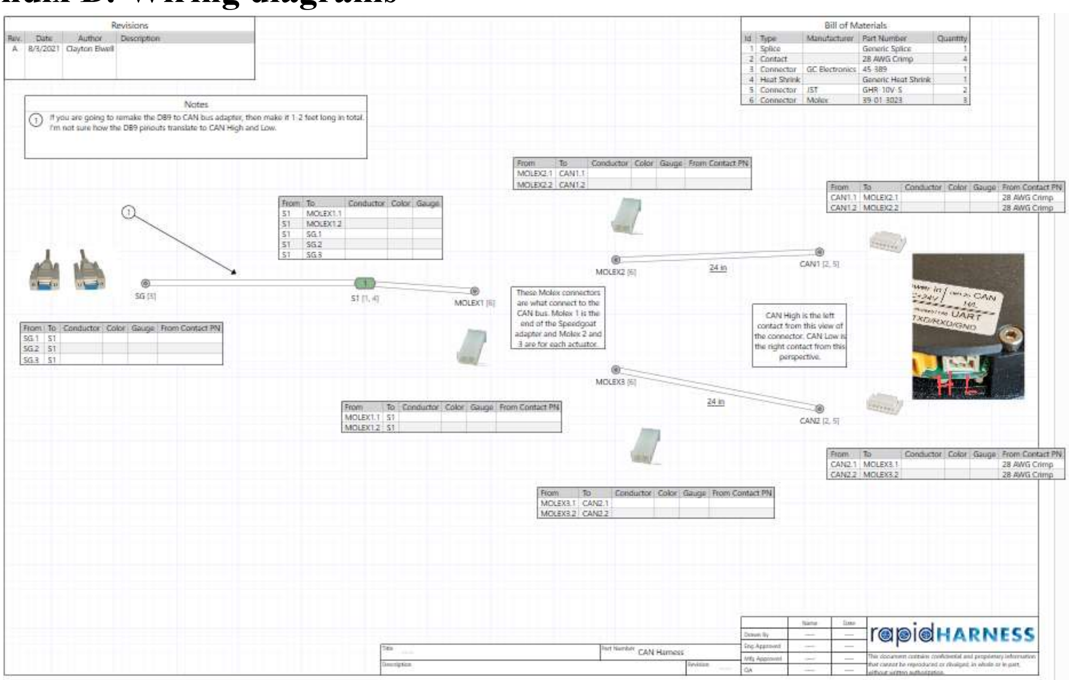


Figure B.1: Wiring diagram for two-actuator configuration.

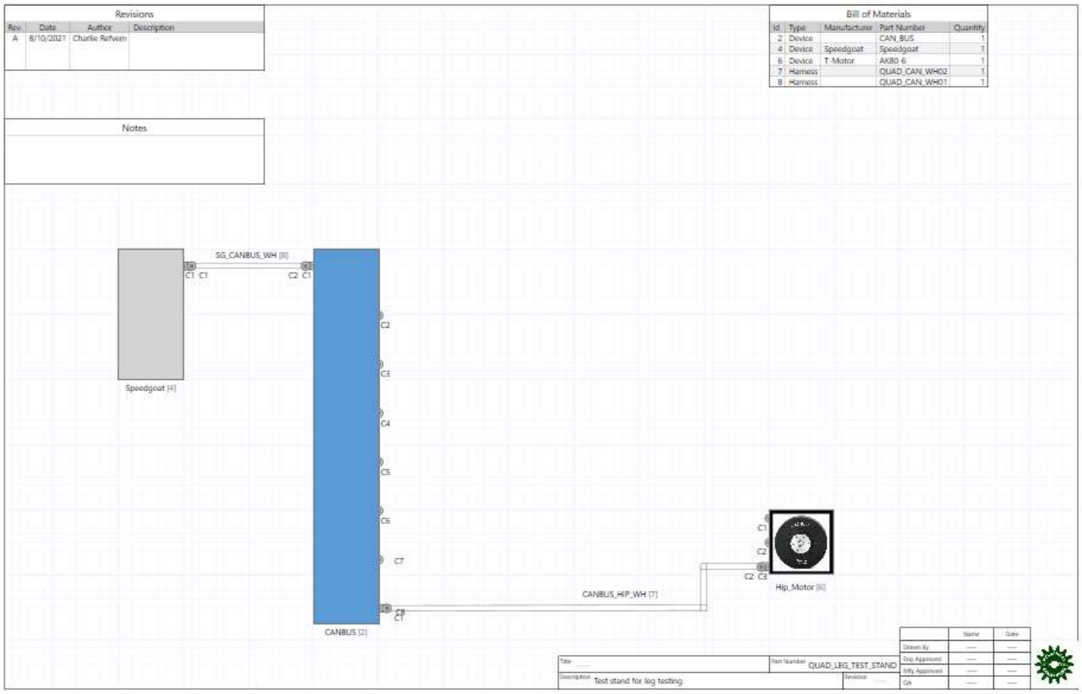


Figure B.2: Speedgoat, CAN bus, and single actuator diagram.

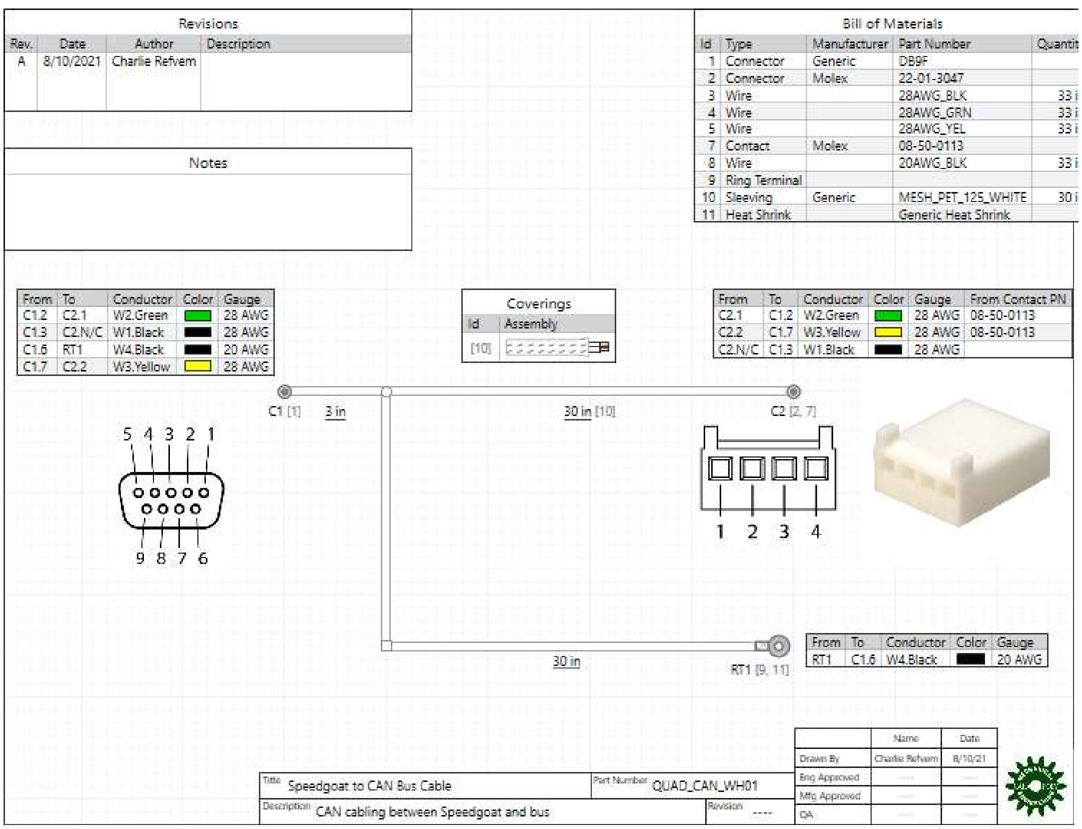


Figure B.3: Speedgoat to CAN bus harness.

Appendix C: Flowcharts and/or pseudocode

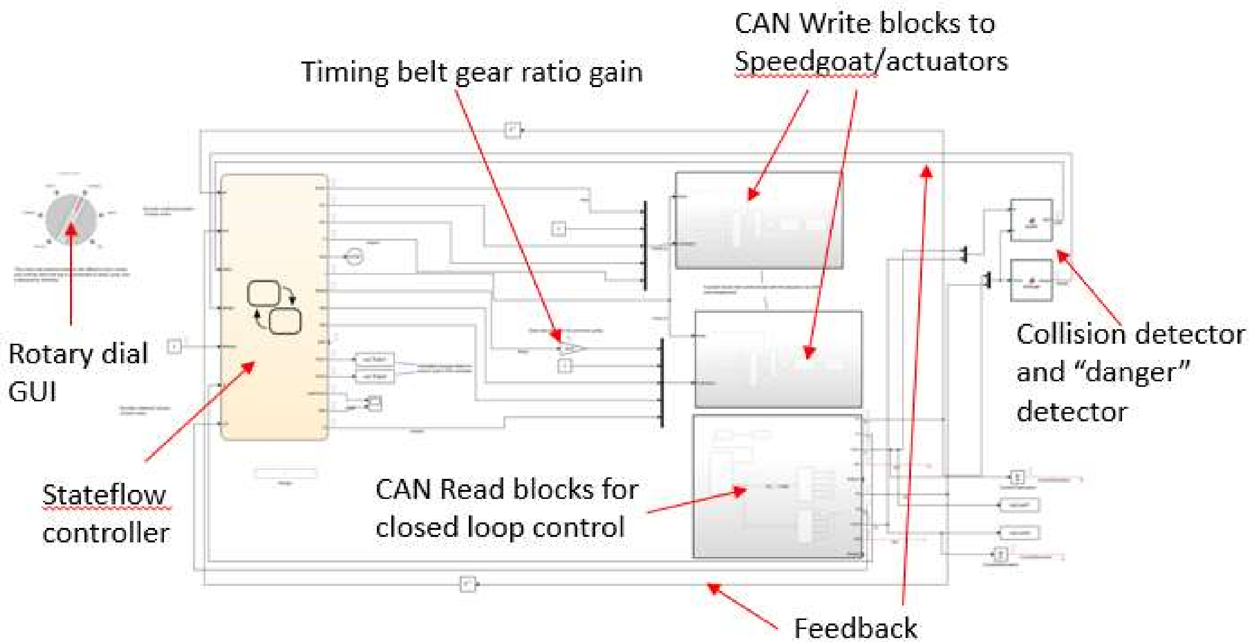


Figure C.1: MATLAB/Simulink closed-loop controller develop for single robotic leg.

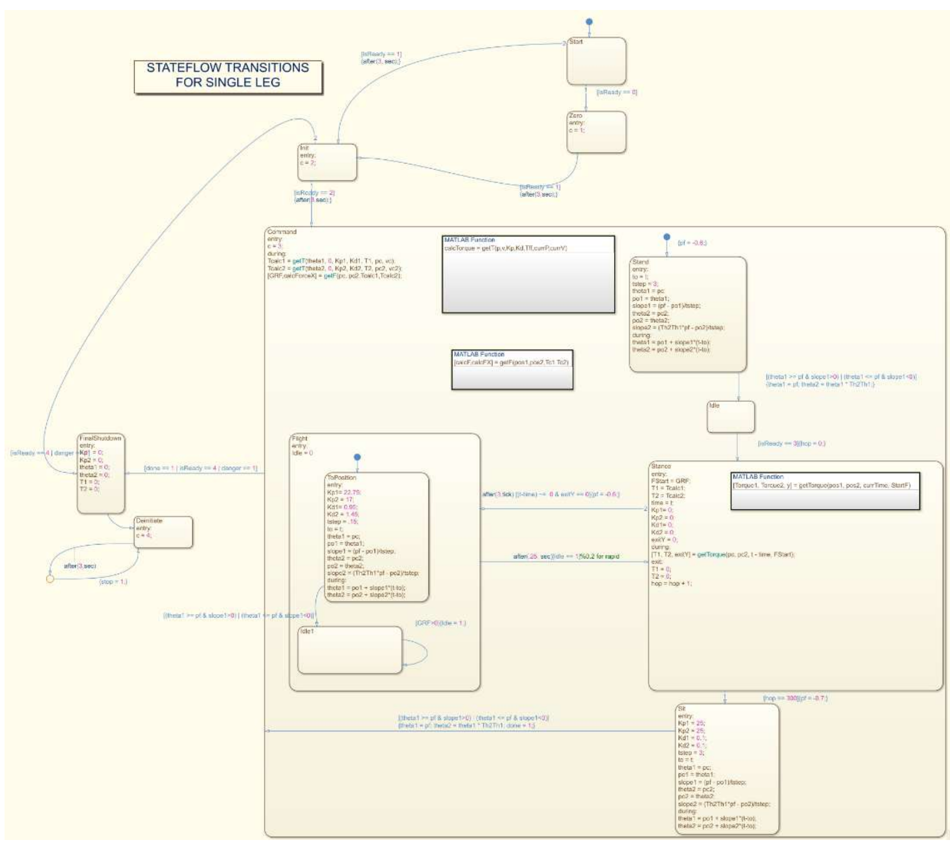


Figure C.2: Simulink Stateflow finite state machine developed during Summer 2021.

Appendix D: Project Budget/iBOM

F72 Hopping 4 Legged Robot iBOM

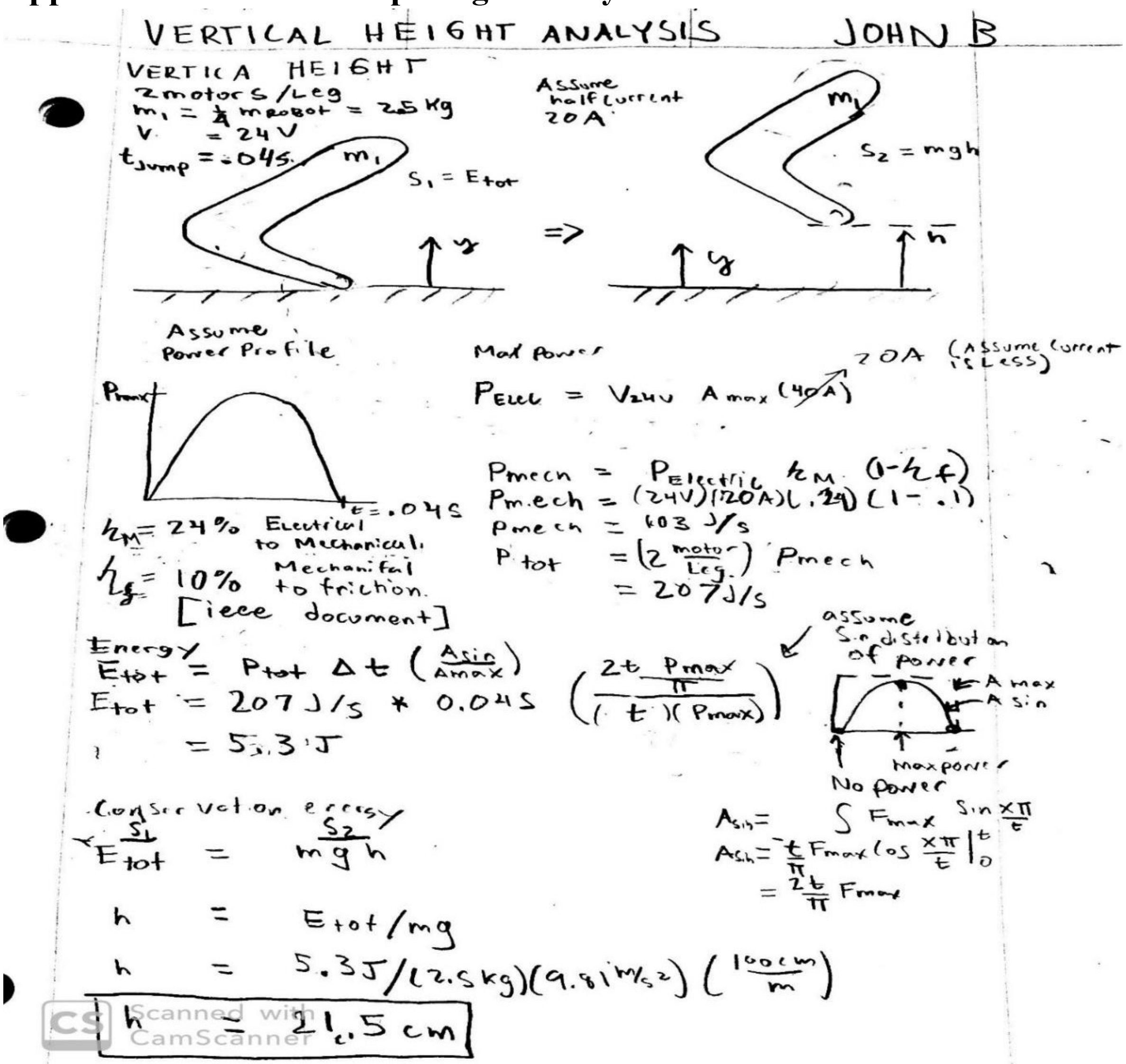
Indented Bill of Material (iBOM)

Assy Level	Part Number	Descriptive Part Name Lvl	Qty	Current Qty	Mat'l Cost	Production	Total Cost	About	Part Source	More Info
		0 1 2 3 4								
0	100000000	BRUCE							------	
1	101000000	Leg Assembly							------	
2	101010000	Upper Link					$ -		custom	mold in ABS
3	101010100	Pulleys	2	0	$ 24.00		$ 48.00	Pulleys to drive torque	Misumi	
3	101010200	Timing belt cover	4	1	$ -		$ -	PLA or polycarbonate	Custom	
3	101010300	Link Structure	4	0	$ -		$ -	Polycarbonate	custom	
3	101010400	Actuator-pulley adapter	4	4	$ -		$ -	Aluminum	Custom	
3	101010500	Hip-knee actuator adapter	4	1	$ -		$ -	Polycarbonate	Custom	
3	101010600	R6 Bearing	4	0	$ 2.50		$ 10.00	Knee bearings	Amazon	item 23-4509
3	101010700	MR696	16	10	$ 1.20		$ 7.20	Belt tensioner bearings	Amazon	https://www.amazon.com/
3	101010800	M4 35 mm SCHS	56	20	$ 0.46		$ 16.44	leg-actuator fasteners	Fastenal	https://www.fastenal.com/
3	101010900	M4 12 mm FHCS	24	6	$ 0.20		$ 3.68	hip Adapter fasteners	Fastenal	https://www.fastenal.com/
3	101011000	Pulley Belt	4	0	$ 22.00		$ 88.00	Timing belt to drive torque	Royal Supply	https://www.royalsupply.co
3	101011100	M3 30 mm dowel pins	20	6	$ 1.45		$ 6.15	Upper link alignment pins	Fastenal? Or Amazo	https://www.fastenal.com/
3	101011200	M3 SHCS 35mm	24	24	$ 0.44		$ -	fasteners	Fastenal	https://www.fastenal.com/
3	101011300	M3 SHCS 25mm	16	4	$ 0.31		$ 3.72	fasteners	Fastenal	https://www.fastenal.com/
3	101011400	M3 Washer	16	4	$ 0.05		$ 0.65	fasteners	Fastenal	https://www.fastenal.com/
3	101011500	M3 Nuts	24	24	$ 0.10		$ -	fasteners	Fastenal	https://www.fastenal.com/
2	101020000	Lower Link					$ -		custom	vac-formed PET
3	101020100	Foot	4	0	$ -		$ -	rubber foot	Custom	
3	101020200	Calf					$ -		Custom	
4	101020201	Calf Plate	8	0	$ 4.38		$ 35.00	Lower link aluminum plates	BB Steel	
3	101020300	R6 Bearing	4	0	$ 2.50		$ 10.00	Knee bearings		item 23-4509
3	101020400	Pulleys	2	0	$ 24.00		$ 48.00	Pulley to receive torque	Misumi	item 48123
3	101020500	#6-32 Ultra low profile macl	24	0	$ -		$10	Knee fasteners	McMaster	
1	102000000	Body Frame Assembly								
2	102010000	Body Frame Structure							McMaster	item 48250
3	102010100	Side frame	2	0	$ -	$ -	$ -	Body frame chassis	B&B Metals/Custom	
3	102010200	Front/back frame	2	0	$ -	$ -	$ -		B&B Metals/Custom	
3	102010300	L-brackets	4	0	$ -	$ -	$ -	Chassis connectors	Home Depot/Custor	https://www.homedepot.co
3	102010400	3D Printed Panel Mounts	4	0	$ 1.00	$ -	$ 4.00	Top/bottom panel adapters	Custom	
3	102010500	M3 Heat set inser	12	0	$ 0.25	$ -	$ 3.00	Heat set inserts for aobve	Amazon	https://www.amazon.com/i
3	102010600	Top/Bottom Pan	2	0	$ -	$ -	$ -	Electronics panel	B&B Metals/Custom	
3	102010700	¼-20 Steel nut	16	0	$ 0.06	$ -	$ 1.00	L-bracket fastener	Fastenal	https://www.fastenal.com/
3	102010800	1/4-20 0.75" Cap S	16	0	$ 0.40	$ -	$ 6.37	L-bracket fastener	Fastenal	https://www.fastenal.com/
3	102010900	¼-20 Steel washer	32	0	$ 0.08	$ -	$ 2.53	L-bracket fastener	Fastenal	https://www.fastenal.com/
3	102011000	M3 16 mm SHCS	8	0	$ 0.10	$ -	$ 0.80	Adapter fastener side	Fastenal	https://www.fastenal.com/
3	102011100	M3 7 mm SHCS	4	0	$ 0.15	$ -	$ 0.60	Adapter fastener top	Fastenal	https://www.fastenal.com/
2	102020000	Body Frame Layout							custom	mold in ABS
3	102020100	Battery	2	0	$ 125.00		$ 250.00	Deployment battery/bms	HobbyKing	https://hobbyking.com/en_
3	102020200	STM32	1	0	$ 1.30		$ 1.30	Deployment computer	AliExpress	https://www.aliexpress.com
3	102020300	Power Distribution Board	1	0	$ -	$ 5.00	$ 5.00	step 24v down to 3.3 v	Bay Area Circuits or i	TBD
3	102020400	Actuators	8	2	$ 400.00		$ 2,400.00	Make robot go brrr	AliExpress	https://www.aliexpress.com
3	102020500	Zip ties	20	20	$ -		$ -	Cable management	Dr. Siyuan Xing	https://www.amazon.com/
3	102020600	Capacitor	1	1	$ -		$ -	Prevent brownout	Charlie Refvem	
3	102020700	Adhesive zip-tie mounts	26	0	$ 0.19		$ 5.06	For mounting zip ties	Digikey	https://www.digikey.com/e
3	102020800	GWN1.00BK25	1	0	$ 53.33		$ 53.33	Nylon cable wrap	Digikey	https://www.digikey.com/e
3	102020900	T3609160101-000	1	0	$ 12.19		$ 12.19	cable glands	Amazon	https://www.amazon.com/
3	102021000	28 AWG Wire [feet]	4	0	$ -		$ -	For CAN transmission	Digikey	https://www.amazon.com/
3	102021100	14 AWG Wire [feet]	8	4	$ -		$ -	For power transmissoin	Digikey	https://www.amazon.com/
3	102021200	Relays	1	2	$ -		$ -	Regulate power transmissoi	Charlie Refvem	TBD
3	102021300	Fuses	8	0	$ -		$ -	Ensure actuators aren't fried	Digikey	Size TBD
3	102021400	Inline fuse holders	8	0	$ 3.00		$ 24.00	For securing fuses to chassi	Digikey	Size TBD
1	103000000	Test Stand Assembly								
2	103010000	Test Stand Frame								
3	103010100	80x20 Frame								
4	103010101	11" diagnal	2	2	$ -	$ -	$ -	Various 80/20 struts	------	
4	103010102	48	4	3	$ 34.56	$ -	$ 34.56	Various 80/20 struts	8020.net	https://8020.net/1515.html
4	103010103	21.5	5	3	$ 15.48	$ -	$ 30.96	Various 80/20 struts	8020.net	https://8020.net/1515.html
4	103010104	29.5	2	0	$ 21.24	$ -	$ 42.48	Various 80/20 struts	8020.net	https://8020.net/1515.html
4	103010105	7.5	4	4	$ 5.40	$ -	$ -	Various 80/20 struts	8020.net	https://8020.net/1515.html
4	103010106	4	5	5	$ 2.88	$ -	$ -	Various 80/20 struts	8020.net	https://8020.net/1515.html
4	103010107	26.5	1	0	$ 19.08	$ -	$ 19.08	Various 80/20 struts		https://8020.net/1515.html
3	103010200	Corner Bracket	34	12	$ 5.69	$ -	$ 125.18	Various test stand structural	8020.net	4301
3	103010300	T Frame Bracket	2	1	$ 12.32	$ -	$ 12.32	Various test stand structural	McMaster	T-Slotted Framing, Silver T
3	103010400	L Frame Bracket	4	0	$ 11.80	$ -	$ 47.20	Various test stand structural	McMaster	https://www.mcmaster.com
3	103010500	M6-1.0 x 18mm	156	54	$ 0.26	$ -	$ 26.01	What are these for? We used	Fastenal	https://www.fastenal.com/
3	103010600	End-Feed Single Nut, M6 T	156	54	$ -	$ -	$ -	T-nuts for test stand		
2	103020000	20mm Guide Rail for Ball Bearing Ca	2	1	$ 400.00	$ -	$ 400.00	Guide rail for ball bearing carr	McMaster	20mm Wide Guide Rail for
2	103030000	wood base	1	0	$ -	$ -	$ -	Base for electronics to sit or	Lumber Scraps/Hayw	24x26"
2	103040000	Castor Wheels	4	4	$ 35.99	$ -	$ -	Allows movement of test sta	Sponsor	https://www.amazon.com/
2	103050000	Jumping Platform	1	0	$ 90.00	$ -	$ 90.00		McMaster	polycarbonate sheets I Mc
2	103060000	Speedgoat	1	1	$ -	$ -	$ -	Convets MATLAB to C++	Dr. Siyuan Xing	
2	103070000	24V/20A Power Supply	1	1	$ -	$ -	$ -	External power supply	Charlie Refvem	
2	103080000	Capacitor	1	1	$ -	$ -	$ -	Keeps current supply steady	Charlie Refvem	
2	103090000	E-Stop	1	1	$ -	$ -	$ -	Manual power cutoff	Charlie Refvem	
2	104110000	12 AWG?	12	6			$ -	Power transmission cables	Charlie Refvem/Digikey	
1	104000000	Test Stand Mount Assembly								
2	104010000	Body Mount-Shaft	2	0	$ -	$ 5.00	$ 10.00	Need weld to assemble		
3	104010100	Body Mount	2	0	$ -	$ -	$ -	Bolts in to Body End Frames	scrap metal from Body frame	
3	104010200	Shaft	2	0	$ 2.51	$ -	$ 5.02	Shaft for test stand mount	MetalsDepot	https://www.metalsdepot.c
2	104020000	Two-Bolt Flange Mount	2	0	$ 36.55	$ -	$ 73.10	Ball bearing that axially const	McMaster	Low-Profile Mounted Seal
2	104030000	Mount Backing Plate	2	0	$ -	$ -	$ -	Protects ball bearing carriage	scrap metal from Body frame	
2	104040000	Spacer Plate	2	0	$ -	$ -	$ -	Adds extra room for fastene	scrap metal from Body frame	
2	104050000	Ball Bearing Carriage	2	1	$ 140.00	$ -	$ 140.00	Slides on guide rail / guides m	McMaster	Ball Bearing Carriage, Flan
2	104060000	30mm M6x1 Fastener	8	0	$ 0.34	$ -	$ 2.69	Connects TSM to ball bearin	Fastenal	11103346
2	104070000	7/16" 3/4in Bolt	4	0	$ 2.50	$ -	$ 10.00	Connects the ball bearing mo	Fastenal	0154547
2	104080000	Hand Brake for Ball Bearing Carriag	2	1	$ 154.35	$ -	$ 154.35	Supports ball bearing carriag	McMaster	Hand Brake for Ball Bearin
2	104090000	7/16" Hex Nut	4	0	$ 0.47	$ -	$ 1.86	fasteners	Fastenal	36498
2	104100000	M6x1 Hex Nut	8	0	$ 0.06	$ -	$ 0.50	fasteners	Fastenal	40154
	Total Parts		**895**	**288**			**$ 4,281.34**			

F72 Hopping 4 Legged Robot Project Budget

Assy Level	Design Part Number	Descriptive Part Name Lvl (0 1 2 3 4)	Qty	Current Qty	Mat'l Cost	Production	Total Cost	About	Part Source/Vend	Date purchased	Procurement	More Info / Vendor Part Number
0	100000000	BRUCE							------			
1	101000000	Leg Assembly							------			
2	101010000	Upper Link					$ -		custom		Sponsor	mold in ABS
3	101010100	Pulleys	2	0	$ 24.00		$ 48.00	Pulleys to drive torque	Misumi		Sponsor	
3	101010200	Timing belt cover	4	1	$ -		$ -	PLA or polycarbonate	Custom		Sponsor	
3	101010300	Link Structure	4	0	$ -		$ -	Polycarbonate	custom		Sponsor	
3	101010400	Actuator-pulley adapter	4	4	$ -		$ -	Aluminum	Custom		Previously manufactured	
3	101010500	Hip-knee actuator adapter	4	1	$ -		$ -	Polycarbonate	Custom		Sponsor	
3	101010600	R6 Bearing	4	0	$ 2.50		$ 10.00	Knee bearings	Amazon		Sponsor	item 23-4509
3	101010700	MR696	16	10	$ 1.20		$ 7.20	Belt tensioner bearings	Amazon		Sponsor	https://www.amazon.com/uxcell-Groov
3	101010800	M4 35 mm SCHS	56	20	$ 0.46		$ 16.44	leg-actuator fasteners	Fastenal		Team reimbursemen	https://www.fastenal.com/product/detai
3	101010900	M4 12 mm FHCS	24	6	$ 0.20		$ 3.68	hip Adapter fasteners	Fastenal		Team reimbursemen	https://www.fastenal.com/product/detai
3	101011000	Pulley Belt	4	0	$ 22.00		$ 88.00	Timing belt to drive torque	Royal Supply		Sponsor	https://www.royalsupply.com/store/pc/
3	101011100	M3 30 mm dowel pins	20	6	$ 1.45		$ 20.30	Upper link alignment pins	Fastenal? Or Amazon		Sponsor	https://www.fastenal.com/product/Fast
3	101011200	M3 SHCS 35mm	24	24	$ 0.44		$ -	fasteners	Fastenal		Team reimbursemen	https://www.fastenal.com/product/detai
3	101011300	M3 SHCS 25mm	16	4	$ 0.31		$ 3.72	fasteners	Fastenal		Team reimbursemen	https://www.fastenal.com/product/detai
3	101011400	M3 Washers	16	4	$ 0.05		$ 0.65	fasteners	Fastenal		Team reimbursemen	https://www.fastenal.com/product/detai
3	101011500	M3 Nuts	24	24	$ 0.10		$ -	fasteners	Fastenal		Team reimbursemen	https://www.fastenal.com/product/detai
2	101020000	Lower Link					$ -		custom		Sponsor	https://www.fastenal.com/product/detai
3	101020100	Foot	4	0	$ -		$ -	rubber foot	Custom		Sponsor	vac-formed PET
3	101020200	Calf					$ -		Custom		Sponsor	
4	101020201	Calf Plate	8	0	$ 4.38		$ 35.00	Lower link aluminum plates	BB Steel		Sponsor	
3	101020300	R6 Bearing	4	0	$ 2.50		$ 10.00	Knee bearings		item 23-4509	Sponsor	
3	101020400	Pulleys	2	0	$ 24.00		$ 48.00	Pulley to receive torque	Misumi	item 48123	Sponsor	item 48123
3	101020500	#6-32 Ultra low profile macl	24	0	$ -		$10	Knee fasteners	McMaster			
1	102000000	Body Frame Assembly									Sponsor	
2	102010000	Body Frame Structure							McMaster		Sponsor	item 48250
3	102010100	Side frame	2	0	$ -		$ -	Body frame chassis	B&B Metals/Custom		Sponsor	
3	102010200	Front/back frame	2	0	$ -		$ -		B&B Metals/Custom		Team reimbursement	
3	102010300	L-brackets	4	0	$ -		$ -	Chassis connectors	Home Depot/Custom		Sponsor	https://www.homedepot.com/p/Everbilt
3	102010400	3D Printed Panel Mounts	4	0	$ 1.00		$ 4.00	Top/bottom panel adapters	Custom		Team reimbursement	
3	102010500	M3 Heat set inser	12	0	$ 0.25		$ 3.00	Heat set inserts for aobve	Amazon		Team reimbursemen	https://www.amazon.com/initeq-M3-0-5
3	102010600	Top/Bottom Pan	2	0	$ -		$ -	Electronics panel	B&B Metals/Custom		Team reimbursement	
3	102010700	¼-20 Steel nut	16	0	$ 0.06		$ 1.00	L-bracket fastener	Fastenal		Team reimbursemen	https://www.fastenal.com/product/detai
3	102010800	1/4-20 0.75" Cap S	16	0	$ 0.40		$ 6.37	L-bracket fastener	Fastenal		Sponsor	https://www.fastenal.com/product/detai
3	102010900	¼-20 Steel washer	32	0	$ 0.08		$ 2.53	L-bracket fastener	Fastenal			https://www.fastenal.com/product/detai
3	102011000	M3 16 mm SHCS	8	0	$ 0.10		$ 0.80	Adapter fastener side	Fastenal			https://www.fastenal.com/product/detai
3	102011100	M3 7 mm SHCS	4	0	$ 0.15		$ 0.60	Adapter fastener top	Fastenal			https://www.fastenal.com/product/detai
2	102020000	Body Frame Layout							custom		Sponsor	mold in ABS
3	102020100	Battery	2	0	$ 125.00		$ 250.00	Deployment battery/bms	HobbyKing		Sponsor	https://hobbyking.com/en_us/zippy-cor
3	102020200	STM32	1	0	$ 1.30		$ 1.30	Deployment computer	AliExpress		Sponsor	https://www.aliexpress.com/item/40010
3	102020300	Power Distribution Board	1	0	$ -	$ 5.00	$ 5.00	step 24v down to 3.3 v	Bay Area Circuits or intl mnfc		Sponsor	TBD
3	102020400	Actuators	8	2	$ 400.00		$ 2,400.00	Make robot go brrr	AliExpress	1/25/22; ME 119-	Sponsor	https://www.aliexpress.com/item/10050
3	102020500	Zip ties	20	20	$ -		$ -	Cable management	Dr. Siyuan Xing	ME 119-117	Sponsor	https://www.amazon.com/dp/B086XGX
3	102020600	Capacitor	1	1	$ -		$ -	Prevent brownout	Charlie Refvem	ME 119-117	Sponsor	
3	102020700	Adhesive zip-tie mounts	26	0	$ 0.19		$ 5.06	For mounting zip ties	Digikey		Sponsor	https://www.digikey.com/en/products/fi
3	102020800	GWN1.00BK25	1	0	$ 53.33		$ 53.33	Nylon cable wrap	Digikey		Sponsor	https://www.digikey.com/en/products/d
3	102020900	T3609160101-000	1	0	$ 12.19		$ 12.19	cable glands	Amazon		Sponsor	https://www.amazon.com/Plastic-Conn
3	102021000	28 AWG Wire [feet]	4	0	$ -		$ -	For CAN transmission	Digikey		Sponsor	https://www.amazon.com/BNTECHGO
3	102021100	14 AWG Wire [feet]	8	4	$ -		$ -	For power transmissoin	Digikey		Sponsor	https://www.amazon.com/BNTECHGO
3	102021200	Relays	1	2	$ -		$ -	Regulate power transmissoin	Charlie Refvem		Sponsor	TBD
3	102021300	Fuses	8	0	$ -		$ -	Ensure actuators aren't fried by power	Digikey		Sponsor	Size TBD
3	102021400	Inline fuse holders	8	0	$ 3.00		$ 24.00	For securing fuses to chassis; TBD	Digikey		Sponsor	Size TBD
1	103000000	Test Stand Assembly										
2	103010000	Test Stand Frame										
3	103010100	80x20 Frame										
4	103010101	11" diagnal	2	2	$ -		$ -	Various 80/20 struts	------		Sponsor	
4	103010102	48	4	3	$ 34.56		$ 34.56	Various 80/20 struts	8020.net		Sponsor	https://8020.net/1515.html
4	103010103	21.5	5	3	$ 15.48		$ 30.96	Various 80/20 struts	8020.net		Sponsor	https://8020.net/1515.html
4	103010104	29.5	2	0	$ 21.24		$ 42.48	Various 80/20 struts	8020.net		Sponsor	https://8020.net/1515.html
4	103010105	7.5	4	4	$ 5.40		$ -	Various 80/20 struts	8020.net		Sponsor	https://8020.net/1515.html
4	103010106	4	5	5	$ 2.88		$ -	Various 80/20 struts	8020.net		Sponsor	https://8020.net/1515.html
4	103010107	26.5	1	0	$ 19.08		$ 19.08	Various 80/20 struts			Sponsor	https://8020.net/1515.html
3	103010200	Corner Bracket	34	12	$ 5.69		$ 125.18	Various test stand structural brackets	8020.net		Sponsor	4301
3	103010300	T Frame Bracket	2	1	$ 12.32		$ 12.32	Various test stand structural brackets	McMaster		Sponsor	T-Slotted Framing, Silver Tee Surface E
3	103010400	L Frame Bracket	4	0	$ 11.80		$ 47.20	Various test stand structural brackets	McMaster		Sponsor	https://www.mcmaster.com/80%2F20-b
3	103010500	M6-1.0 x 18mm	156	54	$ 0.26		$ 26.52	What are these for? We used 3/8 faste	Fastenal		Sponsor	https://www.fastenal.com/product/detai
3	103010600	End-Feed Single Nut, M6 T	156	54	$ -		$ -	T-nuts for test stand			Sponsor	
2	103020000	20mm Guide Rail for Ball Bearing Ca	2	1	$ 400.00		$ 400.00	Guide rail for ball bearing carriage	McMaster		Sponsor	20mm Wide Guide Rail for Quiet-Ride B
2	103030000	wood base	1	0	$ -		$ -	Base for electronics to sit on?	Lumber Scraps/Hayward Lumbe		Sponsor	24x26"
2	103040000	Castor Wheels	4	4	$ 35.99		$ -	Allows movement of test stand	Sponsor	ME 1119-117	Sponsor	https://www.amazon.com/Skelang-Leve
2	103050000	Jumping Platform	1	0	$ 90.00		$ 90.00		McMaster		Sponsor	polycarbonate sheets | McMaster-Carr
2	103060000	Speedgoat	1	1	$ -		$ -	Convets MATLAB to C++	Dr. Siyuan Xing	ME 1119-117	Sponsor	
2	103070000	24V/20A Power Supply	1	1	$ -		$ -	External power supply	Charlie Refvem	ME 1119-117	Sponsor	
2	103080000	Capacitor	1	1	$ -		$ -	Keeps current supply steady	Charlie Refvem	ME 1119-117	Sponsor	
2	103090000	E-Stop	1	1	$ -		$ -	Manual power cutoff	Charlie Refvem	ME 1119-117	Sponsor	
2	103100000	12 AWG?	12	6			$ -	Power transmission cables	Charlie Refvem	ME 1119-117	Sponsor	
1	104000000	Test Stand Mount Assembly									Sponsor	
2	104010000	Body Mount-Shaft	2	0	$ -	$ 5.00	$ 10.00	Need weld to assemble			Sponsor	
3	104010100	Body Mount	2	0	$ -		$ -	Bolts in to Body End Frames	scrap metal from Body frame		Sponsor	
3	104010200	Shaft	2	0	$ 2.51		$ 5.02	Shaft for test stand mount	MetalsDepot		Team reimbursemen	https://www.metalsdepot.com/aluminun
2	104020000	Two-Bolt Flange Mount	2	0	$ 36.55		$ 73.10	Ball bearing that axially constrains sha	McMaster		Sponsor	Low-Profile Mounted Sealed Steel Ball
2	104030000	Mount Backing Plate	2	0	$ -		$ -	Protects ball bearing carriage; may not	scrap metal from Body frame		Sponsor	
2	104040000	Spacer Plate	2	0	$ -		$ -	Adds extra room for fastener head	scrap metal from Body frame		Sponsor	
2	104050000	Ball Bearing Carriage	2	1	$ 140.00		$ 140.00	Slides on guide rail / guides motion	McMaster		Sponsor	Ball Bearing Carriage, Flanged, for 20 m
2	104060000	30mm M6x1 Fastener	8	0	$ 0.34		$ 2.69	Connects TSM to ball bearing carriage	Fastenal		Team reimbursemen	11103346
2	104070000	7/16" 3/4in Bolt	4	0	$ 2.50		$ 10.00	Connects the ball bearing mount to M	Fastenal		Team reimbursemen	0154547
2	104080000	Hand Brake for Ball Bearing Carriag	2	1	$ 154.35		$ 154.35	Supports ball bearing carriage on slide	McMaster		Sponsor	Hand Brake for Ball Bearing Carriage, f
2	104090000	7/16" Hex Nut	4	0	$ 0.47		$ 1.86	fasteners	Fastenal		Team reimbursemen	36498
2	104100000	M6x1 Hex Nut	8	0	$ 0.06		$ 0.50	fasteners	Fastenal		Team reimbursemen	40154
		Parts Not In Final Design:	**Need**	**Current**	**Matl. Co:**	**Prod.**	**Total Cost**	**Item Description**	**Part Source/**	**Date purcha:**	**Procurement**	**More Info / Vendor Part Number**
		24"x6" 22 gauge steel panels	2	0	$ 10.00		$ 20.00	For structural prototype	Home Depot	2/5/2022; ME 11	Team reimbursemen	Store SKU #333763
		36" Aluminum rod 0.5" OD	1	0	$ 8.92		$ 8.92	For structural prototype	Home Depot	2/5/2022; ME 11	Team reimbursemen	Store SKU #476935
		R6 ball bearings	1	0	$ 10.00		$ 10.00	For structural prototype	Amazon	2/5/2022; ME 11	Sponsor	ASIN : [illegible]
		R8 ball bearings	1	0	$ 10.00		$ 10.00	For structural prototype	Amazon	2/5/2022; ME 11	Sponsor	ASIN : [illegible]
		0.5" ID steel shaft collar	1	0	$ 13.99		$ 13.99	For structural prototype	Amazon	2/5/2022; ME 11	Sponsor	ASIN : [illegible]
		3/8 SHCS 1-1/4 Length	4	0	$ 0.88		$ 3.50	For structural prototype	Fastenal	2/5/2022; ME 11	Team reimbursemen	1123307
		5/16 Jam nut	4	0	$ 0.88		$ 3.50	For structural prototype	Fastenal	2/5/2022; ME 11	Team reimbursemen	1136304
		3/8 flange washer	4	0	$ 0.88		$ 3.50	For structural prototype	Fastenal	2/5/2022; ME 11	Team reimbursemen	1133008
		Raw Materials			**subtotal**		$ 73.41					
		NinjaTek NinjaFlex Midnight Black TPU Filament - 1.75mm (0.5kg)			$45.00		$ 45.00					https://www.matterhackers.com/store/
		Raise3D Polycarbonate filament - 1.75 mm (1kg)	1	1	$49.99		$ -					https://profound3d.com/products/raise
		Black MH Build Series PLA Filament - 1.75kg (1kg)	1	0	$18.99		$ 18.99					https://www.matterhackers.com/store/
		0.25 Aluminum Sheet stock 24" x 24"	1	0	$135.99		$ 135.99					B&B Metal
		1/8th inch thick aluminum angle stock 36"	1	0	$8.42		$ 8.42					https://www.homedepot.com/p/Everbilt-
		0.5" OD aluminum round stock 36"	1	0	$11.88		$ 11.88					https://www.metalsdepot.com/aluminun
					subtotal		$ 220.28					
	Total Parts		**895**	**288**			**$ 4,541.69**					

Appendix E: Vertical Leap Height Analysis



Electrical to mechanical efficiency, η = 24% and frictional efficiency, η = 10% were found in MIT document

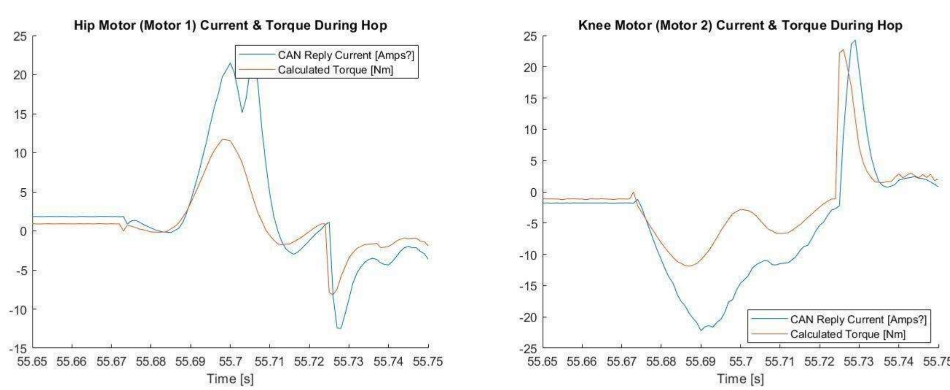
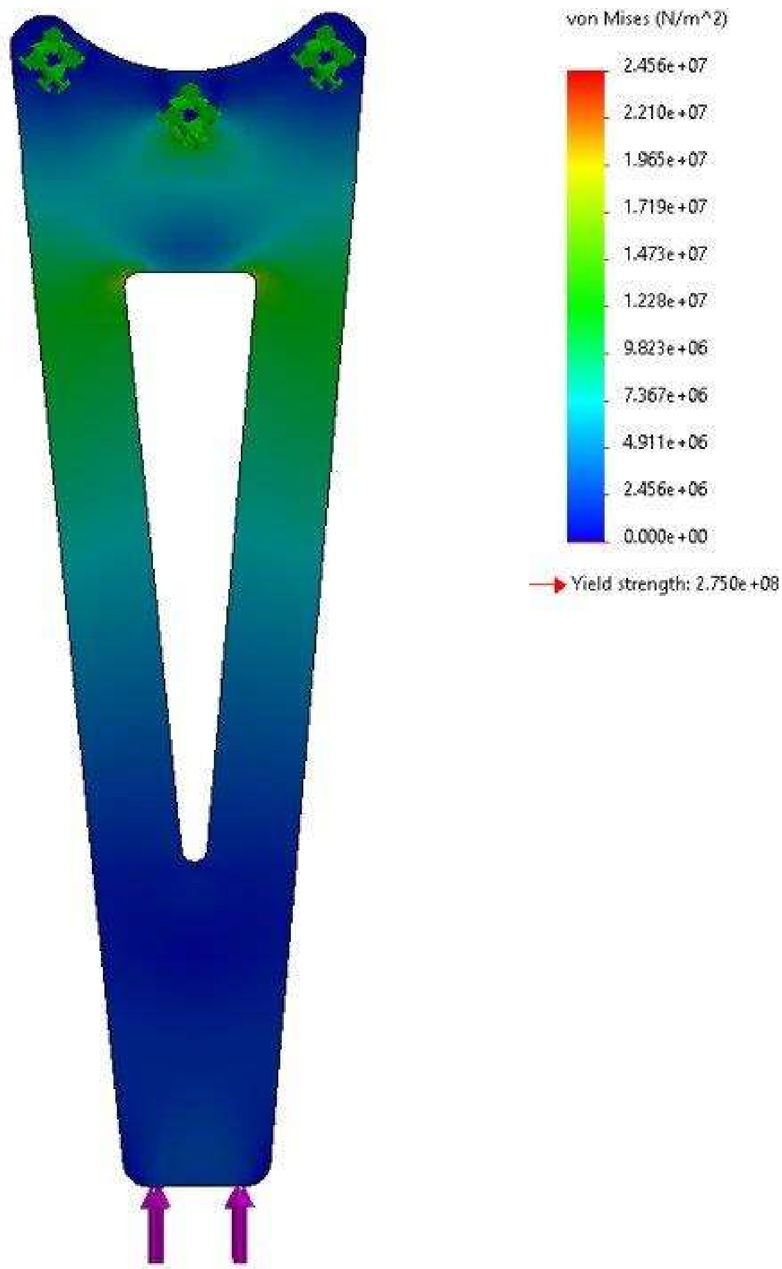


Figure E1: Summer single leg motor data used to approximate jump contact time, t = 0.04s.

Appendix F: Lower Link Stress Analysis



Contour plot above shows the Von Mises stresses of a single lower link experiencing a static load of 98.1 N, or the entire weight of the robot. As the plot shows, stresses are below 10 times the yield strength of the aluminum.

Appendix G: Failure Modes & Effects Analysis (FMEA)

System/Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date
Upper Link / Transmit Torque	Poor gear ratio	Low torque transmission	6	Improper pulley selection	Select proper gear ratio	2	Examining torque output plots	2	24		
Upper Link / Rotate	Leg and frame geometry interfere	Leg and frame geometry interferes	8	Poor upper link geometry	Thoughtfully design body frame and leg-frame connectors	5	Visual inspection	1	40		
Upper link / Durable	Upper link flexes too much	Upper link bends or mechanicall fails	6	Poor material selection or geometry	Stress calculations and stress tests	5	Visual inspection	4	120	Stress calculations and stress tests	1/24/2022
Upper link / Tension belt	Teeth skip	Belt tensioner / belt breaks	6	Belt tensioner doesn't add enough belt tension	Tension belt properly	2	Listening to the leg while operating	2	24		
Upper link / Support body	High stress in fasteners	Upper link to actuator fasteners fail (shear)	8	Poor fastener size selection	Fastener shear analysis	3	Visual inspection	2	48		
Upper link / hold together	Loose fasteners	Upper link section fasenters come undone and leg falls apart	7	Fasteners are too small / no loctite	Non-permanent loctite and fastener torque calculations	4	Visual inspection	3	84		
Upper link / facilitate rotation of L.L.	Knee shaft has improper tolerance	Knee cannot rotate properly	8	Improper knee shaft material selection or design	Stress analysis and proper shaft tolerance selection	7	Visual inspection	2	112	Stress analysis and testing of knee shaft	2/04/2022
Lower link / dampen impact	Foot has plastic impact with ground	Excessive force transmitted to leg	8	Foot material is too stiff or too elastic	Use TPU for foot with proper infill percent	2	Film impact and examine foot compression	7	112	Increase infill percent of foot to ~80%	1/5/2022
Lower link / durable	Lower link flexes too much	Lower link bends or mechanically fails	7	Poor material or geometry selection	Stress analysis and stress tests	6	Visual inspection	3	126	Stress analysis and stress tests	1/24/2022
Lower link / Prevent slipping	Leg landing orientation is not optimal	Robot slips and falls to ground	6	Foot material is too slippery	Choose high-friction test stand floor material and foot material (TPU)	3	Visual inspection	1	18		
Lower link / land in multiple orientations	Foot shape does not allow for multiple landing positions	Robot cannot land in certain leg orientation	5	Poor foot geometry selection	Use a spherical foot	2	Visual inspection	1	10		
Lower link / support body	High stress in fasteners	Upper link to lower link fasteners fail (shear)	8	Knee joint and lower link fasteners are too small	Fastener shear analysis	3	Visual inspection	3	72		
Body Frame/rotate	Interference	Robot doesnt move	9	1.Wear and tear 2.Poor design 3. Part moves out of place	Interference checks	4	Doesn't move	2	72		
Body Frame/provide mechanical power	Actuator loose	No power for legs	8	1. Fasteners break 2. Fasteners come out	Add loctite to fasteners	5	When power is applied robot doesn't move	2	80		
Body Frame / protect battery	Large load on battery	Battery is damaged	7	1. No support over battery 2. shell bends	FEA analysis	4	Battery check after use	4	112	Stress analysis and testing of frame	1/24/2022
Body Frame / Looks cool	Ugly	People don't like to look at it	4	1. Poorly designed 2. Unorganized	CAD overview and organization	6	Beauty pageant	1	24		
Body Frame / Durable	Shell breaks	Breaks if falls over	6	1. Shell too thin 2. Not enought supports	FEA analysis	6	Stress test	5	180	Stress analysis and testing of frame	1/5/2022
Body Frame / Support rest of body	Crumbles under weight	Bends under weight	6	1. Shell too thin 2. Not enought supports	FEA analysis	5	Stress test	5	150	Stress analysis and testing of frame	1/24/2022
Body Frame / Balance	Falls over	Doesn't stand up straight	8	1. Weight all on one side	Check CG in CAD	4	Falls over when stood up	3	96		
Battery / Power Actuators	Battery undersupplies	Some or all actuators will not function	3	1. Battery is damaged from feedback 2.. Power Distribution limits current draw	Input Transient Voltage Protection	1	Measure motor current draw with multimeter	3	9		
Battery / Last 30 minutes	Battery lasts less than 30 minutes	Robot shuts down prematurely	8	1. Battery life wears over time	Make sure battery is replaced after expiration	1	Guage battery life	6	48		
Wire Harness / Transmit Power and Data	None or incorrect data is transmitted	Actuators will not orient correctly	4	1. Loose or shorted wires	Well physically protected circuit to prevent shorts and disconnects	2	Check wiring with multimeter	5	40		
Emergency Stop / Terminate Power Directly	The Emergency Stop does nothing	Robot will continue to run after being stopped	8	1. Loose or shorted wires	Well physically protected circuit to prevent shorts and disconnects	2	Check wiring with multimeter	5	80		
PDB / Regulate Current	Robot draws too much current	Actuators heat up or explode, causing wear	10	1. Current regulating circuit (fuse) is shorted or misvalued	LED lights when no current flows through fuse	2	Check wiring with multimeter and test fuse break	5	100	Reconfigure regulating circuit	1/24/2022
Controller / Command Actuators to make leg jump 10cm	CAN Packets to actuators contain incorrect data	Robot fails to execuse proper jumping algorithm	4	1. Jumping algorithm is misimplemented in microcontroller	Test data on oscilloscope	2	Debug controller to see if intended data is sent	7	56		
	loose connections	1. extra shaking	2	loose fasteners	tighten fasters	8	check tightness of fastners every	3	48		
Test Stand/Stable Testing	Mounts deforms	1. damaged mount 2. scewed jumping gait	4	Robot weight do to bending large arm holding stand	minimize holding distance to reduce bending	4	visual inspection	3	48		

System/Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date
Test Stand/Prevent Pivot	Robot Drops	1. hardwear is damaged	9	The mount stops holding robot	design secure mount that fastens to robot	2	check to see if robot is secure	1	18		
	Loose connections	1. Small fasteners 2. Fastener breaks	6	1. Poor connection method 2. sever torsional plastic deformation	Smart design choises ie. Having fasteners far apart and safe matterial	4	double check tightness	3	72		
Test Stand/Allow Pivot	Friction in Pivot	1. Tight fit 2. Tangeled Wire	4	1. wear on bearing 2. physical interference	lubricant	3	test bearing rotation	8	96	if severe add replace, add more lubracant	
	Pivot is not alligned with the center of mass	1. Poor design 2. Out of tolerance	6	poor design choises	good design choices is location for mount	2	test if pivot favors a specific orientation	4	48		
Test Stand/Provide Power	Cables knot	1. Poor organization	6	1. robot knots cables during testing	pack cables in neat bundles	3	Visual inspection	3	54		
	Cables shear	1. Poor cable routing	5	tugs on wires	1. pack cables in neat bundles 2. Strain relief	4	Visual inspection check is strain reliefe is working	3	60		
	Cables unplug	1. Poor cable routing	5	2. wire strain	1. use strain relief	4	check power Visual inspection	2	40		
	Shakeing	1. Loose fasteners	6	1. Poor connection method 2. poor locations for 80x20	Smart design choises ie. Making sure all components are secured on all side	2	double check tightness	3	36		
Test Stand/ Hold Entire Test Stand	80x20s bends	1. 80x20 buckle	9	1. large loads on member	don't add accesive loads on members ie. Leaning My weight on member	2	Visual inspection	3	54		
	No space for nesisary components	1. test stand become cluttered	2	1. test stand become cluttered	clean up	6	Visual inspection	3	36		
	Components become unsecure	1. Robot falls 2. components brake 3. dis orginazation	8	1. shaking 2. loosening of faseners 3. rolling around test stand carelessly	practice securing teststand before moving/ using	5	manually checking if each thing is secure	3	120	lock all important/ perminate components to test stand	

Appendix H: Design Hazard Checklist and Plan

Table H.1: Design Hazard Checklist.

Y	N	
	✔	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
✔		2. Can any part of the design undergo high accelerations/decelerations? – relatively large forces.
✔		3. Will the system have any large moving masses or large forces? - a potentially broken robot.
	✔	4. Will the system produce a projectile?
	✔	5. Would it be possible for the system to fall under gravity creating injury?
	✔	6. Will a user be exposed to overhanging weights as part of the design?
	✔	7. Will the system have any sharp edges?
✔		8. Will any part of the electrical systems not be grounded? - battery
	✔	9. Will there be any large batteries or electrical voltage in the system above 40 V?
✔		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids? -A large capacitor will be a part of the system.
	✔	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	✔	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	✔	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✔	14. Can the system generate high levels of noise?
	✔	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
✔		16. Is it possible for the system to be used in an unsafe manner? - In theory, though pretty much any system can be unsafe if one tries hard enough
	✔	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Table AH.2: Design Hazard Plan.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Rapid leg acceleration during jumping motion	Operate the leg in an open space; ensure all operators are a safe distance from the test stand; de-initiate motors before attempting to access quadruped	1/03/21	TBD
Large GRF to launch quadruped	Use a strong material for the test stand base; soft material for the quadruped foot	9/20/21	TBD
Non-grounded battery	Battery will be mounted within body frame of quadruped and inaccessible during operation.	1/03/21	TBD
Battery stored energy	Design a power distribution board to ensure that motors are not given an excessive current load.	2/1/21	TBD

Appendix I: Verification Plan (DVP)

DVP&R - Design Verification Plan (& Report)

Project: F72 8DOF Quadrupedal Robot | Sponsor: Dr. Siyuan Xing and Charlie Refvem | Edit Date: 2/4/2022

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
1	Vertical leap height	Measure the height that the ball bearing carriage is displace when the quadruped is executing a vertical hopping motion. Alternatively, measure the hieght that the foot reaches off the ground	Vertical displacement of the ball bearing carriage and foot of robot	10 cm vertical displacement	24V power; large open space	Quadrupedal prototype and modular test stand	Clayton	3/22/2022			
2	Fatigue durability	Cycle the quadrupedal robot and single leg redesign through >1000 cycles. Evaluate and inspect if any fatigue or wear has occurred at any points of the robot. Specifically inspect the knee joint in the leg, and the brackets/fasteners on the body frame	Number of jumping cycles the leg has executed	>1000 cycles	24V power supply; large open space; either a Nucleo (if C/C++ controller is ready) or Speedgoat (if C/C++ controller is not ready)	Modular test stand (for quadruped); summer test stand (for single leg) supply	Clayton	3/22/2022			
3	Assembly time	Assemble the quadruped (excluding the test stand). This includes the legs, body frame, and setting up the various cable harnesses and installing necessary electronic components	Time to assemlble quadruped	<10 minutes	Variety of allen keys, large open space and table to assemble at (likely in 119-118)	Quadrupedal prototype	Clayton	3/21/2022			
4	Weight management	Measure the total weight of the quadrupedal robot when fully assembled	Weight of the quadruped	<10 kg	Large plate scale or spring scale	Quadrupedal prototype	Clayton	3/21/2022			

Complete these columns when you conduct the tests.

DVP&R - Design Verification Plan (& Report)

Project: F72 8DOF Quadrupedal Robot | Sponsor: Dr. Siyuan Xing and Charlie Refvem | Edit Date: 2/4/2022

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
5	Center of mass location	Examine the behavior of the quadruped during flight; does it roll to the left or right? If so, the COM is poorly located. To measure the robot's tendency to pitch, we may examine the COM of the body frame/internal electronics in SOLIDWORKS, and verify the numerical values with hand calculations of the COM location	X, Y, X coordinates of the COM	<0.5 inches from the body frame's geometric center	24V power, large open space	Quadrupedal prototype and modular test stand	John	3/21/2022			
6	Compilation time	Record the amount of time it takes for the controller to run once compilation begins	Time to compile controller code	<5 minutes	STM microcontroller	None	Daniel	4/20/2022			
7	Total cost of components	Total the cost of the components for quadruped and test stand	Cost of components	<$5,000	None	None	Tyler	2/24/2022			
8	Avoid rolling during flight	Examine the quadruped's tendency roll during flight (film the flight of the robot too); if the left and right side legs of the quadruped do not impact at the same time, then the robot has rolled.	Time difference between left and right side leg impacts	Time difference between left and right sides <0.05 seconds	24V power; large open space	Quadrupedal prototype and modular test stand	John	4/1/2022			

DVP&R - Design Verification Plan (& Report)

Project: F72 8DOF Quadrupedal Robot | Sponsor: Dr. Siyuan Xing and Charlie Refvem | Edit Date: 2/4/2022

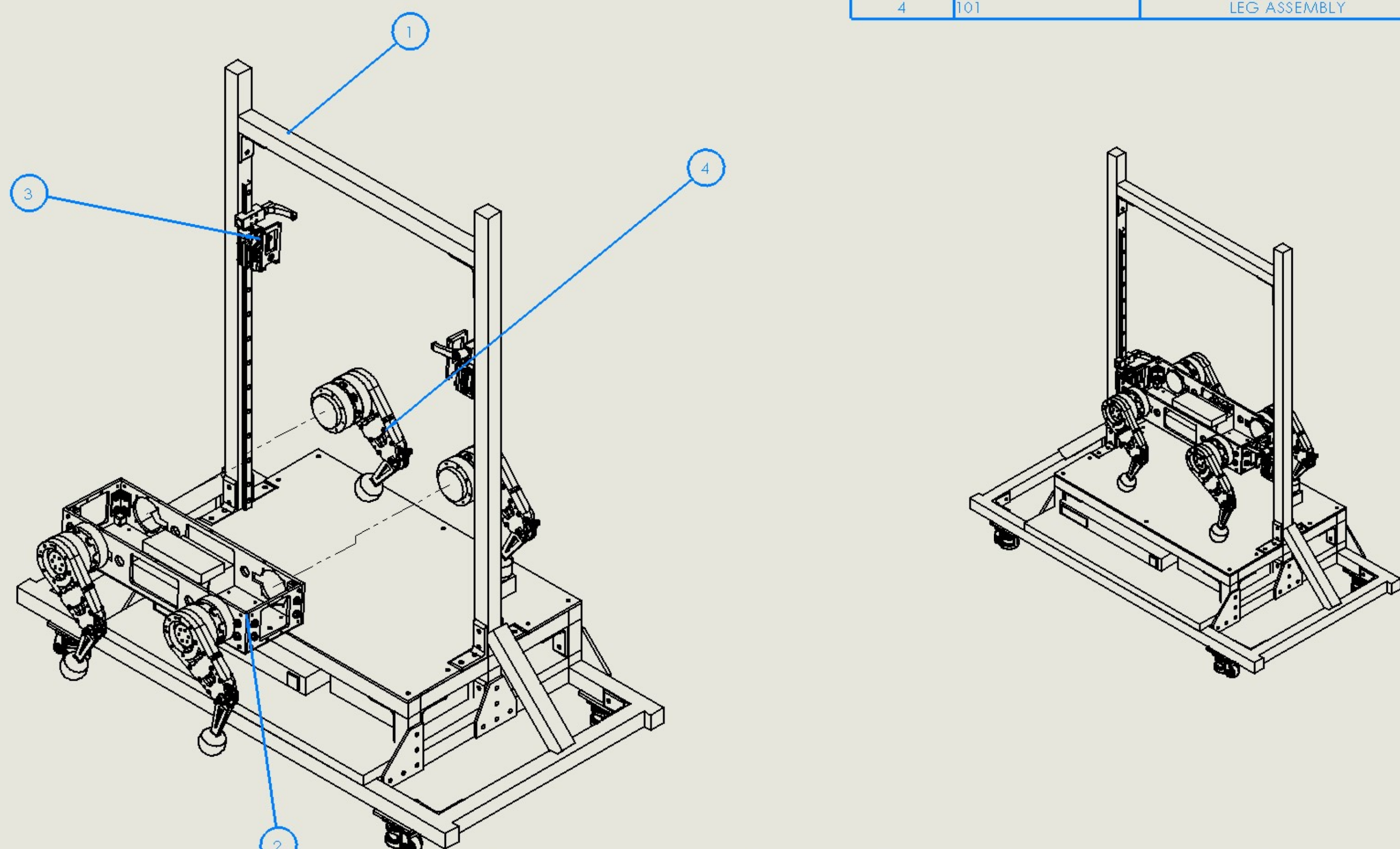
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
9	Leg response overcorrection / steady state error	Observe the steady state error of the angular position of the leg upon landing after a jump. Angular position will be inspected on a plot of angular position versus time with data collected from the motor encoders.	Angular position error between desired and measured steady state values	Steady state error < 0.03 radians	24V power, large open space	Summer test stand and/or modular test stand. Single leg prototype (for initial controller tuning) quadruped prototype (for final controller tuning)	Tyler	4/2/2022			
10	Leg response time	Observe the time required for the leg to move from fully extended (immediately after liftoff) to the desired landing angle. Angular position versus time plot will be inspected to determine these values	Time to move from fully extended position to desired landing position	Response time of < 0.1 seconds	24V power, large open space	Summer test stand and/or modular test stand. Single leg prototype (for initial controller tuning) quadruped prototype (for final controller tuning)	John	4/3/2022			

Appendix J: Drawing and Specification Package

100000000	BRUCE			
	101000000	Leg Assembly		
		101010000	Upper Link	
			101010100	Pulleys
			101010200	Timing belt cover
			101010300	Link Structure
			101010400	Actuator-pulley adapter
			101010500	Hip-knee actuator adapter
			101010600	R6 Bearing
			101010700	MR696
			101010800	M4 35 mm SCHS
			101010900	M4 12 mm FHCS
			101011100	M3 30 mm dowel pins
			101011200	M3 SHCS 35mm
			101011300	M3 SHCS 25mm
			101011400	M3 Washers and nuts
			101011500	M3 Nuts
			101011600	M3 Heat set insert
			101011700	Belt tensioner shaft
		101020000	Lower Link	
			101020100	Foot
			101020200	Calf
				101020201 Calf Plate
			101020300	R6 Bearing
			101020400	Pulleys
			101020500	#6-32 ULP screws
	102000000	Body Frame Assembly		
		102010000	Body Frame Structure	
			102010100	Side frame
			102010200	Front/back frame
			102010300	L-brackets
			102010400	3D Printed Panel Mounts
			102010500	M3 Heat set inserts
			102010600	Top/Bottom Panel
			102010700	¼-20 Steel nut
			102010800	1/4-20 0.75" Cap Screws
			102010900	¼-20 Steel washer
			102011000	M3 16 mm SHCS
			102011100	M3 7 mm SHCS
		102020000	Internal Electronics	
			102020100	Battery
			102020200	STM32
			102020300	Power Distribution Board
			102020400	Actuators

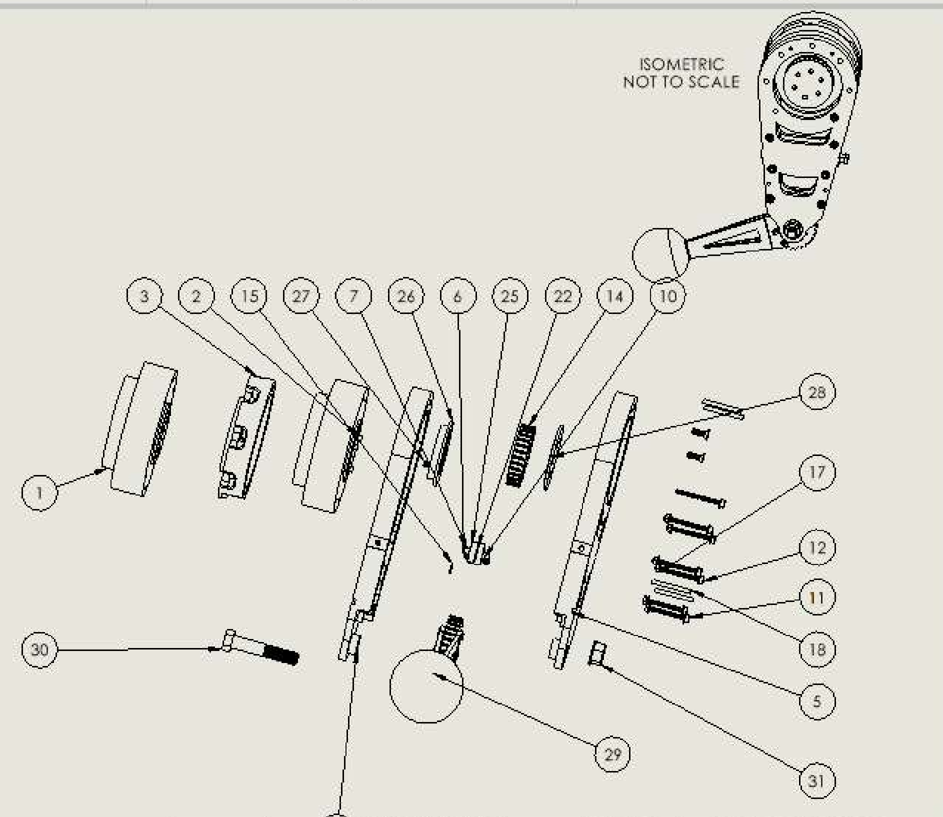
		102020500	Zip ties			
		102020600	Capacitor			
		102020700	Adhesive zip-tie mounts			
		102020800	GWN1.00BK25			
		102020900	T3609160101-000			
		102021000	28 AWG Wire			[feet]
		102021100	14 AWG Wire			[feet]
		102021200	Relays			
		102021300	Fuses			
		102021400	Inline fuse holders			
103000000	Test Stand Assembly					
	103010000	Test Stand Frame				
		103010100	80x20 Frame			
				103010101	11" diagonal	
				103010102	48”	
				103010103	21.5”	
				103010104	29.5”	
				103010105	7.5”	
				103010106	4”	
				103010107	26.5”	
		103010200	Corner Bracket			
		103010300	T Frame Bracket			
		103010400	L Frame Bracket			
		103010500	M6-1.0 x 18mm			
		103010600	M6 End-Feed Nut, 30 mm Single Rail			
	103020000	20mm Guide Rail				
	103030000	wood base				
	103040000	Castor Wheels				
	103050000	Jumping Platform				
	103060000	Speedgoat				
	103070000	24V/20A Power Supply				
	103080000	Capacitor				
	103090000	E-Stop				
	104110000	12 AWG?				
104000000	Test Stand Mount Assembly					
	104010000	Body Mount-Shaft				
		104010100	Body Mount			
		104010200	Shaft			
	104020000	Two-Bolt Flange Mount				
	104030000	Mount Backing Plate				
	104040000	Spacer Plate				
	104050000	Ball Bearing Carriage				
	104060000	30mm M6x1 Fastener				
	104070000	7/16" 3/4in Bolt				
	104080000	Hand Brake				

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	103	TEST STAND ASSEMBLY	1
2	102	BODY FRAME ASSEMBLY	1
3	104	TEST STAND MOUNT ASSEMBLY	2
4	101	LEG ASSEMBLY	4



Cal Poly Mechanical Engineering	Lab Section: 07	SP DRAWINGS	Title: BRUCE ASSEMBLY 1		Drwn. By: JOHN BENNETT
ME 429 - WINTER 2022	Dwg. #: 1	Nxt Asb: NA	Date: 2/10/22	Scale:1:8	Chkd. By:

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	C_E_AK80-6_Model		1
2	C_E_AK80-6_Model		1
3	leg_motorPlate3		1
4	Motor Leg 4 (hip-knee)		1
5	Motor Leg 4 (hip-knee)		1
6	94459A140		2
7	Tensioner Shaft		1
8	Lower Link Rev 1.2		1
9	Lower Link Rev 1.2		1
10	94669A099		2
11	91274A109_COATED ALLOY STEEL SOCKET HEAD CAP SCREW		4
12	91274A109_COATED ALLOY STEEL SOCKET HEAD CAP SCREW		11
13	91274A109_COATED ALLOY STEEL SOCKET HEAD CAP SCREW		1
14	GPA30MR5150_A_H10_KSC28_K4		1
15	M3 Black Oxide Washer 6mm OD		19
16	6 mm OD		1
17	90592A085		7
18	M3 Alignment pin		4
19	90592A095		1
20	98269A440		2
21	91290A270		1
22	7487N57	Precision Stainless Steel Ball Bearing	2
23	Hip Pulley Spacer Rev 2		2
24	Hip Pulley Spacer Rev 2		2
25	Belt Tensioner Sleeve		1
26	Hip pulley adapter		1
27	91294A192		3
28	Hip pulley outer flange		1
29	Lower_Leg_Assembly		1
30	91268A537	High-Strength Grade 8 Steel Hex Head Screw	1
31	99904A103	Medium-Strength Steel Serrated Flange Locknut	1



PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

PART NO. 101000000

TITLE:

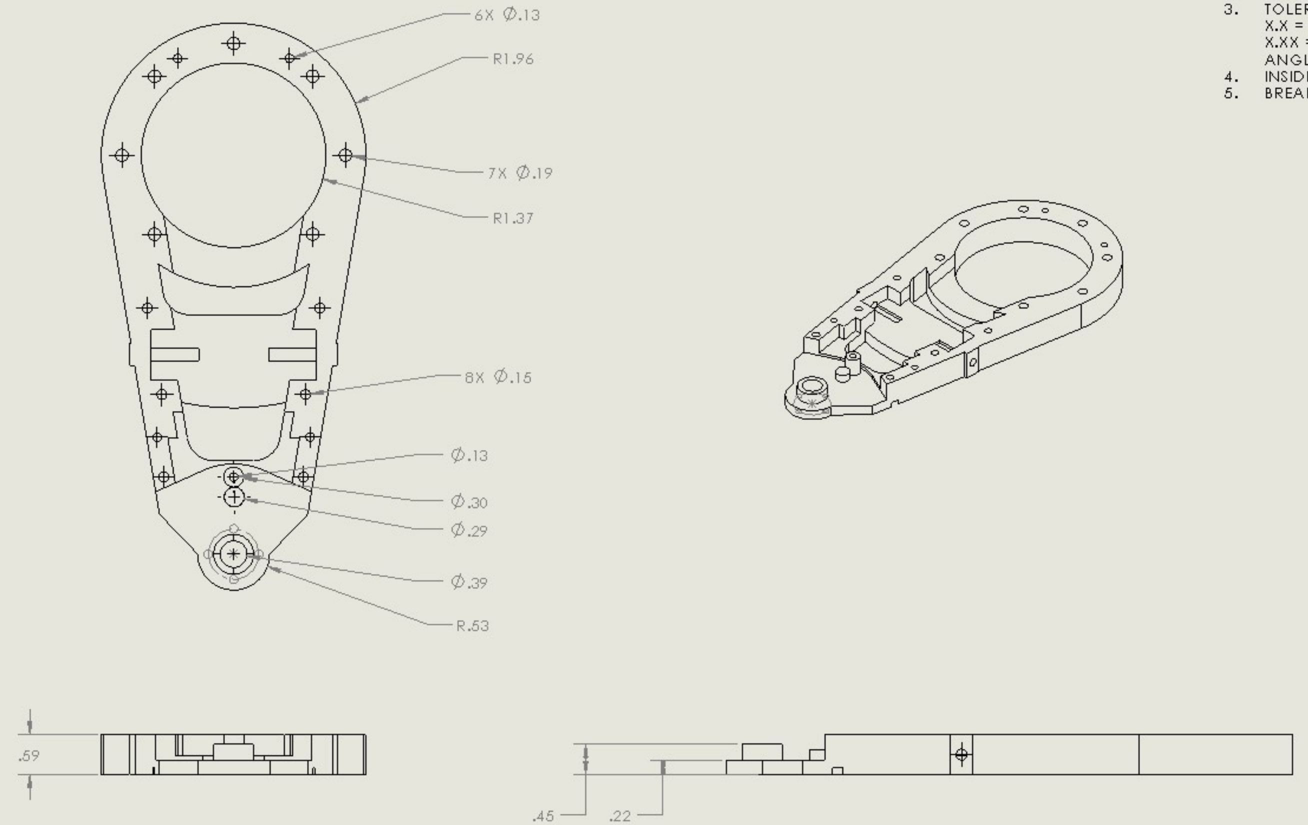
Leg assembly for B.R.U.C.E.

SIZE B | DWG. NO. Full Leg Assembly V2 | REV

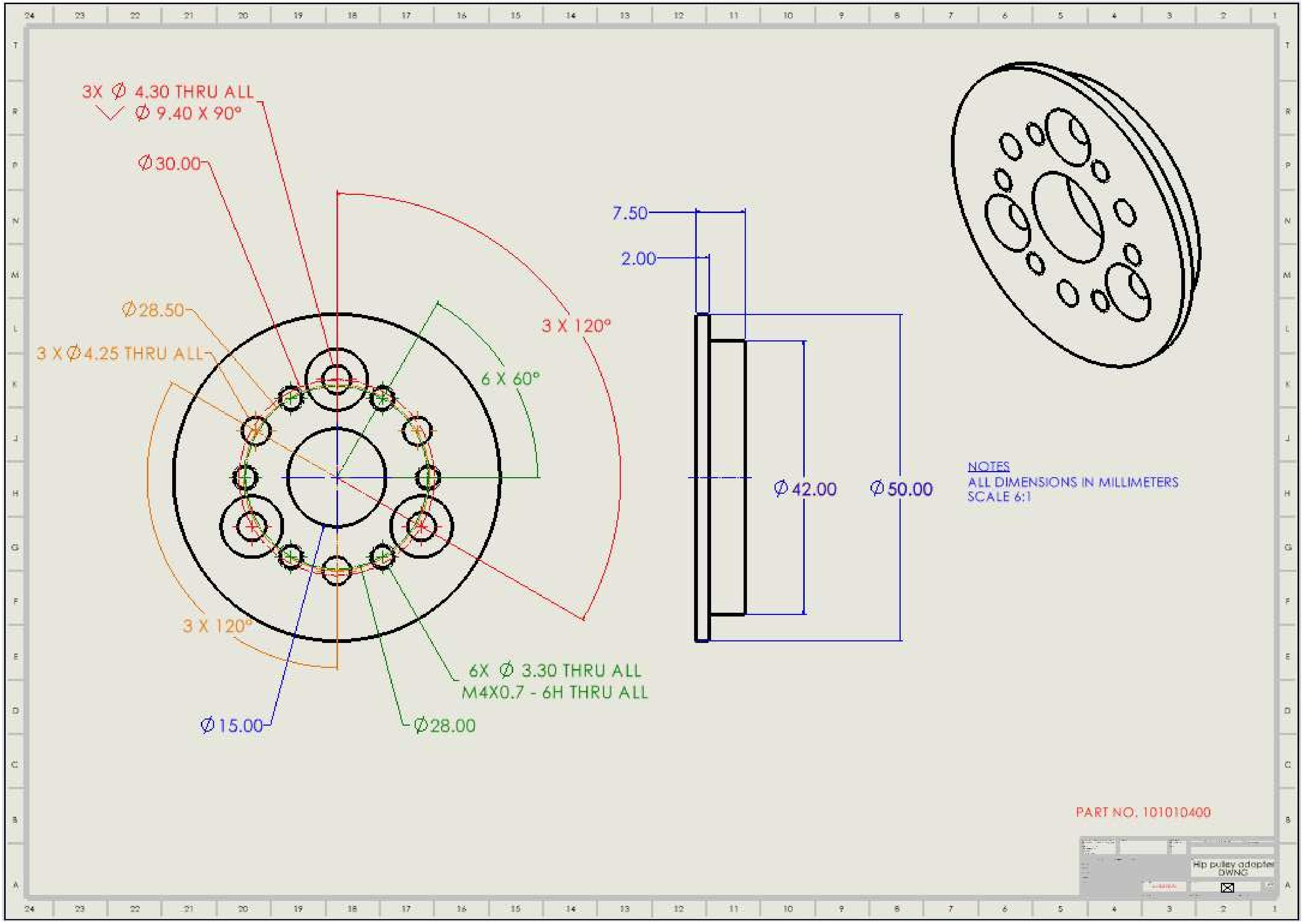
SCALE: 1:3 | WEIGHT: | SHEET 1 OF 1

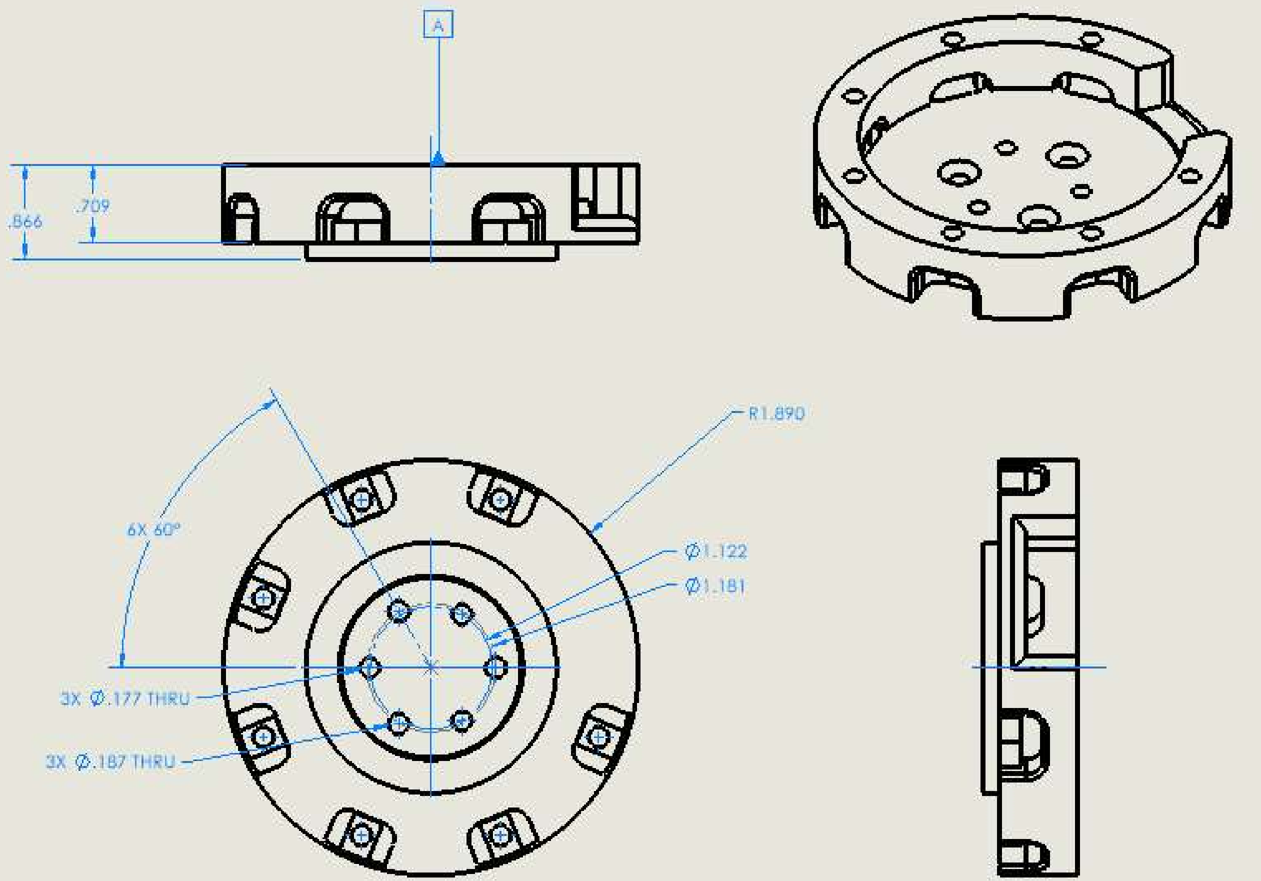
NOTES

UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
   X.X = ±.1
   X.XX = ±.05
   ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX



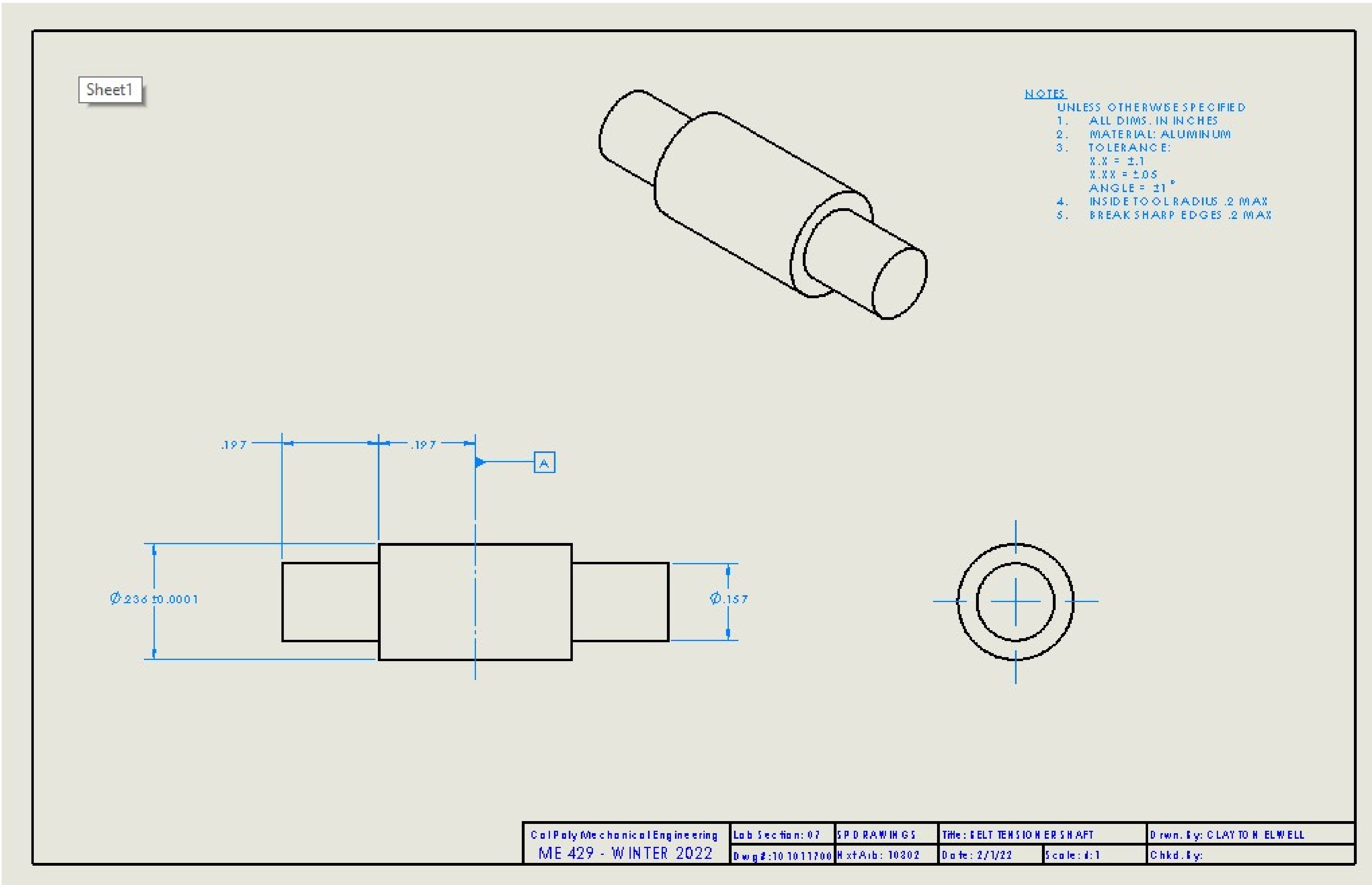
Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: MOTOR LEG		Drwn. By: TYLER MCCUE
ME 429 - QTR YEAR	Dwg#:101010200	Nxt Asb:	Date: 2/7/2022	Scale: 2:3	Chkd. By: ME STAFF


3X Ø 4.30 THRU ALL
Ø 9.40 X 90°
Ø30.00
Ø28.50
3 X Ø4.25 THRU ALL
3 X 120°
6 X 60°
3 X 120°
Ø15.00
6X Ø 3.30 THRU ALL
M4X0.7 - 6H THRU ALL
Ø28.00
7.50
2.00
Ø 42.00
Ø 50.00
NOTES
ALL DIMENSIONS IN MILLIMETERS
SCALE 6:1
PART NO. 101010400
Hip pulley adapter
DWNG

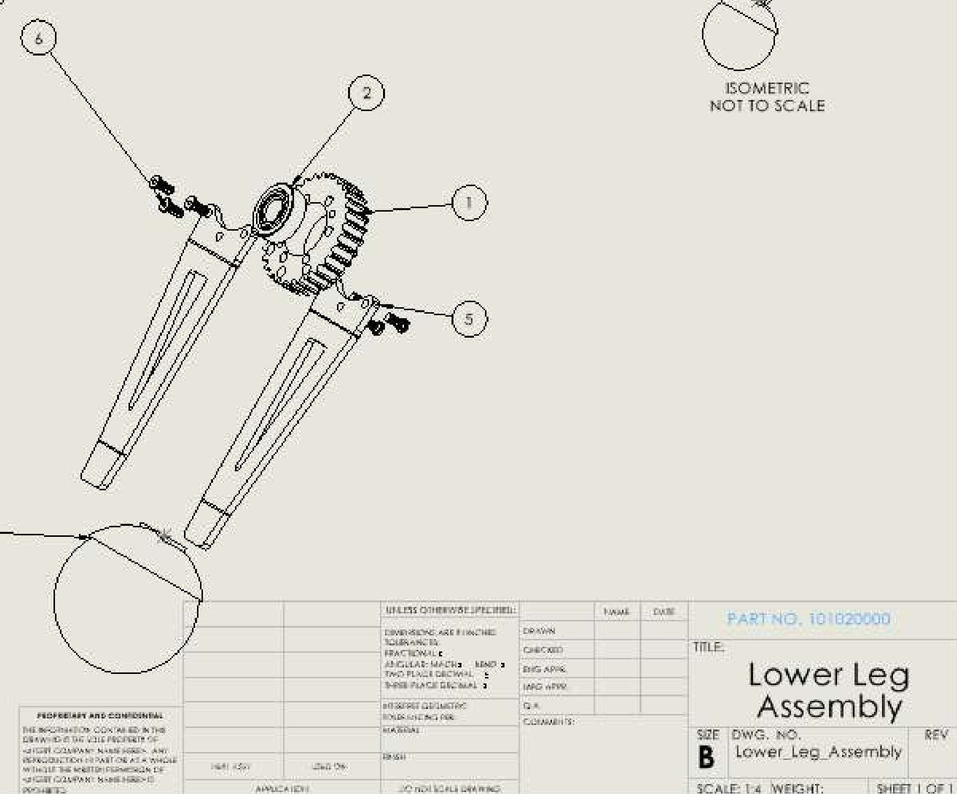


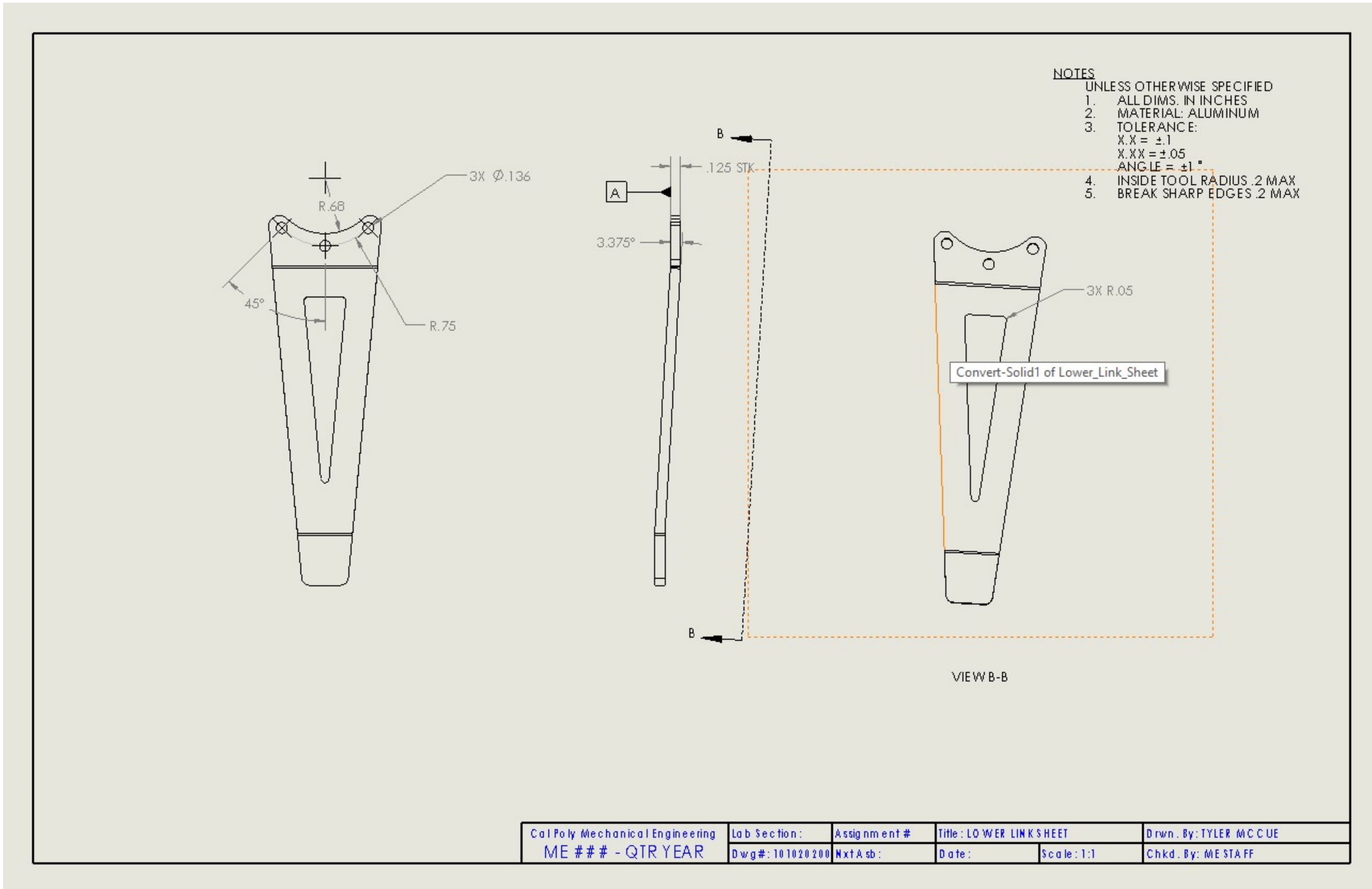
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: POLYCARBONATE
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX

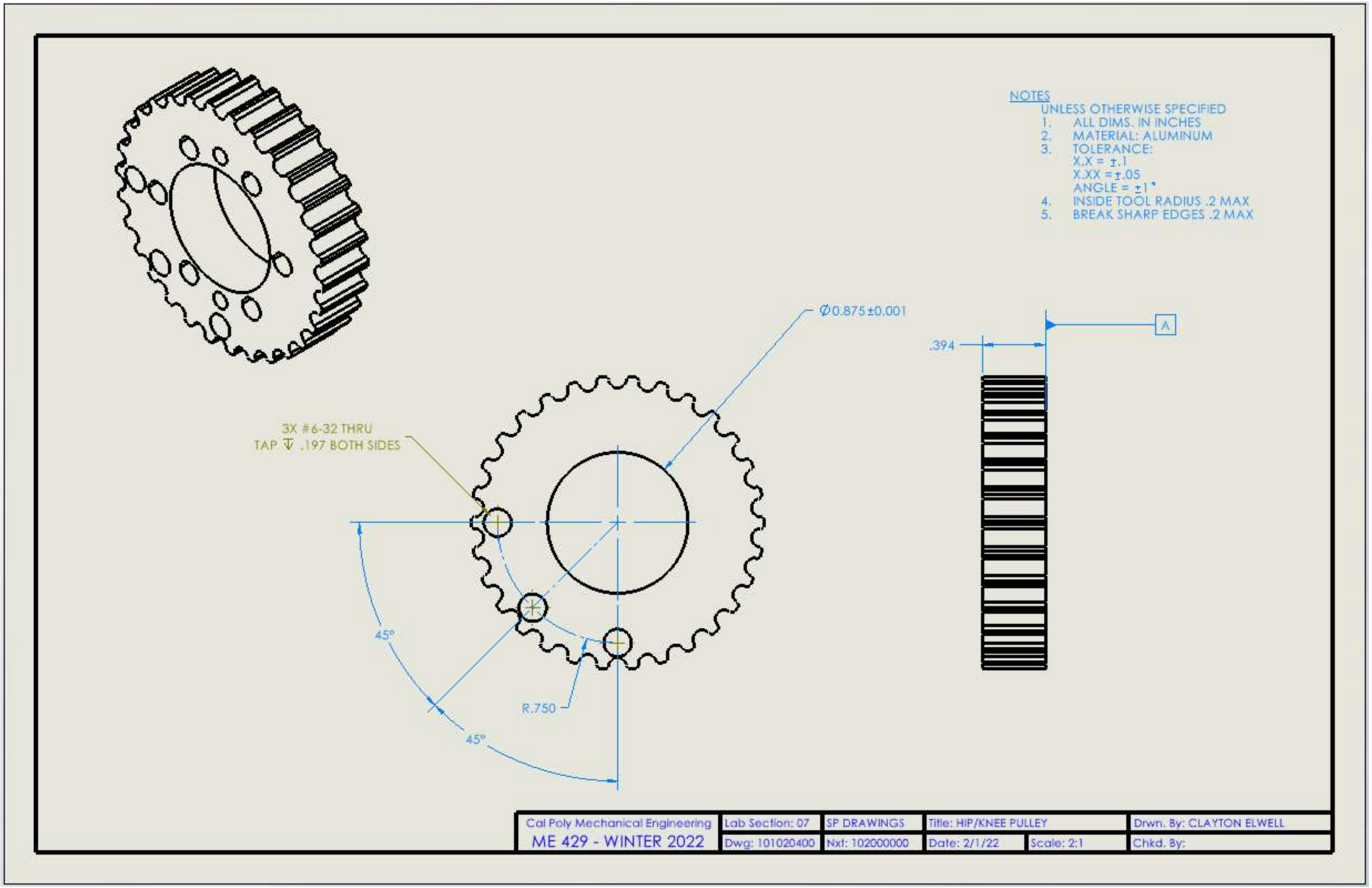
Cal Poly Mechanical Engineering	Lab Section: 07	SP DRAWINGS	Title: ACTUATOR ADAPTER		Drwn. By: CLAYTON ELWELL
ME 429 - WINTER 2022	Dwg: 101010500	Nxt: 102000000	Date: 2/1/22	Scale: 1:1	Chkd. By:

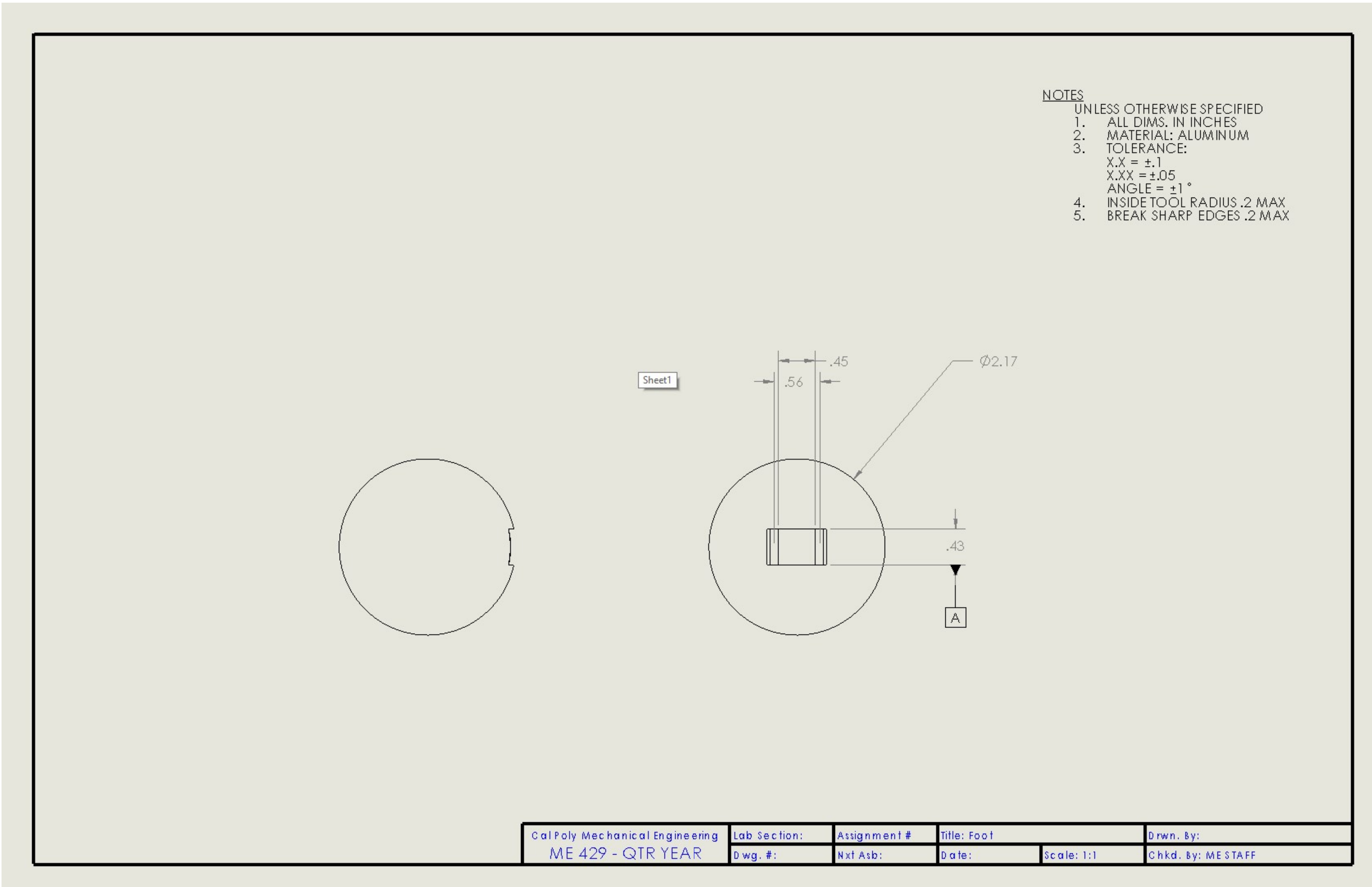

Sheet1
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
.197
.197
A
Ø.236 ±0.0001
Ø.157
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg#:101011700
SPD RAWINGS
NxtAsb: 10302
Title: BELT TENSIONER SHAFT
Date: 2/1/22
Scale: 4:1
Drwn. By: CLAYTON ELWELL
Chkd. By:

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	GPA30MR5150_A_H10_KSC28_K4_3		1
2	5908K14		1
3	Ball for foot		1
4	Foot-calf adapter		1
5	Lower_Link_Sheet		2
6	91223A314	316 Stainless Steel Ultra-Low-Profile Socket Head Screw	6



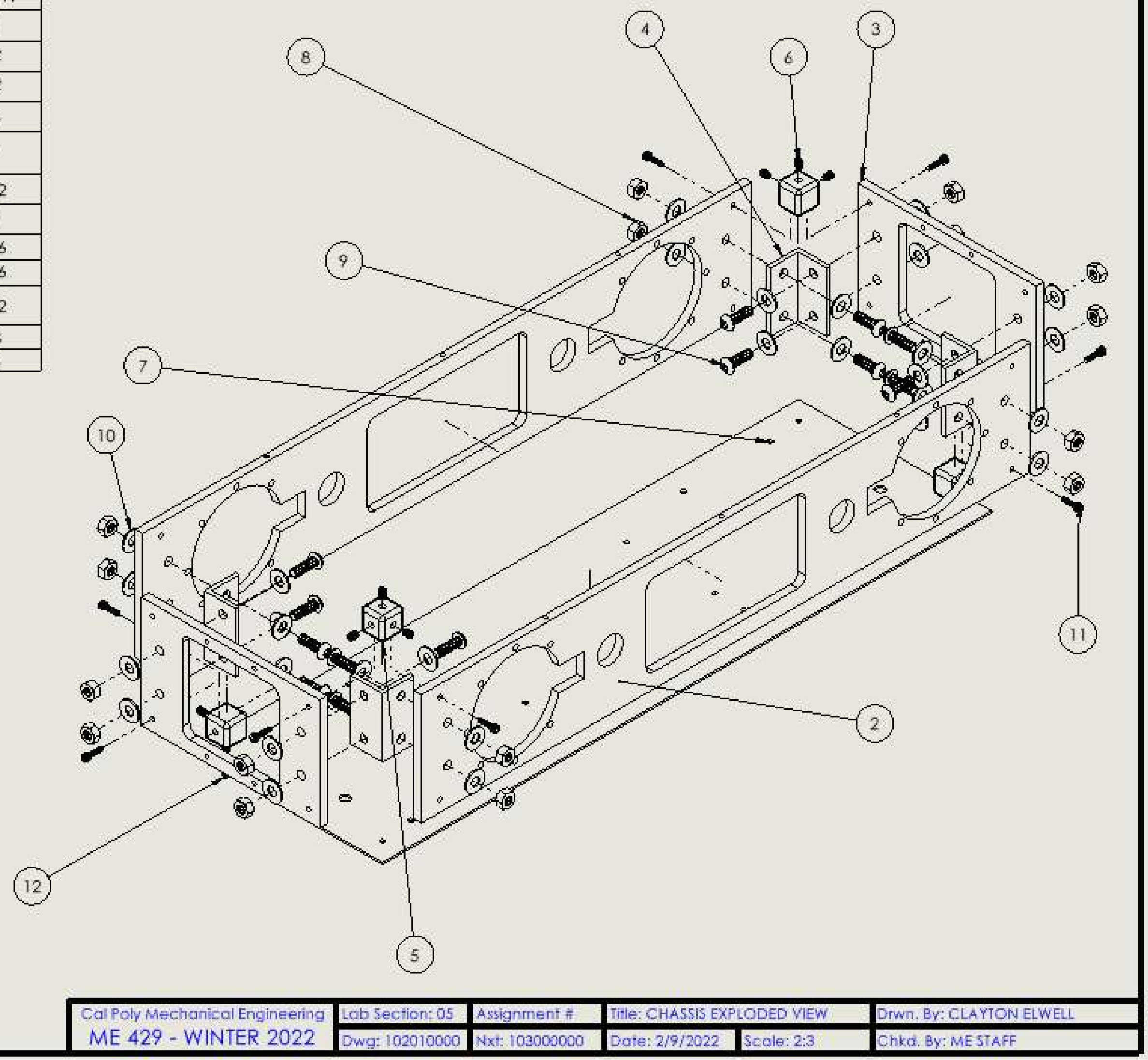

NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1 °
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
3X Ø.136
R.68
45°
R.75
A
.125 STK
3.375°
B
B
3X R.05
Convert-Solid1 of Lower_Link_Sheet
VIEW B-B
Cal Poly Mechanical Engineering
ME ### - QTR YEAR
Lab Section:
Dwg#: 101020200
Assignment #
NxtAsb:
Title: LOWER LINK SHEET
Date:
Scale: 1:1
Drwn. By: TYLER MCCUE
Chkd. By: ME STAFF

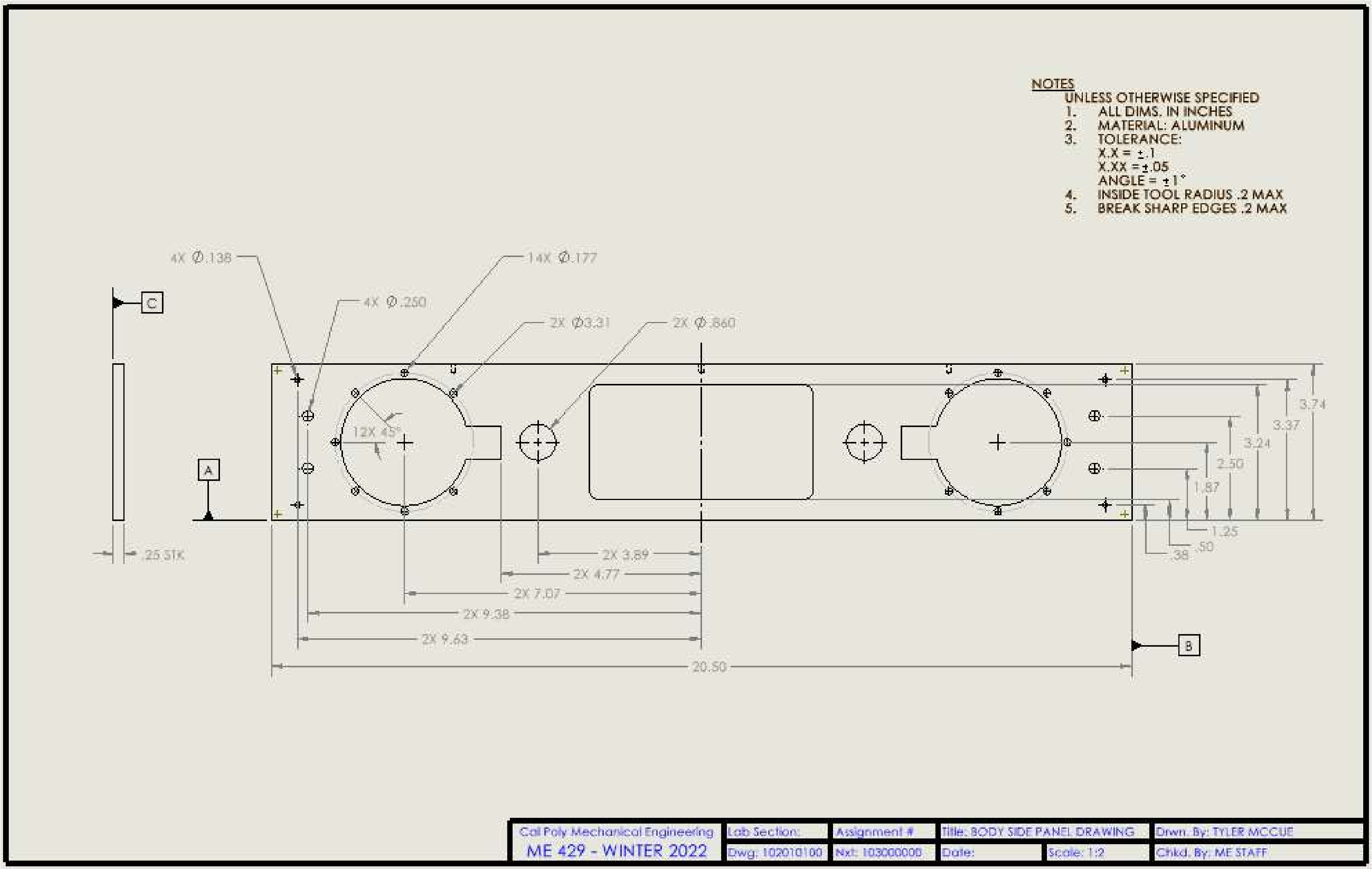

NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
Ø0.875±0.001
.394
A
3X #6-32 THRU
TAP ↧ .197 BOTH SIDES
45°
45°
R.750
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg: 101020400
SP DRAWINGS
Nxt: 102000000
Title: HIP/KNEE PULLEY
Date: 2/1/22
Scale: 2:1
Drwn. By: CLAYTON ELWELL
Chkd. By:


NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1 °
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
Sheet1
.45
.56
Ø2.17
.43
A
Cal Poly Mechanical Engineering
ME 429 - QTR YEAR
Lab Section:
Dwg. #:
Assignment #
Nxt Asb:
Title: Foot
Date:
Scale: 1:1
Drwn. By:
Chkd. By: ME STAFF

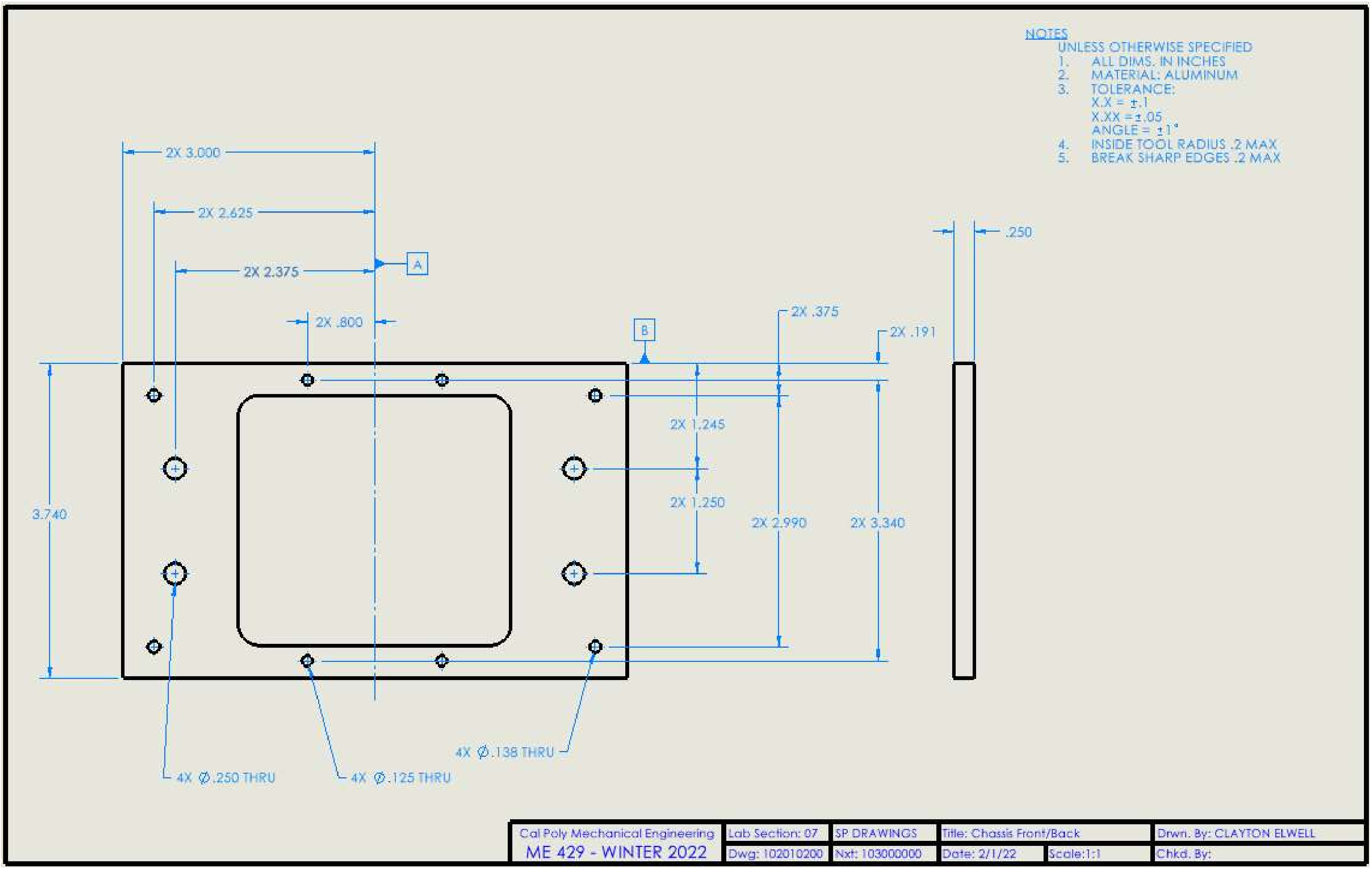
102000000 – Full body assembly with internal electronics TBD

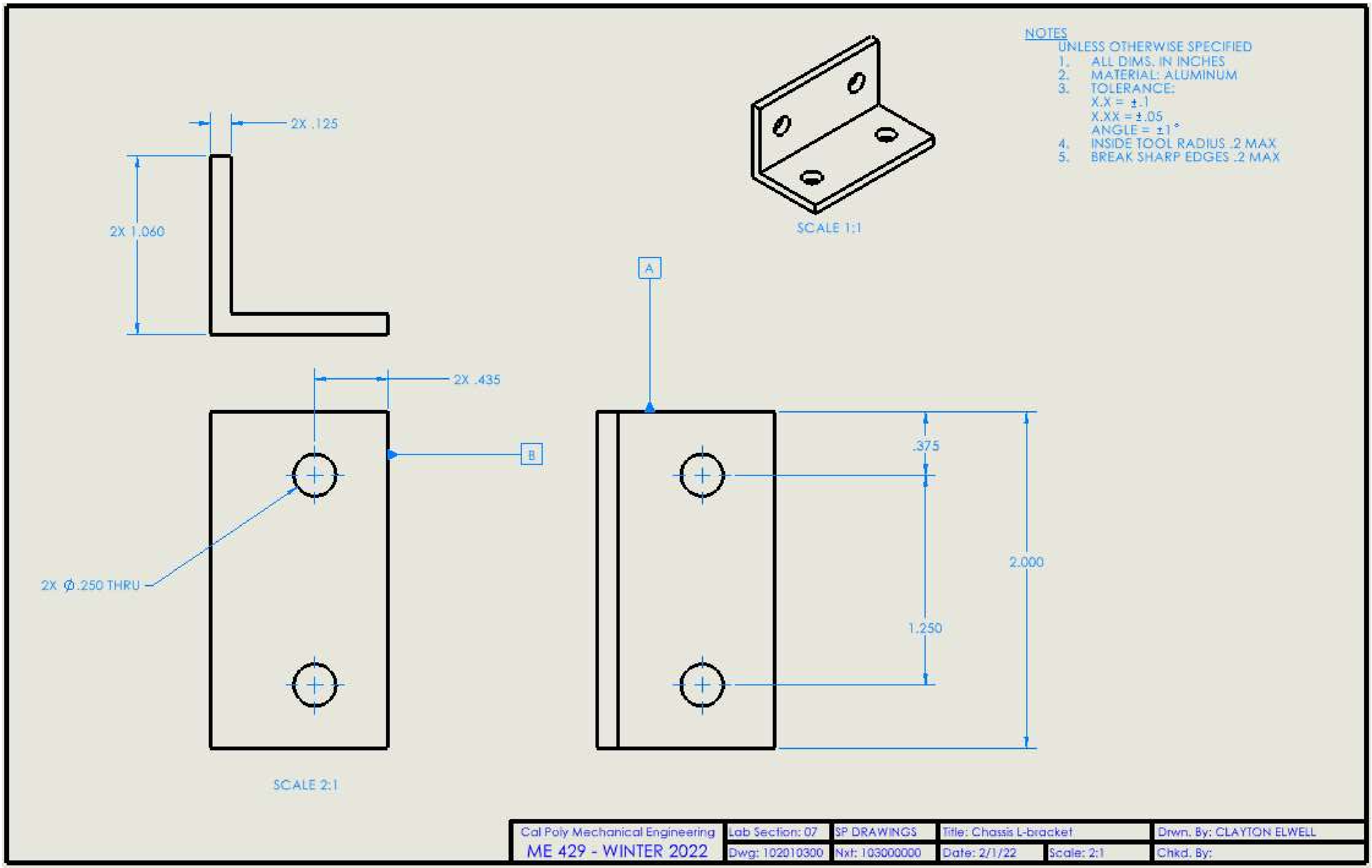
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	102010000	Chassis assembly	1
2	102010100	Body frame side panels	2
3	102010200	Body frame front/back	2
4	102010300	L-brackets for chassis	4
5	102010400	3D printed panel adapter	1
6	10201500	M3 Heat set inserts	12
7	102010600	Top/bottom Panel	1
8	102010700	1/4-20 Steel Nut	16
9	102010800	1/4-20 0.75" Cap Screws	16
10	102010900	316 Stainless Steel Washer	32
11	10201000	M3 16 mm SHCS	8
12	10201100	M3 7mm SHCS	4



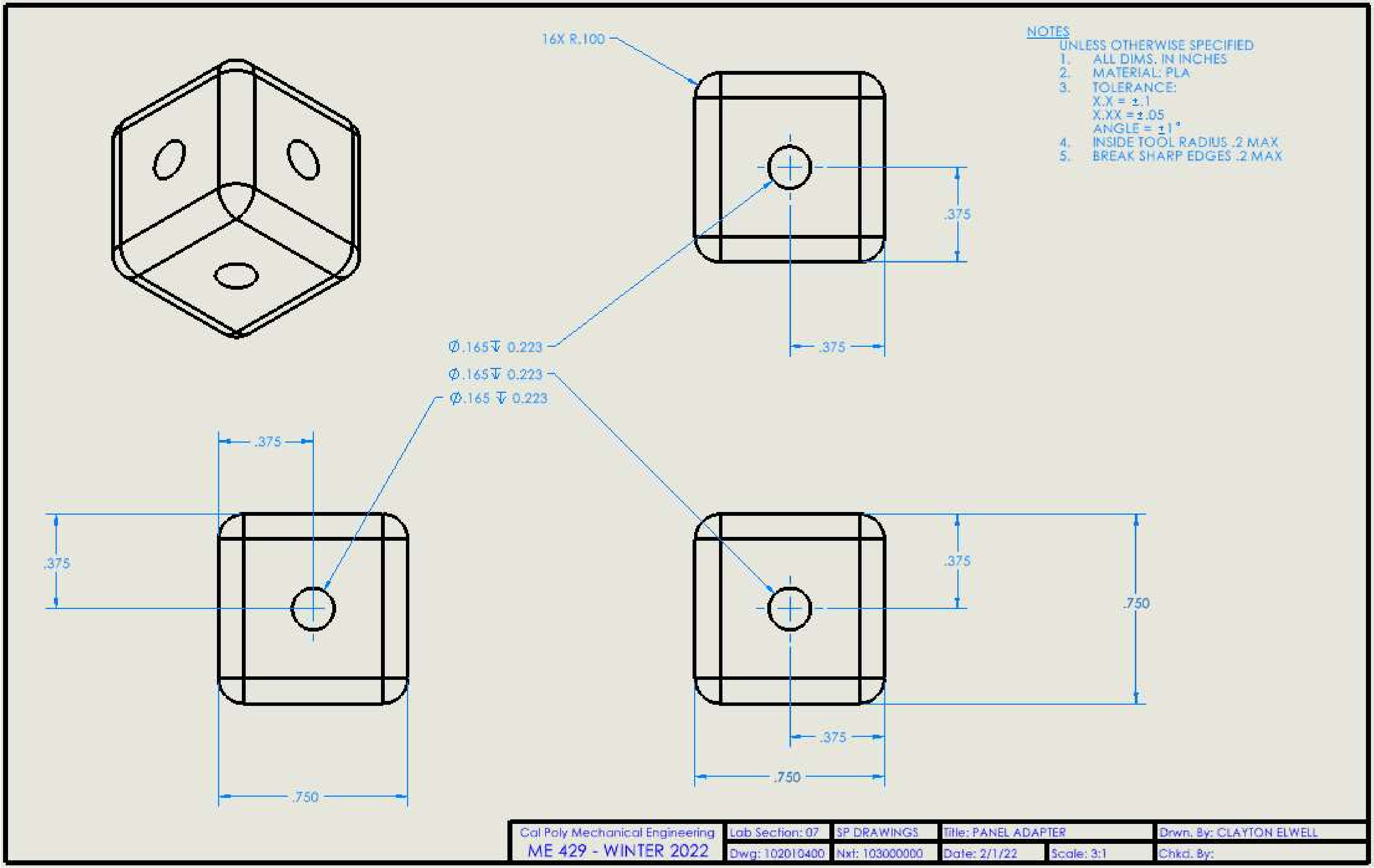


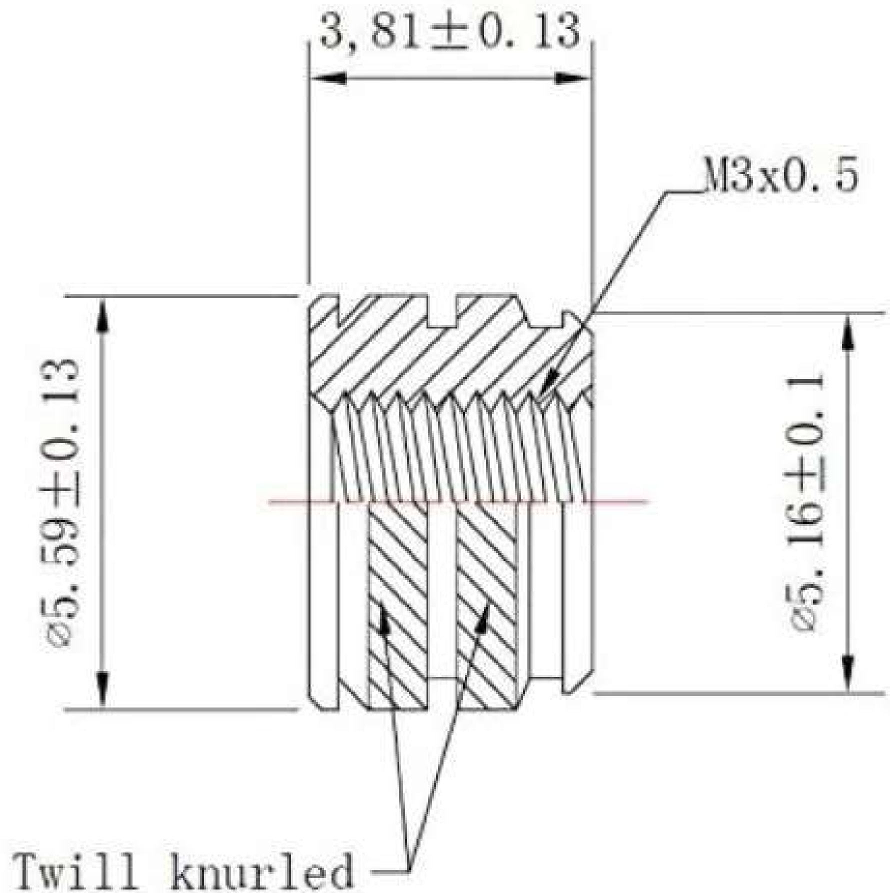
4X Ø.138
14X Ø.177
4X Ø.250
2X Ø3.31
2X Ø.860
C
A
B
12X 45°
.25 STK
2X 3.89
2X 4.77
2X 7.07
2X 9.38
2X 9.63
20.50
3.74
3.37
3.24
2.50
1.87
1.25
.50
.38
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section:
Dwg: 102010100
Assignment #
Nxt: 103000000
Title: BODY SIDE PANEL DRAWING
Date:
Scale: 1:2
Drwn. By: TYLER MCCUE
Chkd. By: ME STAFF


NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
2X 3.000
2X 2.625
2X 2.375
A
2X .800
B
2X .375
2X .191
.250
2X 1.245
2X 1.250
2X 2.990
2X 3.340
3.740
4X Ø.138 THRU
4X Ø.250 THRU
4X Ø.125 THRU
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg: 102010200
SP DRAWINGS
Nxt: 103000000
Title: Chassis Front/Back
Date: 2/1/22
Scale:1:1
Drwn. By: CLAYTON ELWELL
Chkd. By:



2X .125
2X 1.060
2X .435
B
2X ⌀.250 THRU
SCALE 2:1
A
.375
1.250
2.000
SCALE 1:1
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg: 102010300
SP DRAWINGS
Nxt: 103000000
Title: Chassis L-bracket
Date: 2/1/22
Scale: 2:1
Drwn. By: CLAYTON ELWELL
Chkd. By:

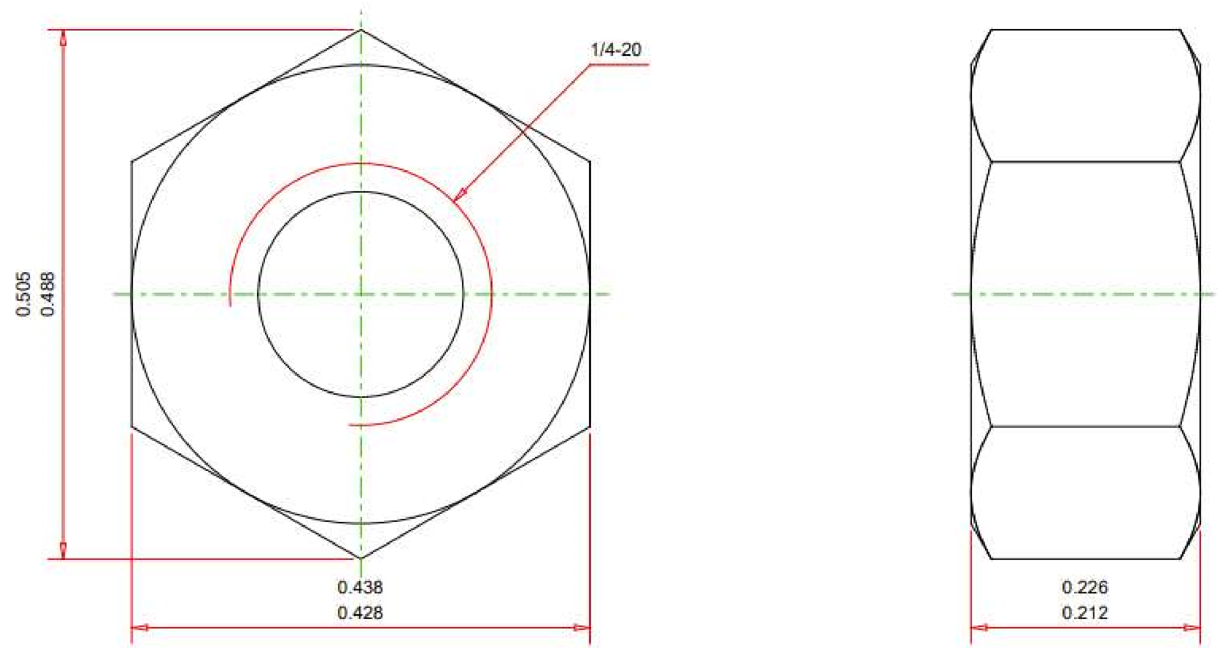

16X R.100
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: PLA
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
Ø.165 ↧ 0.223
Ø.165 ↧ 0.223
Ø.165 ↧ 0.223
.375
.375
.375
.375
.375
.375
.750
.750
.750
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg: 102010400
SP DRAWINGS
Nxt: 103000000
Title: PANEL ADAPTER
Date: 2/1/22
Scale: 3:1
Drwn. By: CLAYTON ELWELL
Chkd. By:



Units in mm
#102010400

102010600 – Top/Bottom Panel Design TBD pending internal electronics layout

#102010700

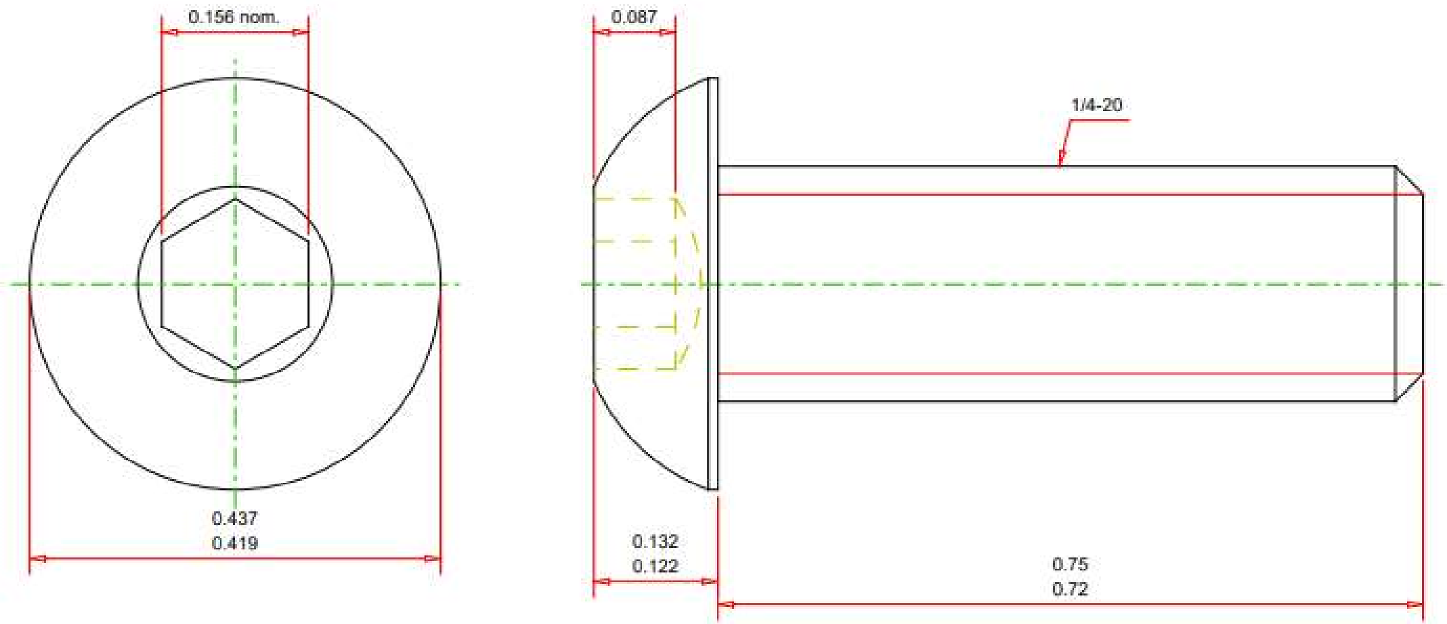


Dimensions: ASME B18.2.2
Material & Mechanical Properties: Grade A per ASTM A563
Thread Requirements: ASME B1.1, UNC, Class 2B
Finish: Fe/Zn 3AN per ASTM F1941/F1941M

PART. # : 1136102	
FHN.GRA.Z.03	
PART DESCR : 1/4-20, Finished Hex Nut, Grade A, Zinc	
NOT TO SCALE	April 5, 2021

FASTENAL®

#102010800

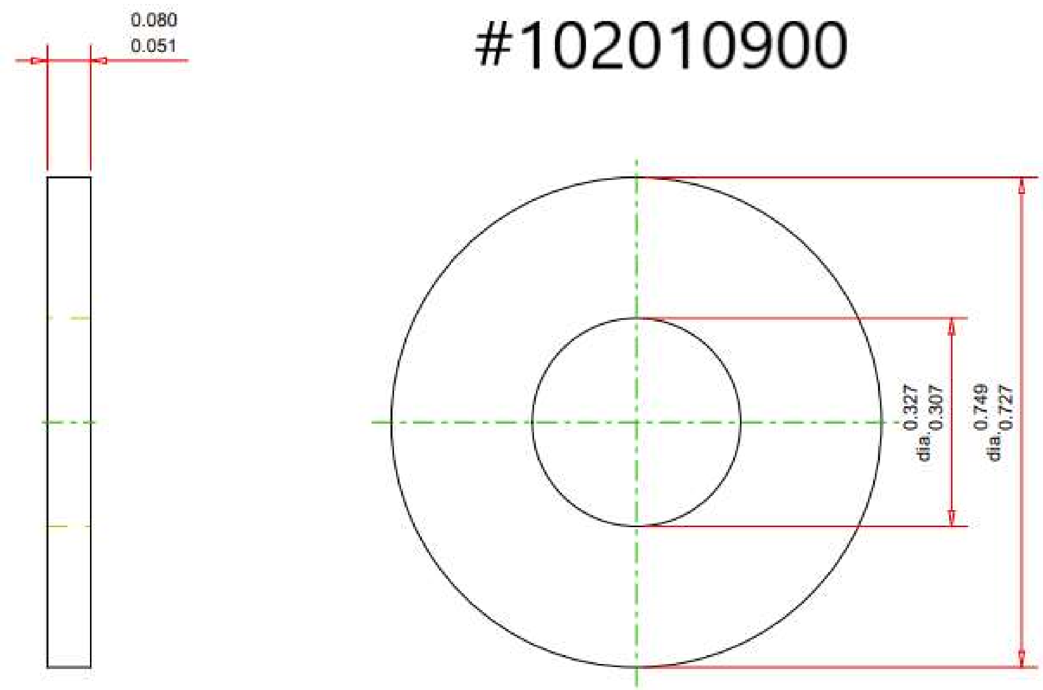


Dimensions: ASME B18.3 *Exception: FullyThreaded
Material & Mechanical Properties: 18-8 Stainless Steel, Alloy Group 1, Condition CW per ASTM F879
Thread Requirements: ASME B1.1, UNRC, Class 3A
Finish: ASTM A380/A380M

PART. # : 1173754	
BHSCS.SS.01	
PART DESCR : 1/4-20x3/4 Button Head Socket Cap Screw, Stainless Steel	
NOT TO SCALE	February 9, 2021

FASTENAL

#102010900



Dimensions: ASME B18.21.1, Type A, Wide Plain Washers
Finish: Fe/Zn 3AN per ASTM F1941/F1941M
Material: Low Carbon Steel

PART. # : 1133004

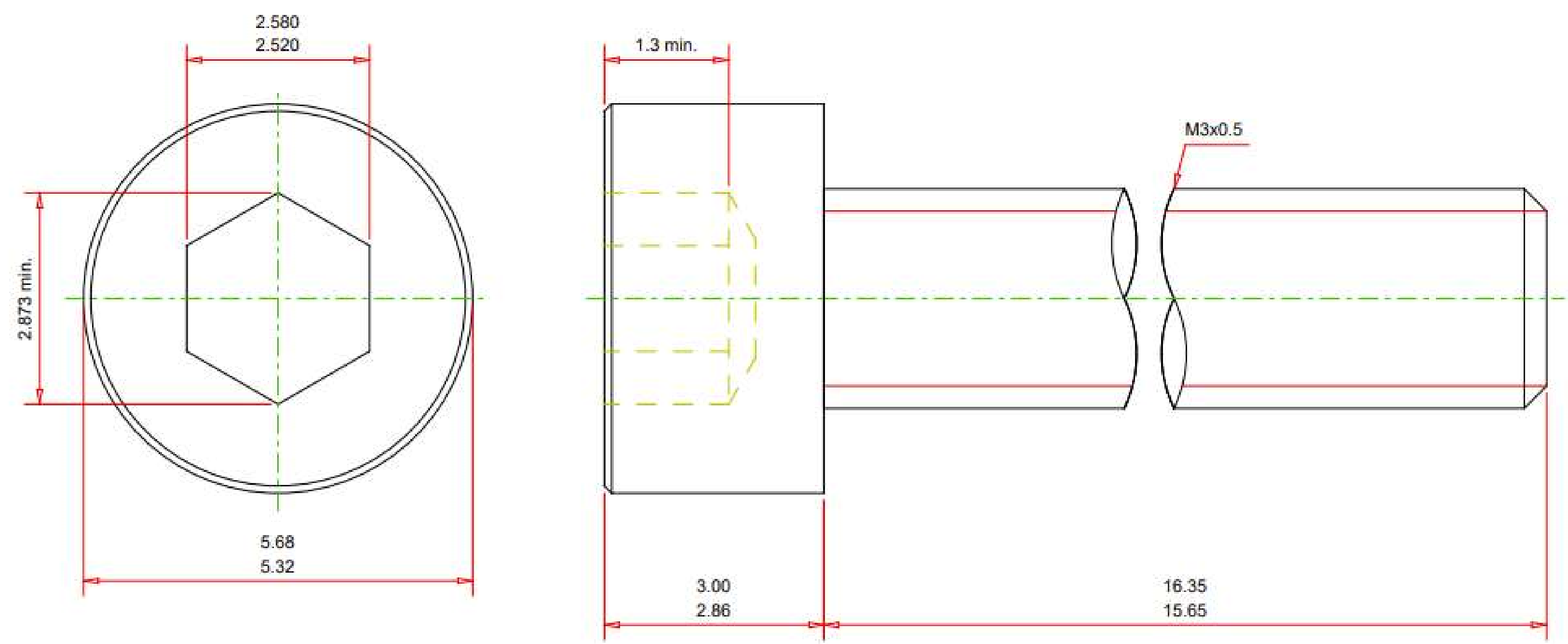
FW.LC.USS.A.Z.00

PART DESCR : 1/4, Flat Washer, Low Carbon, USS, Type A, Zinc

NOT TO SCALE | November 5, 2018

FASTENAL

#101021000

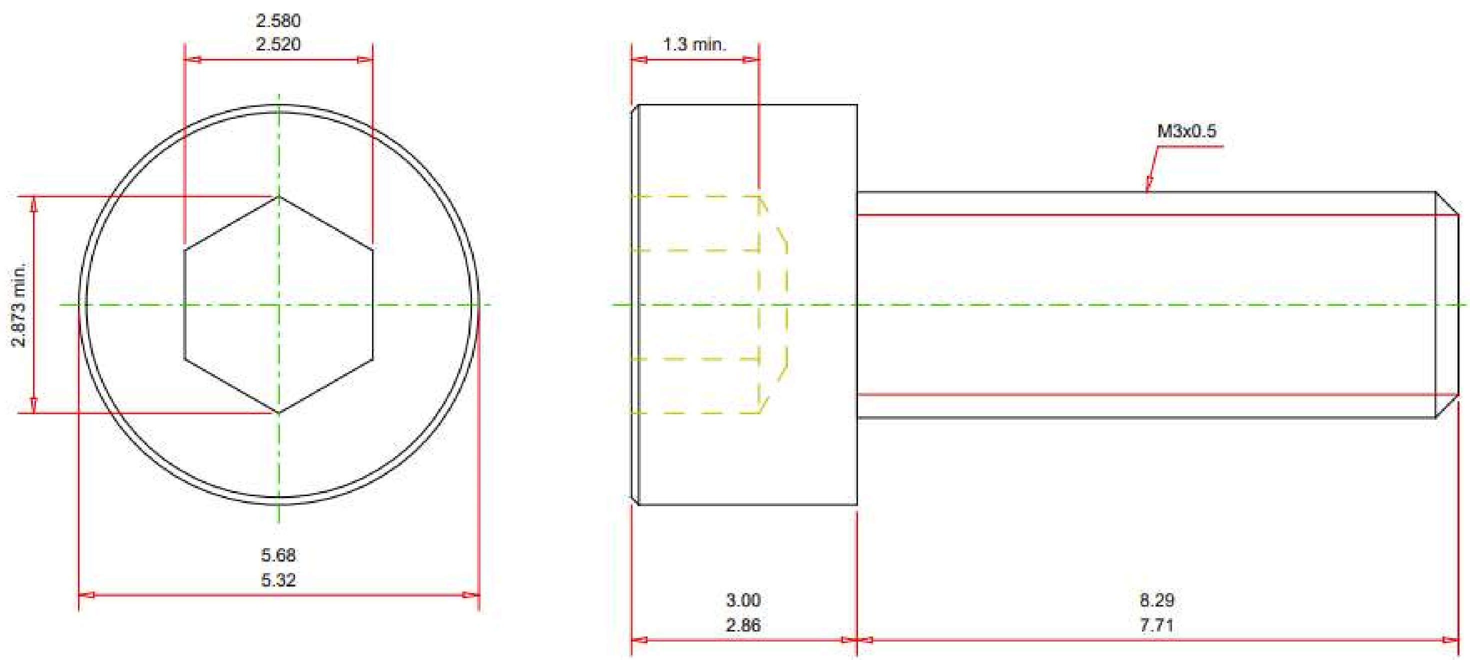


Dimensions: ISO 4762
Material & Mechanical Properties: A2-70 Stainless Steel per ISO 3506 Part 1
Finish: ASTM A380/A380M
Threads: 6g per ISO 724; ISO 965-1

PART. # : MS2510016A20000	
M.SHCS.4762.A2-70.02	
PART DESCR : M3x0.5x16, Metric, Socket Head Cap Screw, ISO 4762, A2-70 Stainless Steel	
NOT TO SCALE	August 4, 2020

FASTENAL

#102011100



Dimensions: ISO 4762
Material & Mechanical Properties: A2-70 Stainless Steel per ISO 3506 Part 1
Finish: ASTM A380/A380M
Threads: 6g per ISO 724; ISO 965-1

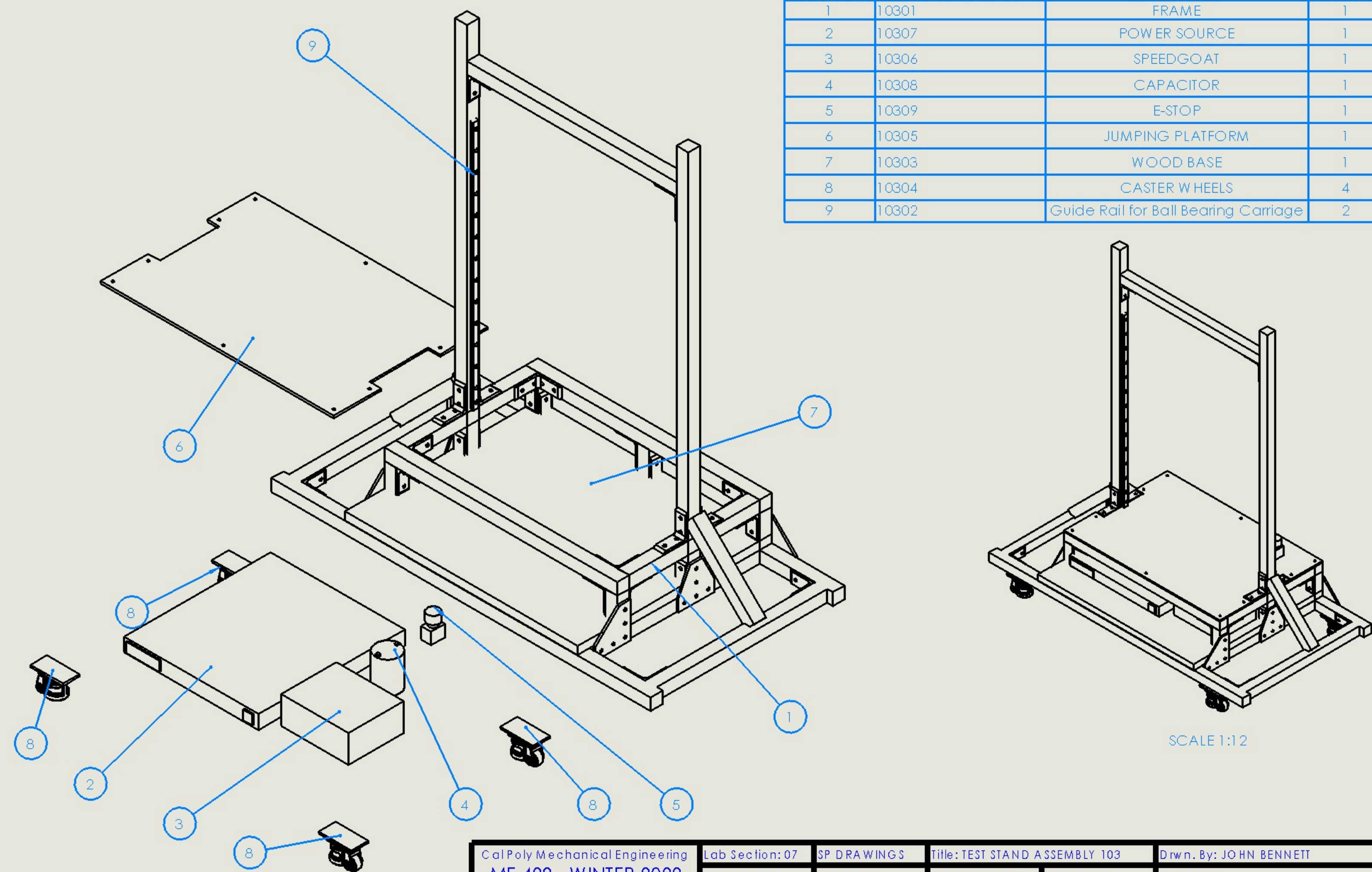
PART. # : MS2510008A20000	
M.SHCS.4762.A2-70.02	
PART DESCR : M3x0.5x8, Metric, Socket Head Cap Screw, ISO 4762, A2-70 Stainless Steel	
NOT TO SCALE	August 4, 2020

FASTENAL®

102020000 – Internal electronics TBD; part numbers not included:

102020100	Battery
102020200	STM32
102020300	Power Distribution Board
102020400	Actuators
102020500	Zip ties
102020600	Capacitor
102020700	Adhesive zip-tie mounts
102020800	GWN1.00BK25
102020900	T3609160101-000
102021000	28 AWG Wire
102021100	14 AWG Wire
102021200	Relays
102021300	Fuses
102021400	Inline fuse holders

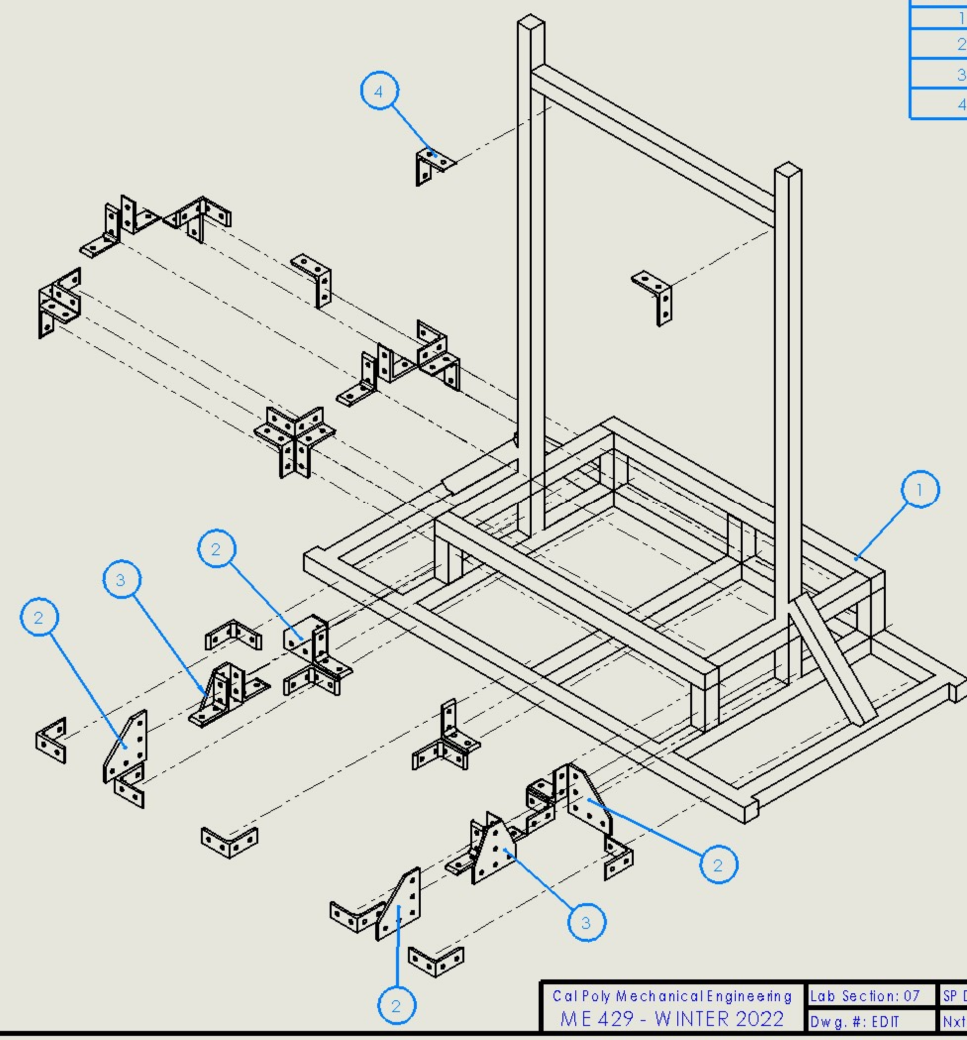
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10301	FRAME	1
2	10307	POWER SOURCE	1
3	10306	SPEEDGOAT	1
4	10308	CAPACITOR	1
5	10309	E-STOP	1
6	10305	JUMPING PLATFORM	1
7	10303	WOOD BASE	1
8	10304	CASTER WHEELS	4
9	10302	Guide Rail for Ball Bearing Carriage	2



Cal Poly Mechanical Engineering	Lab Section: 07	SP DRAWINGS	Title: TEST STAND ASSEMBLY 103	Drwn. By: JOHN BENNETT
ME 429 - WINTER 2022	Dwg. #: EDIT	Nxt Asb: 1	Date: 2/6/22 Scale:1:8	Chkd. By:

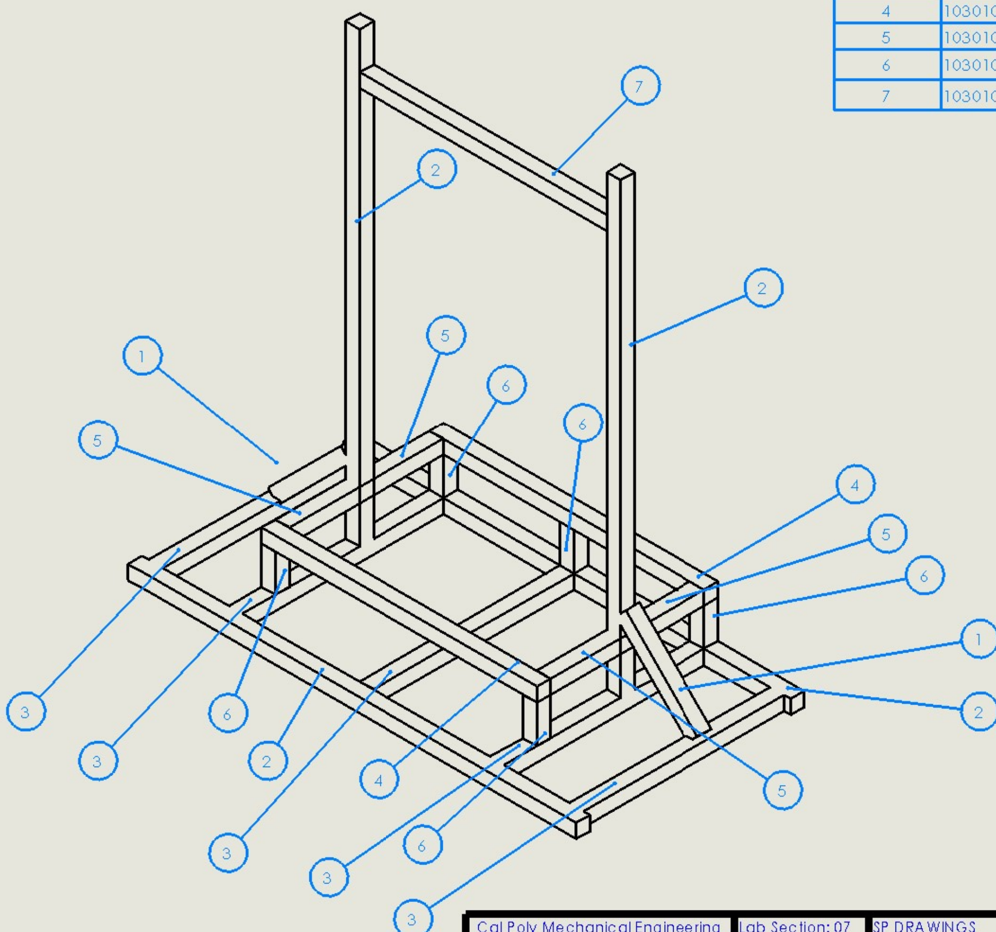
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1030101	Test Stand 8020 Frame	1
2	1030104	L-Slot Frame	4
3	1030103	T-Slot Frame	2
4	1030102	Corner Bracket	34

NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL UNNUMBERED BRACKETS ARE CORNER BRACKETS 4
2. SEE MANUFACTURING PLAN FOR ASSEMBLY STEPS
3. 1030105: M6-1.0x18mm IS NOT INCLUDED SINCE THERE ARE 156 INSTANSES; 1030106: M6 END FEED NUT IS NOT INCLUDED SINCE THERE ARE 156 INSTANSES. THESE PARTS ARE ATTACH TO ALL BRACKETS



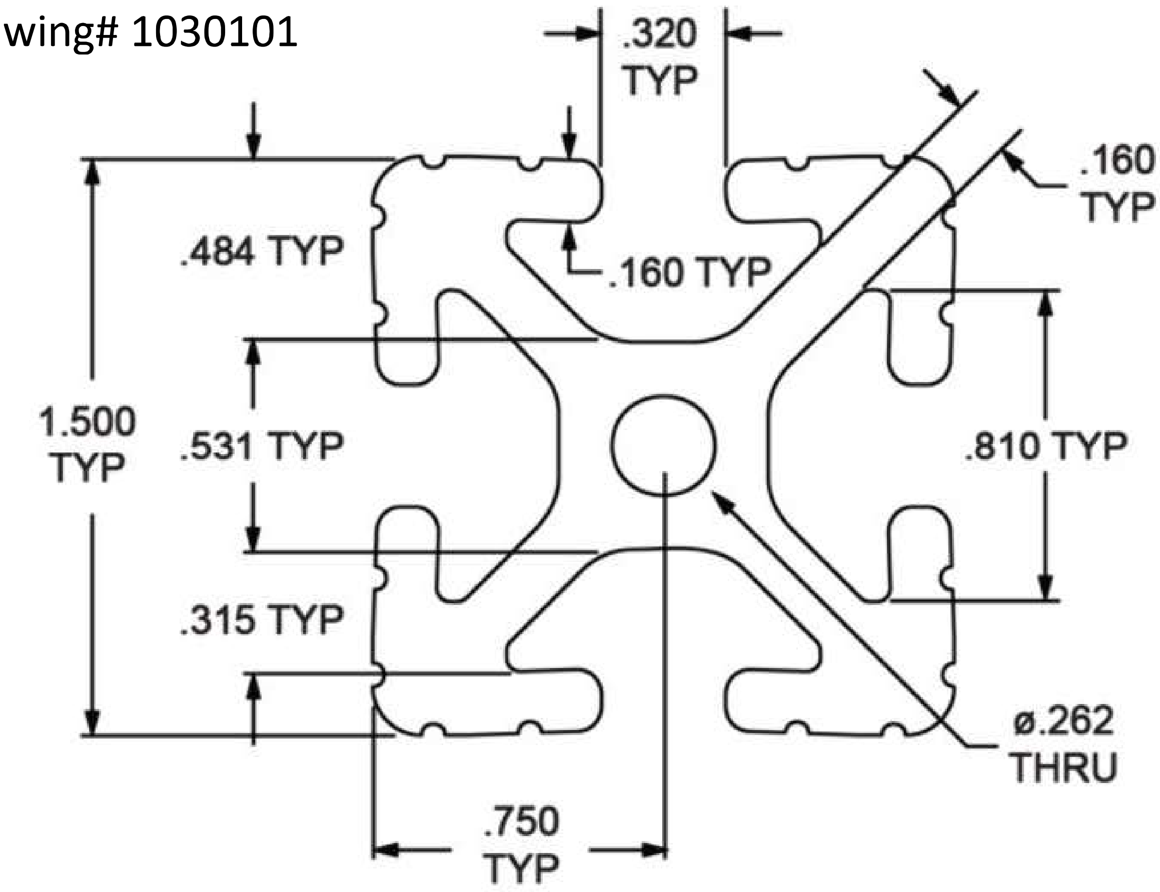
Cal Poly Mechanical Engineering ME 429 - WINTER 2022	Lab Section: 07	SP DRAWINGS	Title: TEST STAND FRAME 10301		Drwn. By: JOHN BENNETT
	Dwg. #: EDIT	Nxt Asb: 103	Date: 2/6/22	Scale:1:8	Chkd. By:

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	103010101	11" DIAGNAL SUPPORT	2
2	103010102	48"	4
3	103010103	21.5"	5
4	103010104	29.5"	2
5	103010105	7.5"	4
6	103010106	4"	5
7	103010107	26.5"	1



Cal Poly Mechanical Engineering	Lab Section: 07	SP DRAWINGS	Title: 8020 FRAME 1030101	Drwn. By: JOHN BENNETT
ME 429 - WINTER 2022	Dwg. #: EDIT	Nxt Asb: 10301	Date: 2/6/22 Scale: 1:8	Chkd. By:

Part Numbers:
#103010101 - #103010107
Note: Parts very by length,
see drawing# 1030101



Part Numbers:

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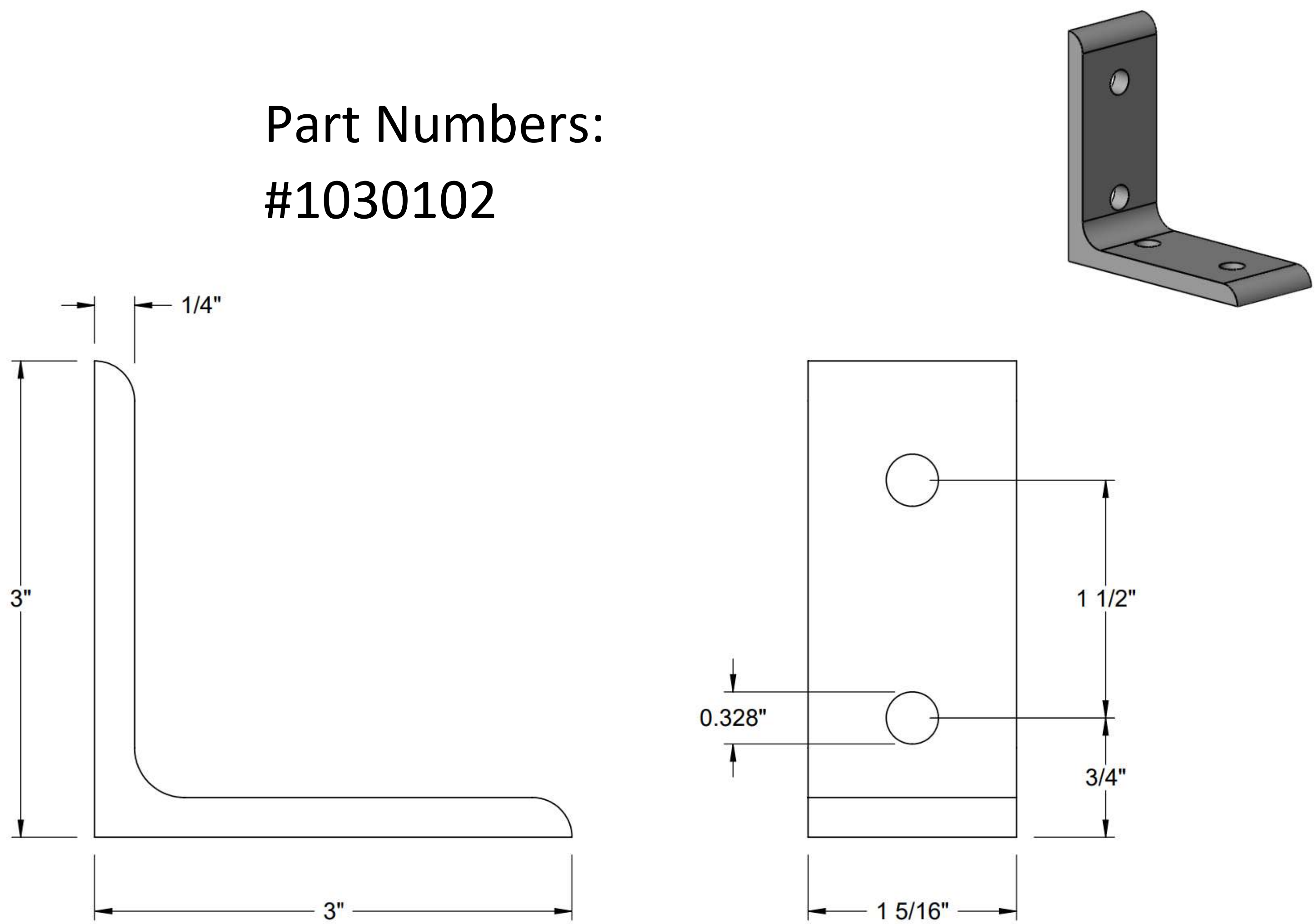


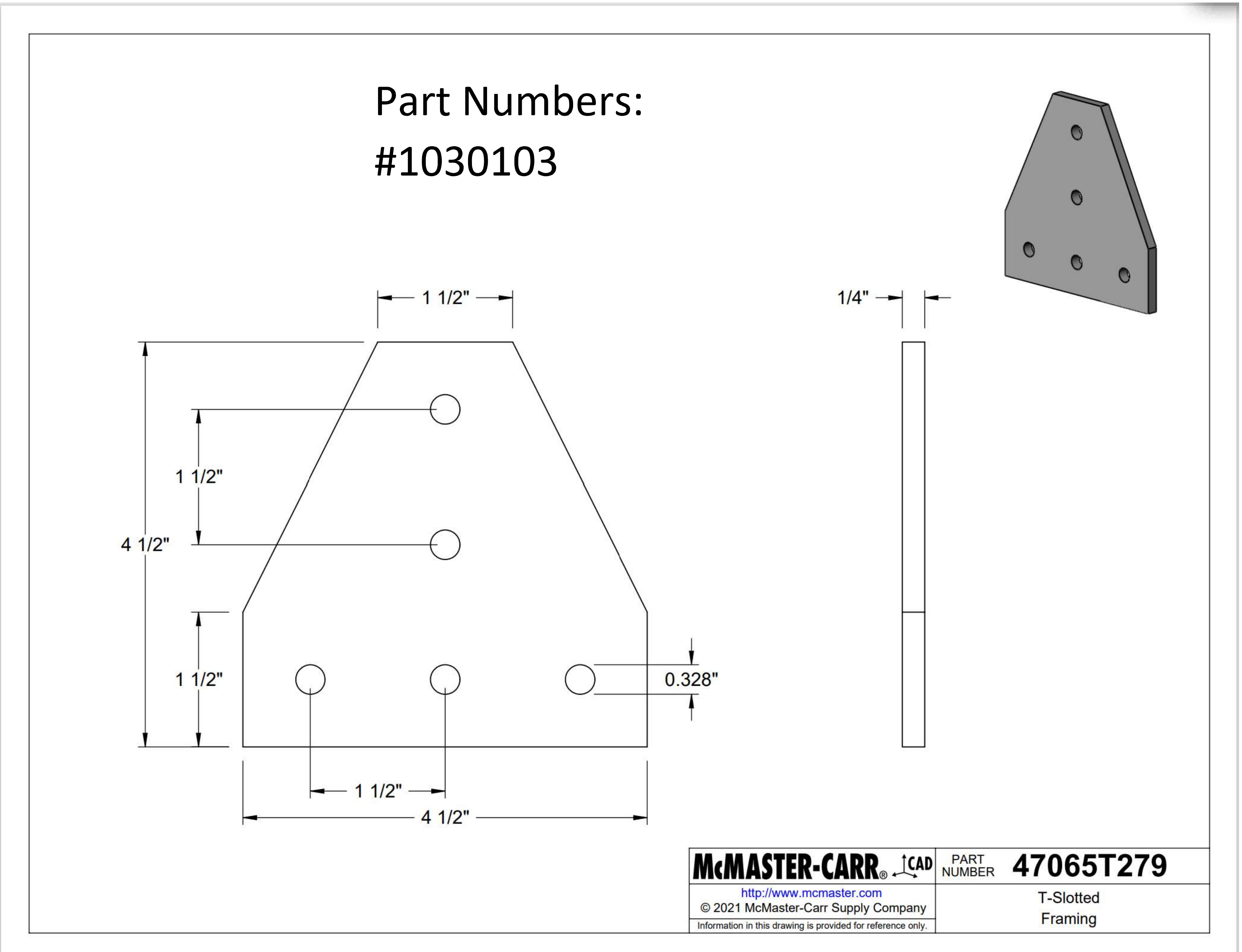
McMASTER-CARR® CAD

PART NUMBER 47065T241

http://www.mcmaster.com

Silver Corner Bracket

Part Numbers:
#1030103



Part Numbers:
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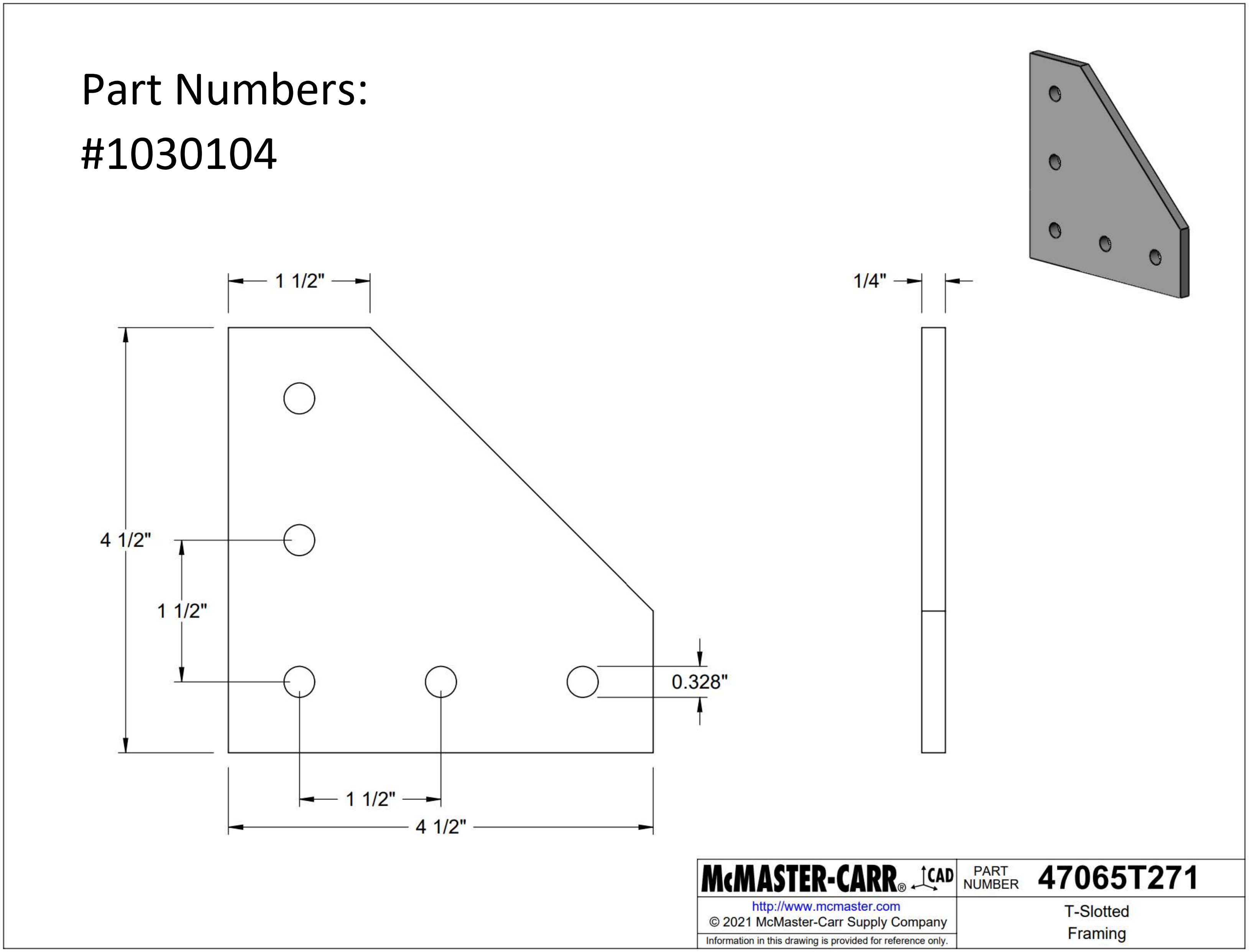

Part Numbers:
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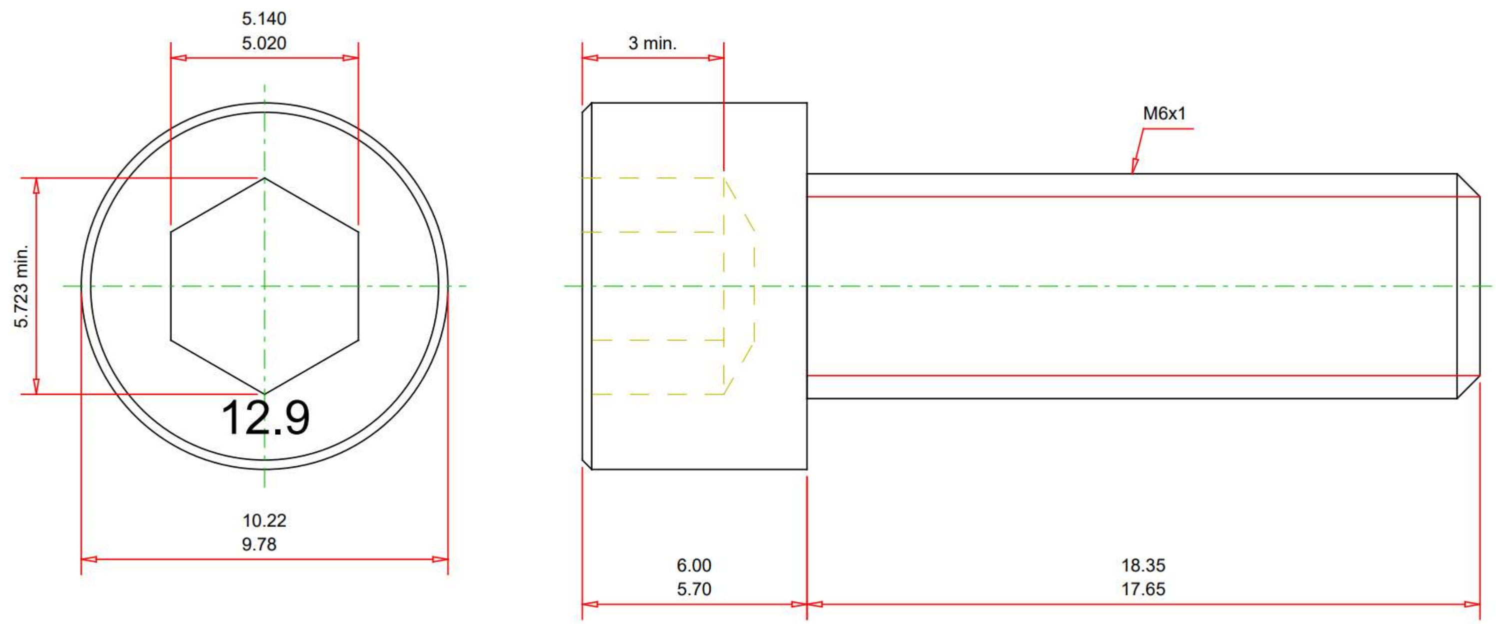
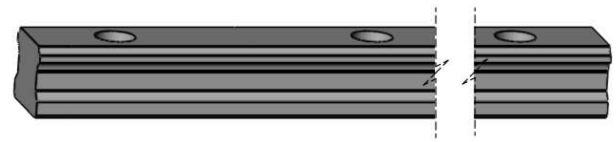


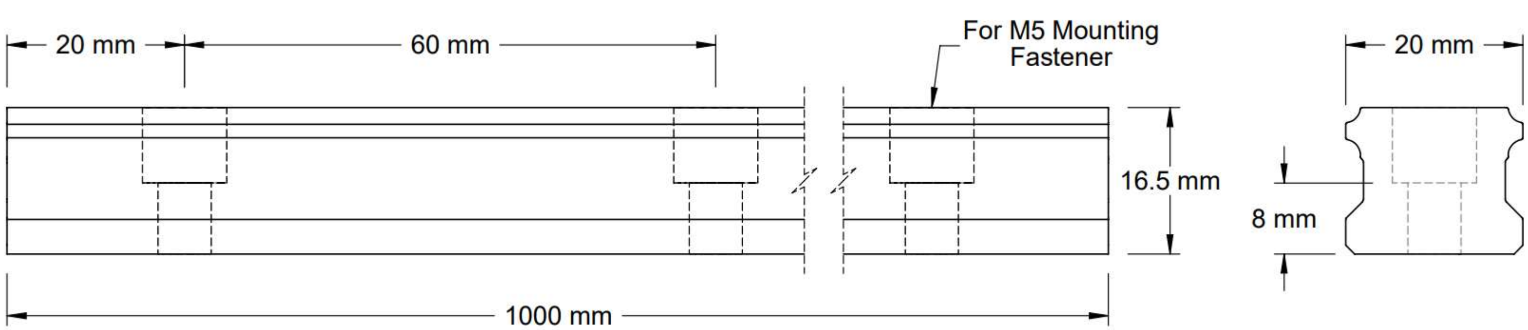
Dimensions: ISO 4762
Material & Mechanical Properties: ISO 898-1; Class 12.9
Head Marking: Manufacturer's ID and 12.9
Finish: Black Oxide (Thermal or Chemical)
Threads: 5g6g per ISO 724; ISO 965-1

PART. # : 1139582	
M.SHCS.4762.12.9.BO.01	
PART DESCR : M6x1x18, Metric, Socket Head Cap Screw, ISO 4762, Class 12.9, Black Oxide	
NOT TO SCALE	April 7, 2020

FASTENAL®

Part Numbers:
#10302

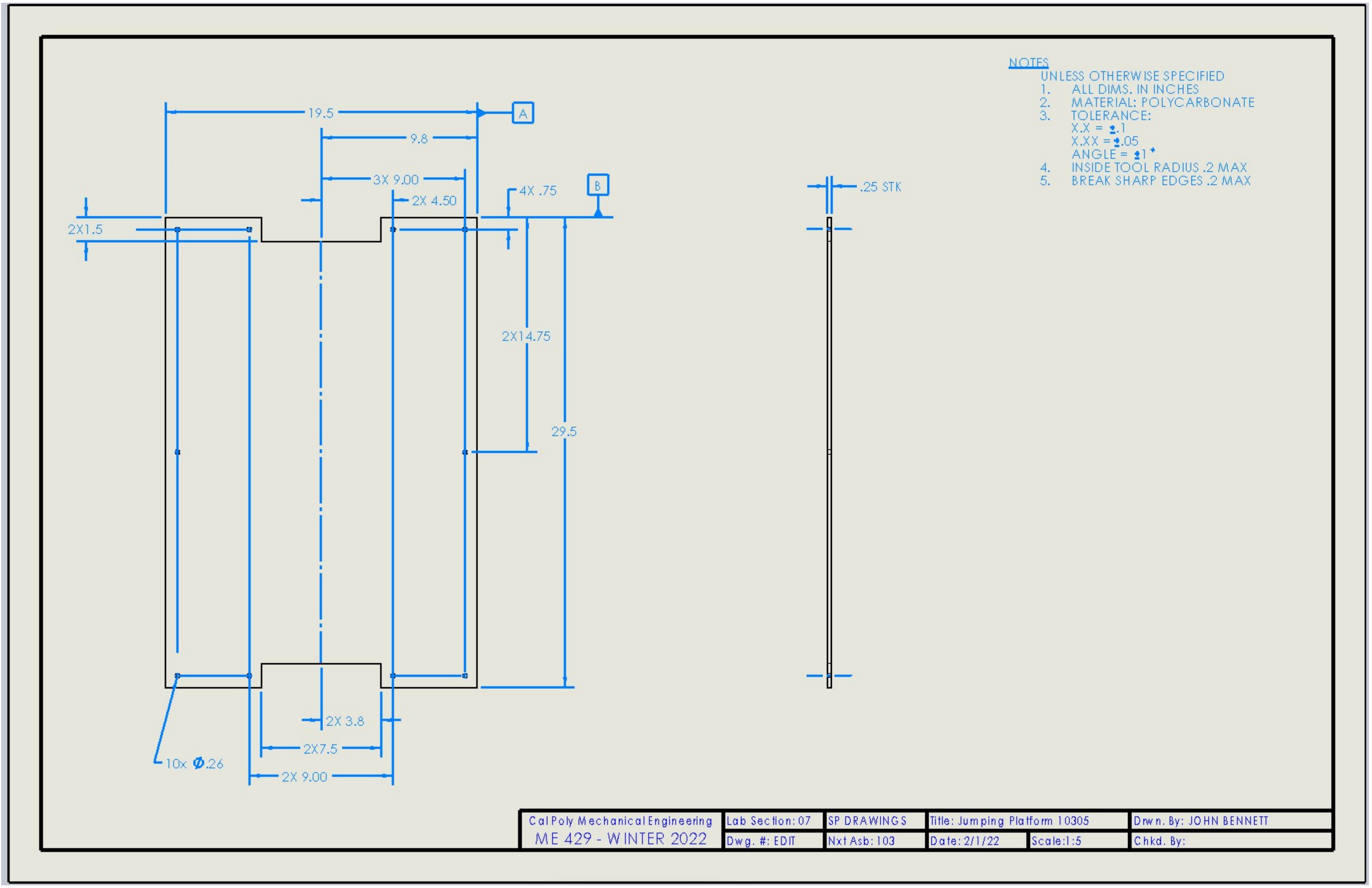




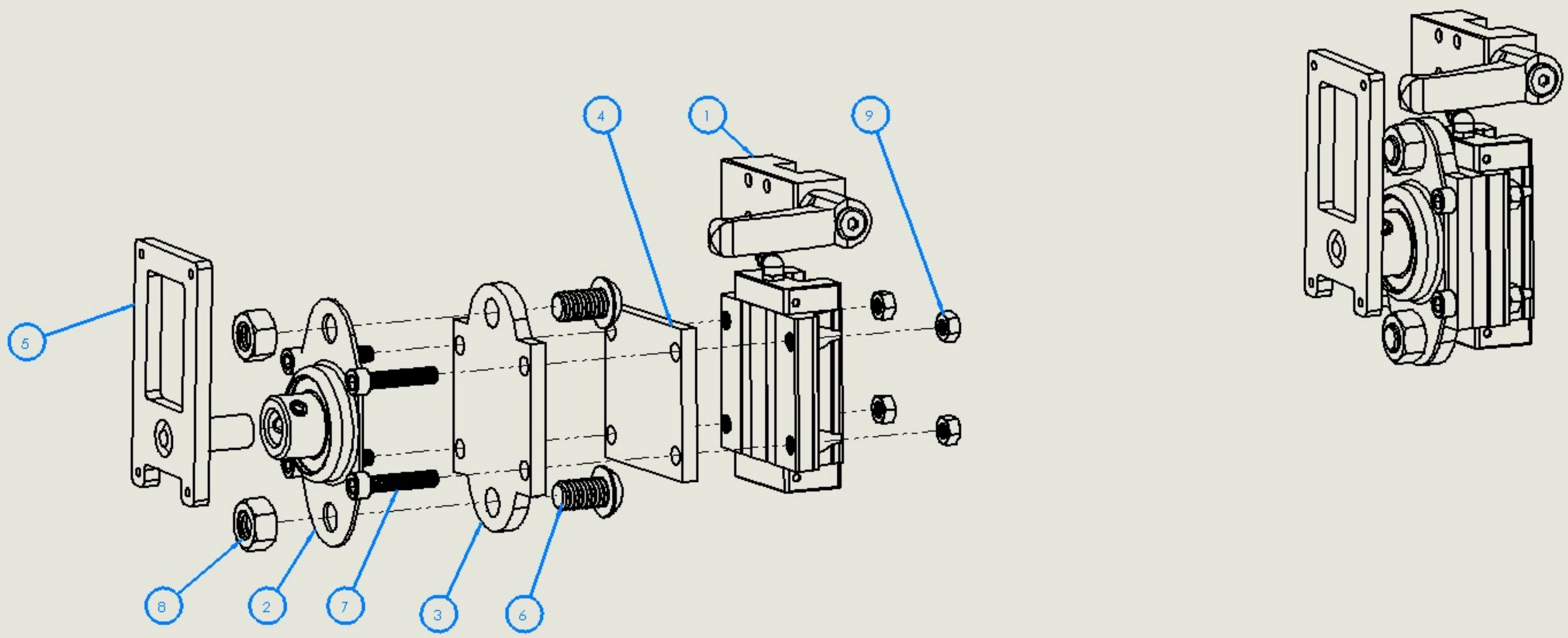
McMASTER-CARR® CAD	PART NUMBER	6688K442
http://www.mcmaster.com © 2021 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	20mm Wide x 1000mm Long Guide Rail for Quiet-Ride Ball Bearing Carriage	

Part Numbers:

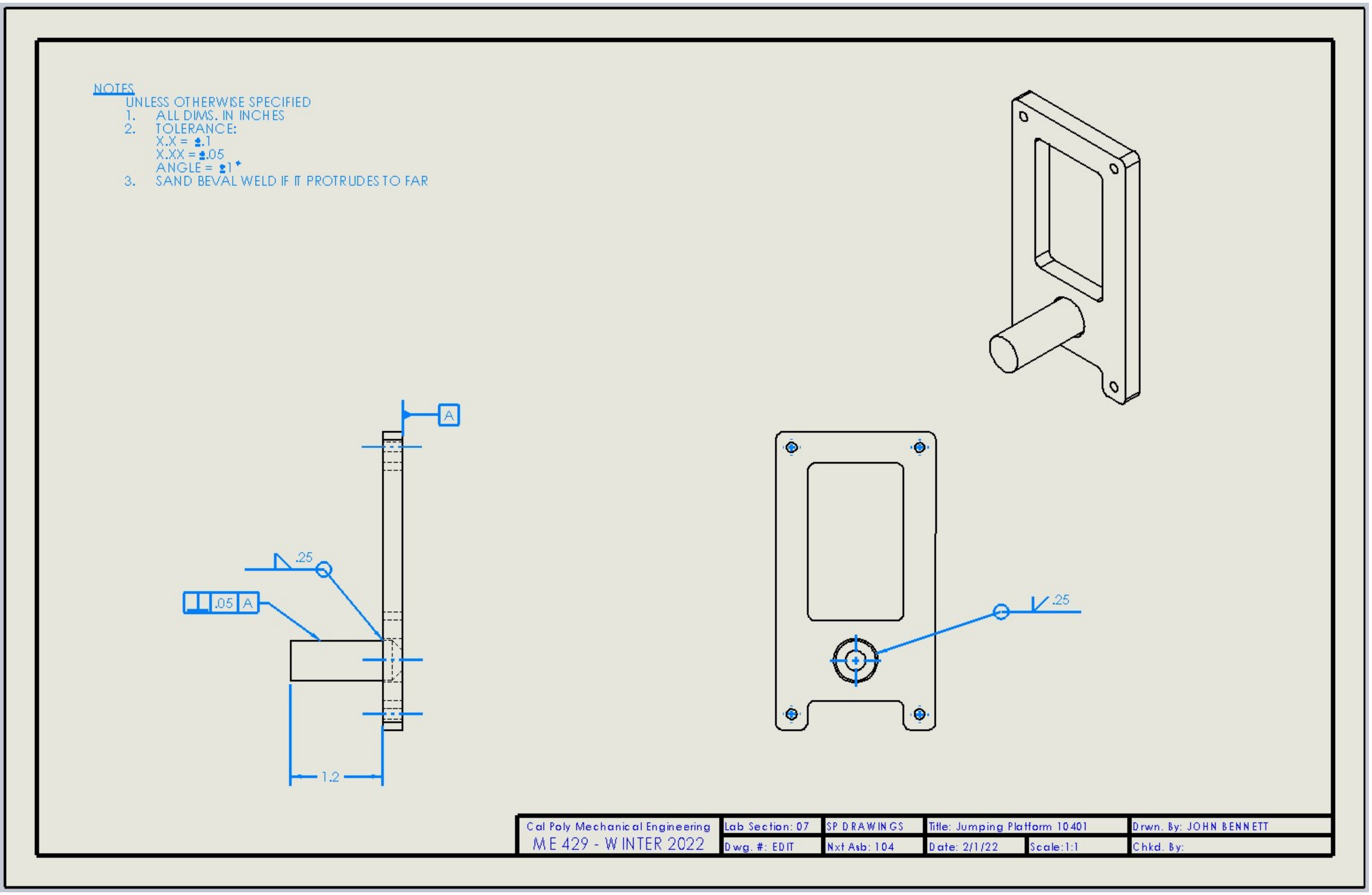
#10304

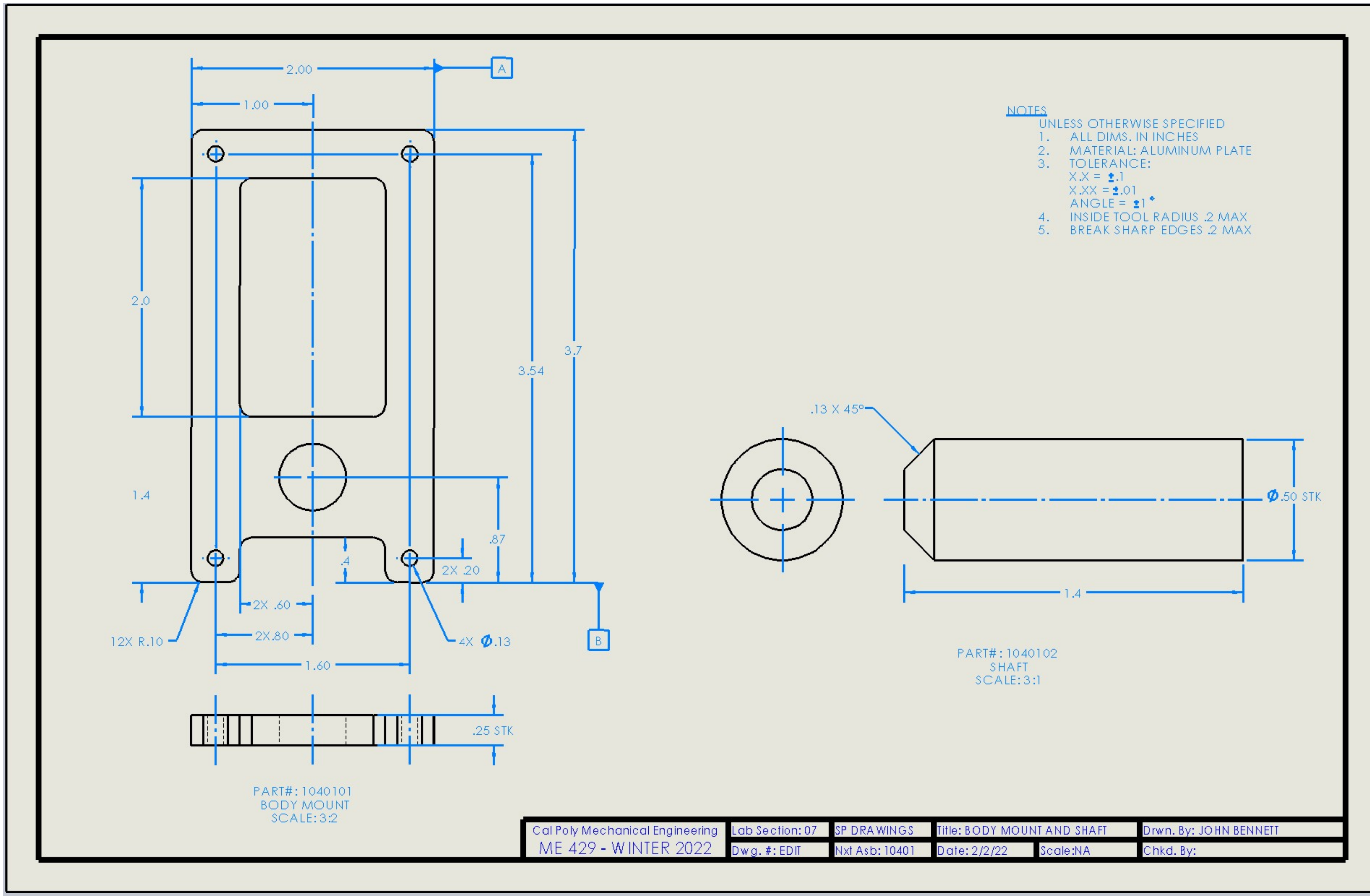

19.5
A
9.8
3X 9.00
2X 4.50
4X .75
B
2X1.5
2X14.75
29.5
.25 STK
2X 3.8
2X7.5
10x Ø.26
2X 9.00
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: POLYCARBONATE
3. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg. #: EDIT
SP DRAWINGS
Nxt Asb: 103
Title: Jumping Platform 10305
Date: 2/1/22
Scale:1:5
Drwn. By: JOHN BENNETT
Chkd. By:

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10405 & 10408	CARRIAGE AND HAND BREAK	1
2	10402	Mounted Ball Bearing	1
3	10403	MOUNT BACKING PLATE	1
4	10404	SPACER PLATE	1
5	10401	BODY MOUNT AND SHAFT	1
6	10407	7/16" HEX DRIVE SCREW	2
7	10406	M6x1 HEX DRIVE SCREW	4
8	10409	7/16" HEX NUT	2
9	10410	M6x1 HEX NUT	4

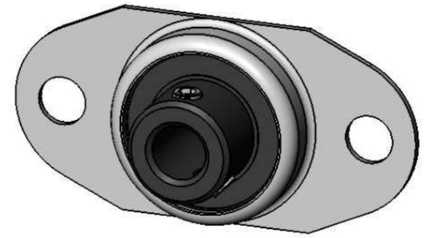


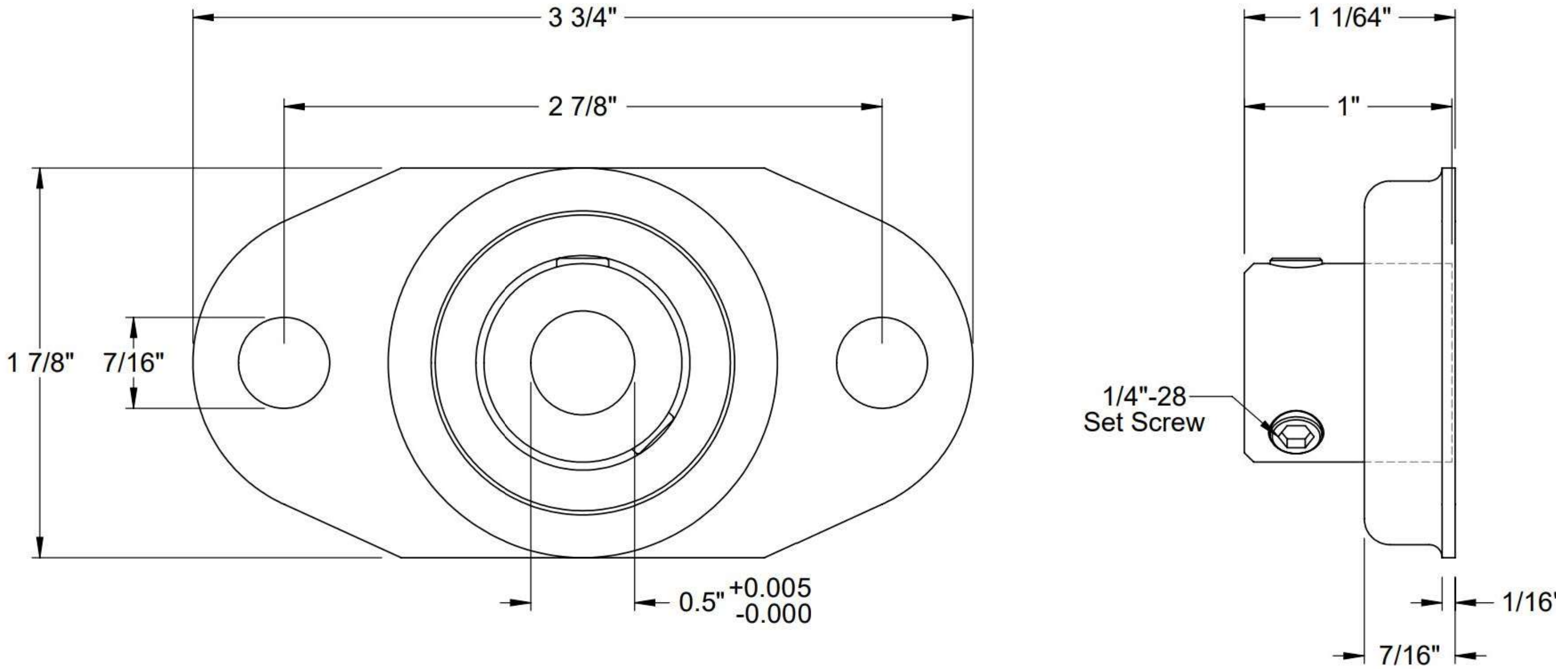
Cal Poly Mechanical Engineering	Lab Section: 07	SP DRAWINGS	Title: TEST STAND MOUNT 104	Drwn. By: JOHN BENNETT
ME 429 - WINTER 2022	Dwg. #: EDIT	Nxt Asb: 1	Date: 2/6/22 / Scale: 2:3	Chkd. By:


NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. TOLERANCE:
X.X = ±.1
X.XX = ±.05
ANGLE = ±1°
3. SAND BEVAL WELD IF IT PROTRUDES TO FAR
A
.25
.05 A
1.2
.25
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg. #: EDIT
SP DRAWINGS
Nxt Asb: 104
Title: Jumping Platform 10401
Date: 2/1/22
Scale: 1:1
Drwn. By: JOHN BENNETT
Chkd. By:


2.00
A
1.00
2.0
1.4
3.54
3.7
.87
.4
2X .20
2X .60
2X.80
1.60
12X R.10
4X Ø.13
B
.25 STK
PART#: 1040101
BODY MOUNT
SCALE: 3:2
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM PLATE
3. TOLERANCE:
X.X = ±.1
X.XX = ±.01
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
.13 X 45°
Ø.50 STK
1.4
PART#: 1040102
SHAFT
SCALE: 3:1
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg. #: EDIT
SP DRAWINGS
Nxt Asb: 10401
Title: BODY MOUNT AND SHAFT
Date: 2/2/22
Scale:NA
Drwn. By: JOHN BENNETT
Chkd. By:

Part Numbers:
#10402



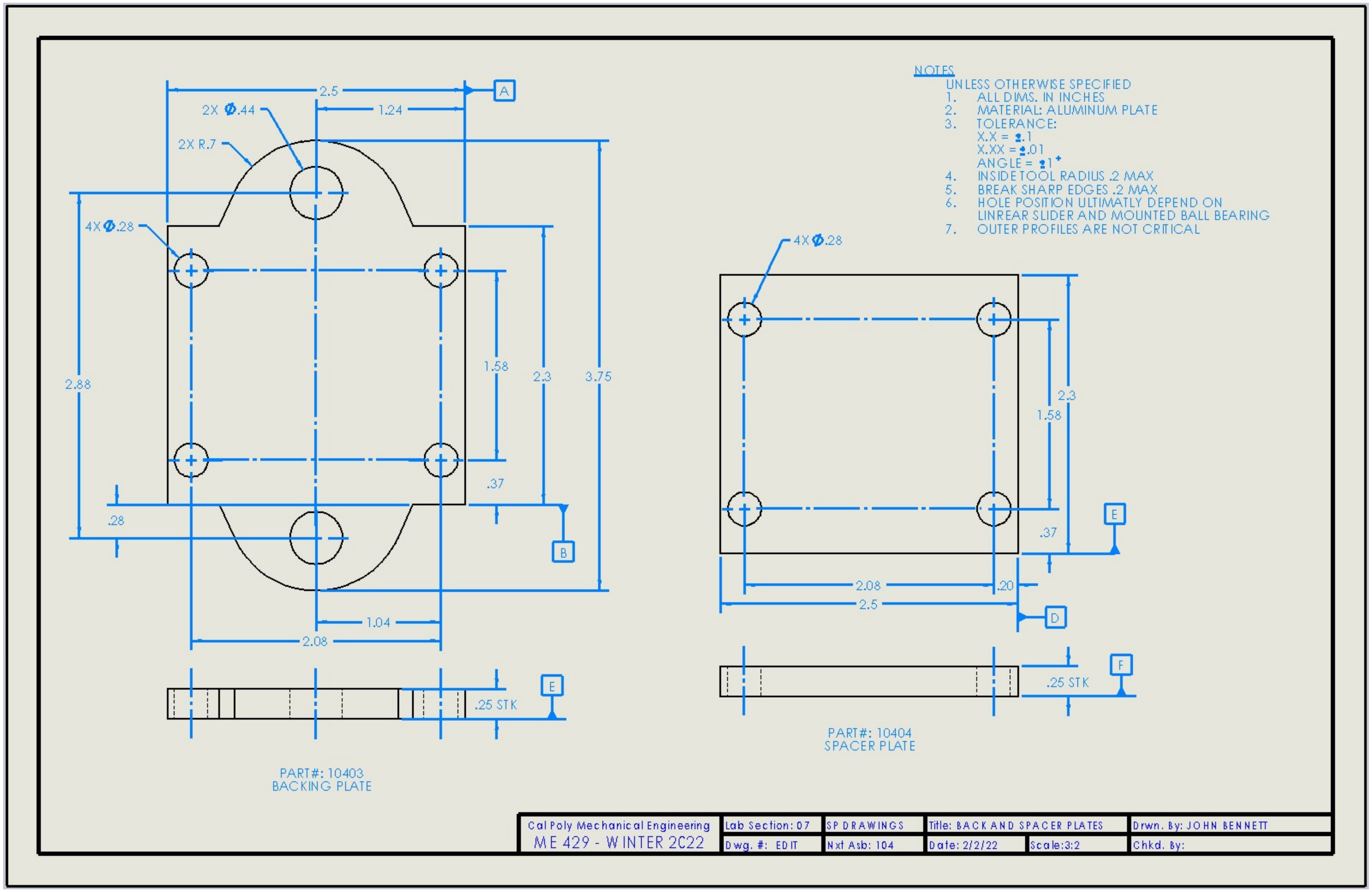


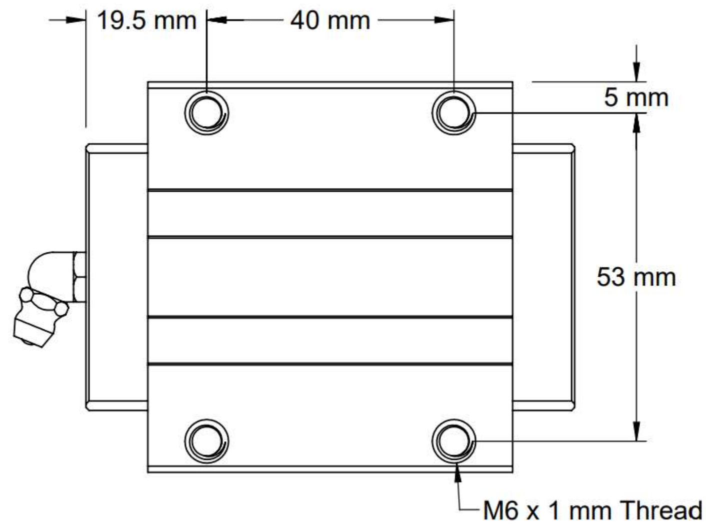
McMASTER-CARR® CAD

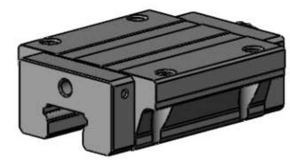
http://www.mcmaster.com

PART NUMBER **7208K52**

Low-Profile Mounted Sealed Steel Ball Bearing


NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS. IN INCHES
2. MATERIAL: ALUMINUM PLATE
3. TOLERANCE:
X.X = ±.1
X.XX = ±.01
ANGLE = ±1°
4. INSIDE TOOL RADIUS .2 MAX
5. BREAK SHARP EDGES .2 MAX
6. HOLE POSITION ULTIMATLY DEPEND ON LINREAR SLIDER AND MOUNTED BALL BEARING
7. OUTER PROFILES ARE NOT CRITICAL
2.5
1.24
A
2X Ø.44
2X R.7
4X Ø.28
2.88
1.58
2.3
3.75
.37
.28
B
1.04
2.08
.25 STK
E
PART#: 10403
BACKING PLATE
4X Ø.28
2.3
1.58
.37
E
2.08
.20
2.5
D
.25 STK
F
PART#: 10404
SPACER PLATE
Cal Poly Mechanical Engineering
ME 429 - WINTER 2022
Lab Section: 07
Dwg. #: EDIT
SP DRAWINGS
Nxt Asb: 104
Title: BACK AND SPACER PLATES
Date: 2/2/22
Scale: 3:2
Drwn. By: JOHN BENNETT
Chkd. By:





Part Numbers:
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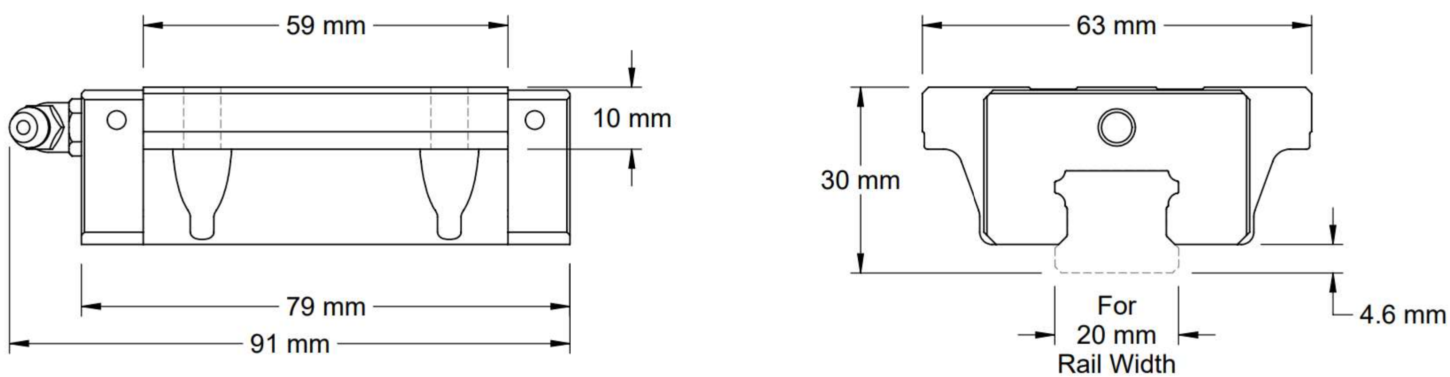
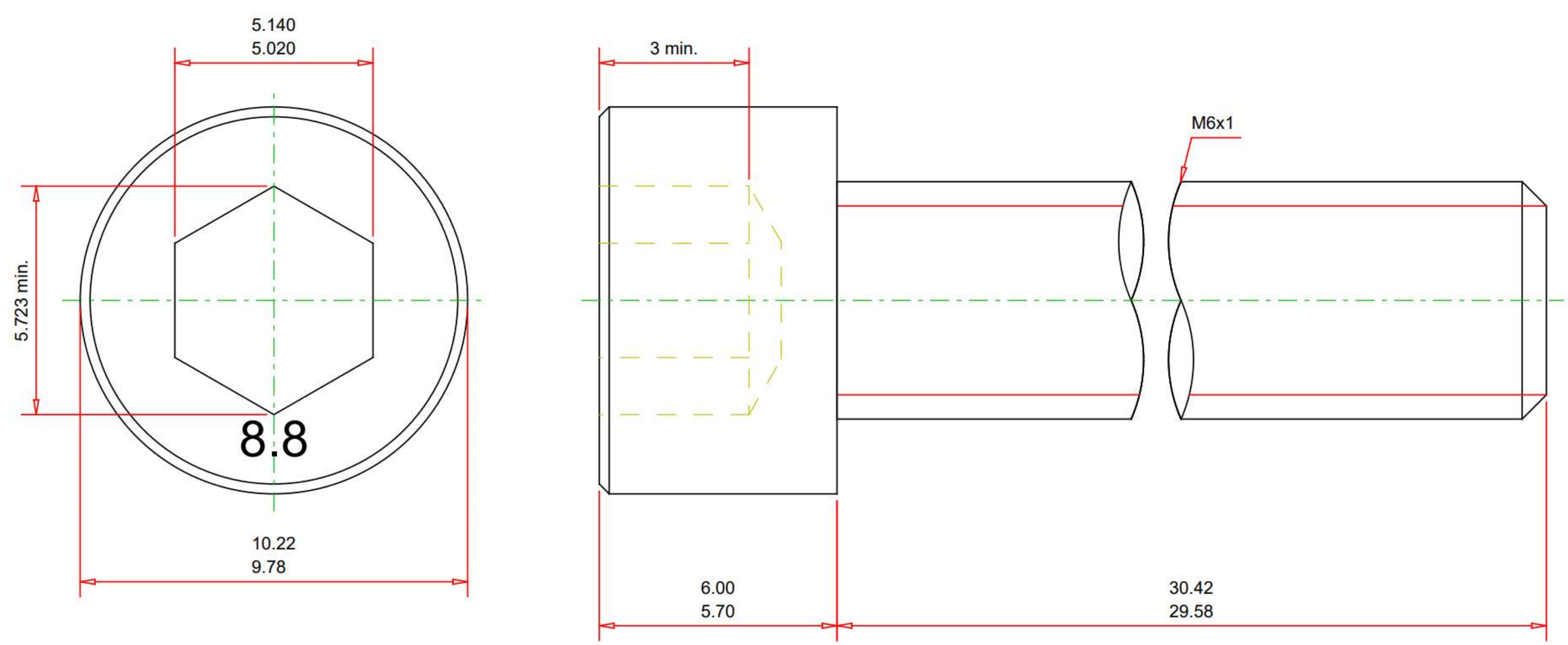


McMASTER-CARR® CAD	PART NUMBER	6688K22
http://www.mcmaster.com © 2021 McMaster-Carr Supply Company Information in this drawing is provided for reference only.		Ball Bearing Carriage

Part Numbers:
#10406



Dimensions: ISO 4762
Material & Mechanical Properties: ISO 898-1; Class 8.8
Head Marking: Manufacturer's ID and 8.8
Finish: Black Oxide (Thermal or Chemical)
Threads: 6g per ISO 724; ISO 965-1

PART. # : 11103346	
M.SHCS.4762.8.8.BO.02	
PART DESCR : M6x1x30, Metric, Socket Head Cap Screw, ISO 4762, Class 8.8, Black Oxide	
NOT TO SCALE	February 25, 2020

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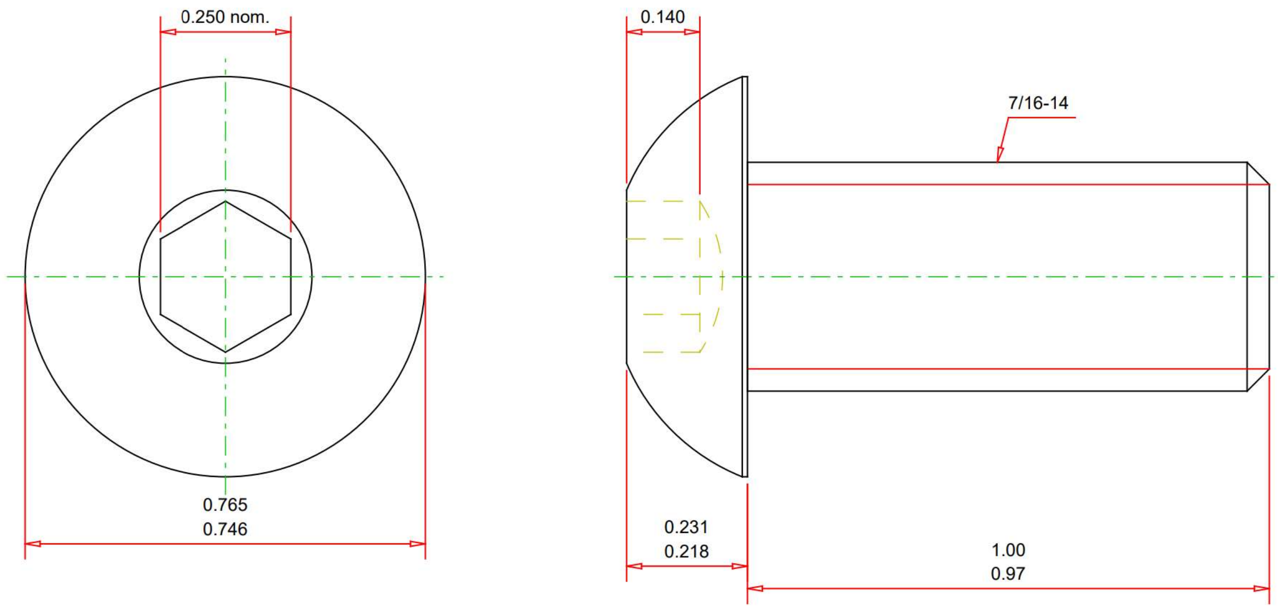
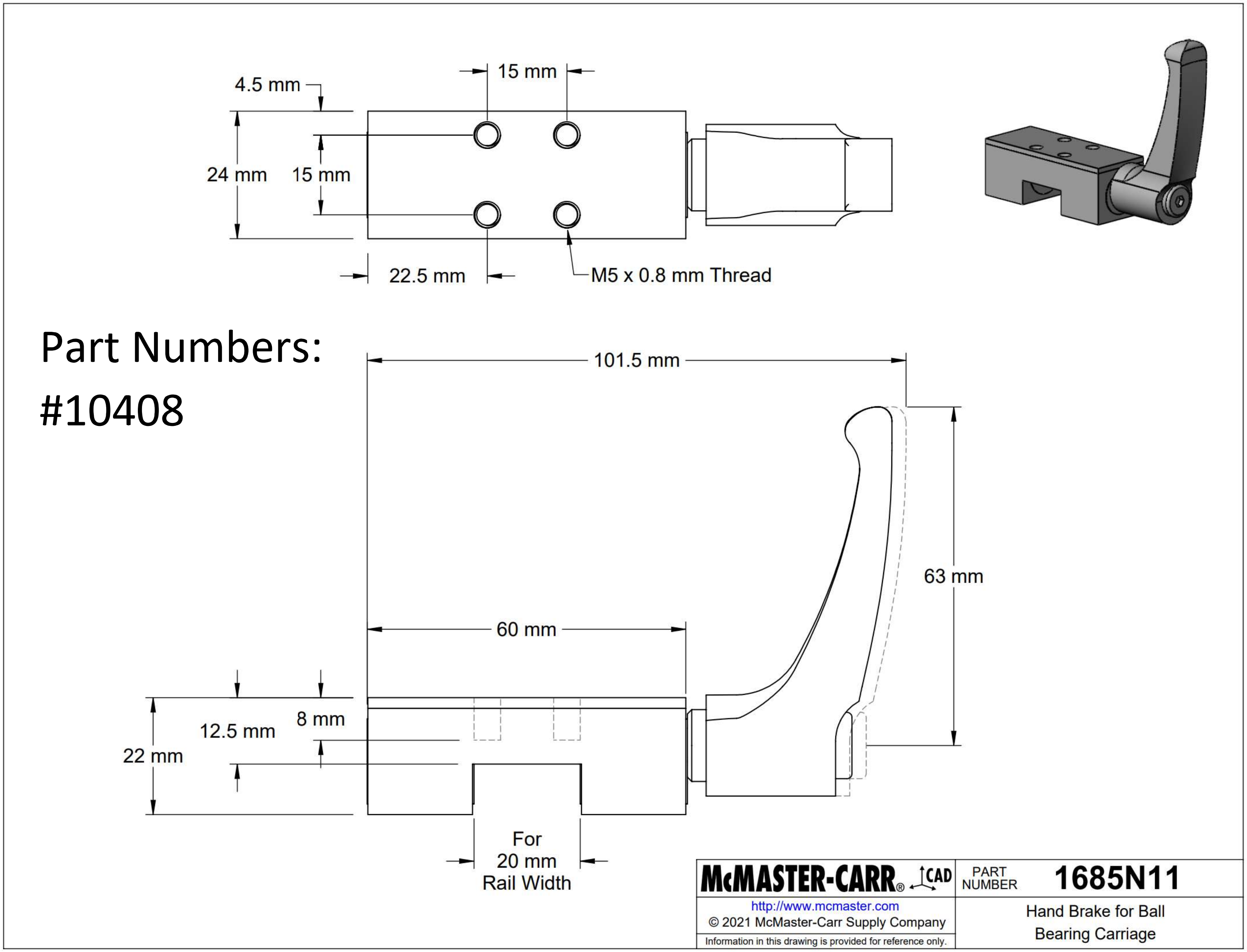
Part Numbers:
#10407

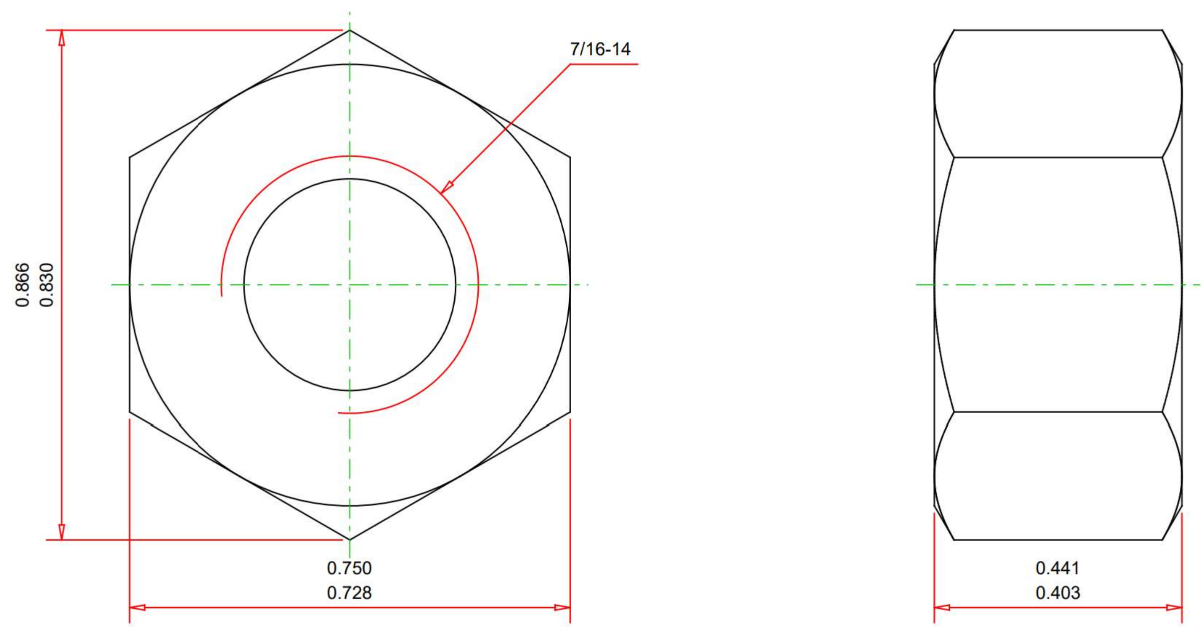


Dimensions: ASME B18.3 *Exception: Fully Threaded
Material & Mechanical Properties: ASTM F835
Thread Requirements: ASME B1.1, UNRC, Class 3A
Finish: Black Oxide (Thermal or Chemical)
Product Marking: Manufacturer's ID
Hardness: 37 to 44 HRC

PART. # : 0154547	
BHSCS.ALLOY.BO.02	
PART DESCR : 7/16-14x1 Button Head Socket Cap Screw, Alloy Black Oxide	
NOT TO SCALE	December 13, 2018

Part Numbers:
#10408





Part Numbers:

#10409

Dimensions: ASME B18.2.2
Material & Mechanical Properties: Grade 2H per ASTM A194/A194M and ASME SA194/SA194M
Thread Requirements: ASME B1.1, UNC, Class 2B
Finish: Light Protective Oil
Product Marking: Manufacturer ID and 2H (or 2HB when manufactured from bar stock)

PART. # : 36498	
HHN.A194.2H.P.00	
PART DESCR : 7/16-14, Heavy Hex Nut, ASTM A194/A194M and ASME SA194/SA194M, Grade 2H, Plain	
NOT TO SCALE	January 11, 2018

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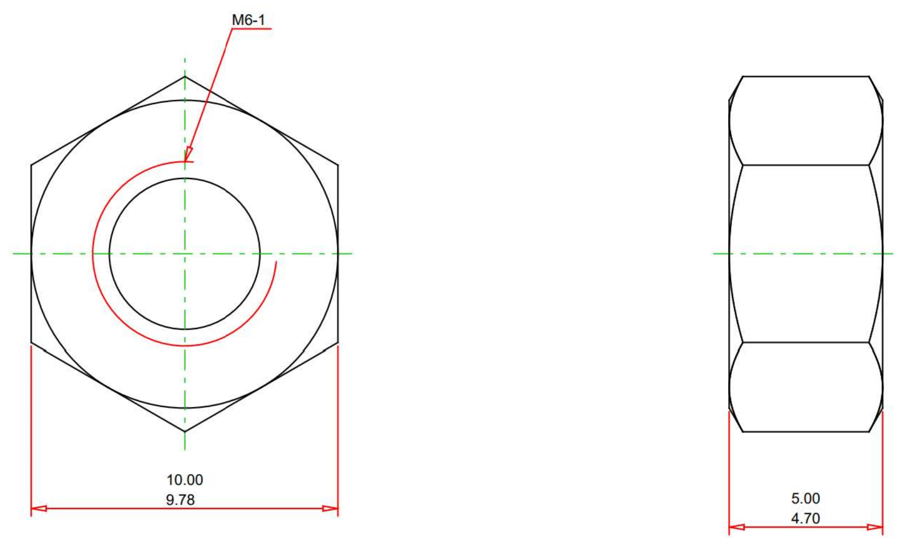


Part Numbers:

#10410

Dimensions: DIN 934
Material & Mechanical Properties: All nuts shall meet the material and all mechanical requirements of DIN 267, Part 4; using the tensile stress area and the hardness of Class 8.
**Except that nuts larger than M39 shall have a hardness of 30 HRC maximum
Finish: Light Protective Oil
Threads: 6H per ISO 724; ISO 965-1
Product Marking: Manufacturer ID and Class 8 per DIN 267 Part 4 on M5 nominal diameter and larger

PART. # : 40154	
M.FHN.934.8.P.01	
PART DESCR : M6-1.00, Metric, Finished Hex Nut, DIN 934, Class 8, Plain	
NOT TO SCALE	April 8, 2020

FASTENAL®

8 DOF Quadrupedal Hopping Robot

Final Design Review

June 3, 2021

Spring 2022 ME 430-05 Group F72

The B.R.U.C.E. Bot Engineers

Tyler McCue Daniel Munic

Clayton Elwell John Bennett

Technical Assistance: Henry Bouma

8dofseniorproject@gmail.com

Prepared for Dr. Siyuan Xing and Charlie Refvem

Department of Mechanical Engineering

California Polytechnic State University, San Luis Obispo

sixing@calpoly.edu crefvem@calpoly.edu

Table of Contents

1. Design Updates

There were minimal mechanical updates to our design since CDR; however, we dramatically reduced the scope of our electrical system to ensure that we were able to conduct vertical leap testing with the quadruped.

Addressing the mechanical changes, we first shortened the length of the upper link in the leg to properly tension the timing belt. Since we change the size of the knee gear, the belt would need to be longer to be properly tensioned. However, the timing belt length that we needed is not standard. Thus, we decided to shorten the upper link to properly tension the belt. The correct upper link length is 7.85 inches. In addition, we changed how the chassis panels are fastened together. We originally planned to use custom made L-brackets to fasten the chassis panels, and 3D printed connectors for the panels that connect to the electronics. Our engineering intuition told us that the L-brackets were not robust enough to endure the stresses seen during jumping. Thus, we swapped the L-brackets and plastic adapters for 1”x1” aluminum struts that are cut to 3.75”, which is the height of the chassis. We tapped the top and bottom holes of these struts to connect the electronics panel, which we made from polycarbonate since we had extra stock left over and hadn’t yet ordered the proper aluminum stock. The quadruped also looks cooler with the polycarbonate panel.

Regarding the electronic system updates, we eliminated the power distribution board (PDB), on-board power (in the form of batteries), and the new controller in C or C++. Delays with the power distribution board resulted in an inability to use the on-board batteries and prevented us from starting the development of the controller in C/C++. However, despite these challenges we found solutions to our design challenge that utilized our MATLAB/Simulink controller, an external power supply, and a much simpler internal electronic system that consists of a large capacitor for motor over-current protection and a perfboard that sends CAN messages to each actuator. This new electronic system was much simpler to develop and gave us the extra time that we needed to manufacture the mechanical portion of our project and conduct the necessary testing to verify the functionality of our controller and mechanical system.

2. Manufacturing

This section explains our manufacturing process for our verification prototype. We discuss procurement, manufacturing for each subsystem and the overall assembly process. Reference Appendix B for final list of expenses.

2.1 Material Procurement

Our part procurement process consisted of purchasing parts through Dr. Xing directly, using funds acquired from the CP Connect grant program, and purchases made by teammates and reimbursements by Dr. Xing. Additionally, Charlie Refvem provided a variety of fasteners, end nuts, and many electrical components.

The majority of our system’s components were purchased by Dr. Xing, through online vendors. We used McMaster for the reasonably priced test stand components, B&B steel for the chassis aluminum, MatterHackers for thermoplastic filament, Amazon for an array of components, and AliExpress for the actuators.

Our CP Connect application requested funding for the expensive components on the test stand, and funding to reimburse the money spent on the actuators. The expensive components on the test stand are the guide rails and their corresponding ball bearing carriages, as well as the hand brake that is used to fix the ball bearing carriage's location on the guide rail. Other components that were purchased using the CP Connect funding include the polycarbonate sheet that comprises the test stand base, and various brackets and lengths of aluminum struts used to construct the test stand. These components were initially purchased by Dr. Xing and reimbursed using the CP Connect funding.

Charlie Refvem has been an invaluable resource for small fasteners and electrical components that are often inconvenient to specify online, or even find online. A list of all the items provided to us is highlighted in Appendix B, the final project budget.

2.2 Manufacturing Process

In this section the manufacturing processes and any outsourcing is outlined for each subsystem in detail.

2.2.1 Legs

We outsourced most of the 3D printing to a graduate student, Craig Kimball, because he has an excellent 3D printer that can extrude all the types of filaments that we need. The adapters between each actuator are printed from polycarbonate referred to as PC (Figure 1).

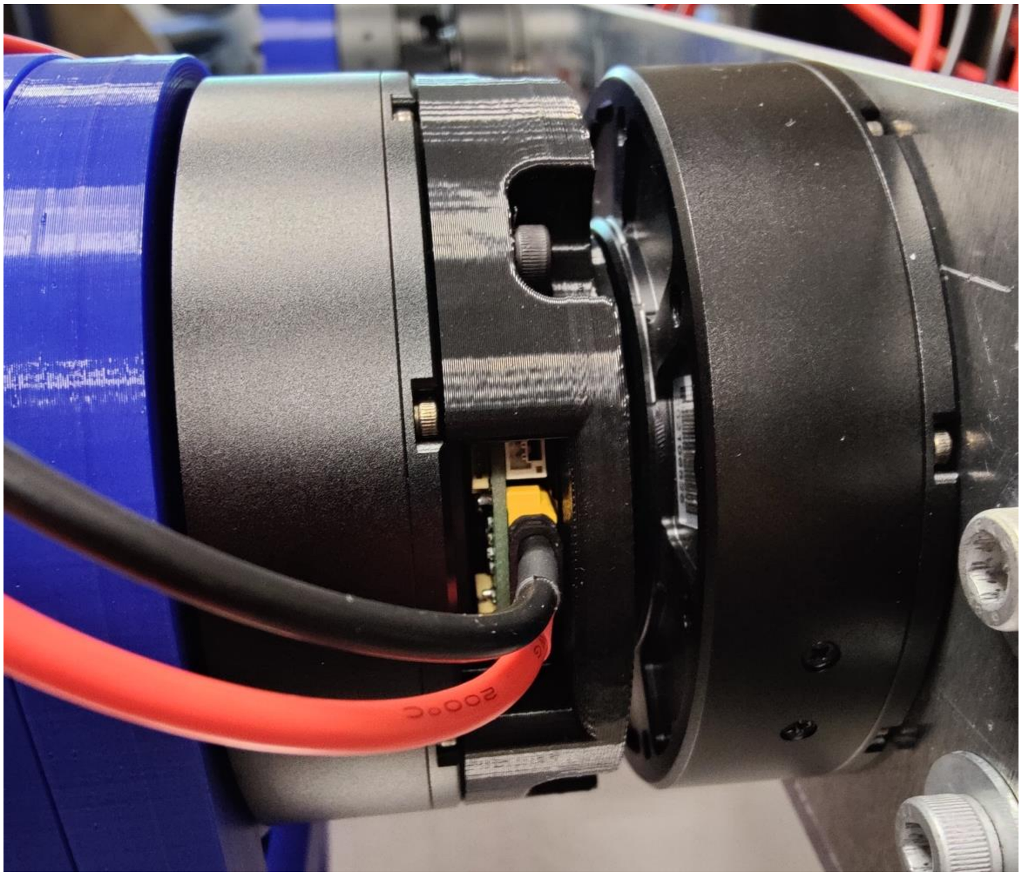


Figure 1: Polycarbonate Actuator Adapter.

The feet are printed from TPU and PLA (eventually PC, but we are currently experiencing printer issues when extruding TPU and PC). TPU is a rubber filament that has ideal friction and damping properties (Figure 2). We originally intended to print the upper links in polycarbonate as well, but we ended up doing our testing with PLA upper links (Figure 3) due to a shortage of time after multiple print fails with the polycarbonate upper links. The PLA upper links showed no signs of wear. However, this summer we plan to reattempt printing the upper links in polycarbonate, with more finely tuned printer settings.

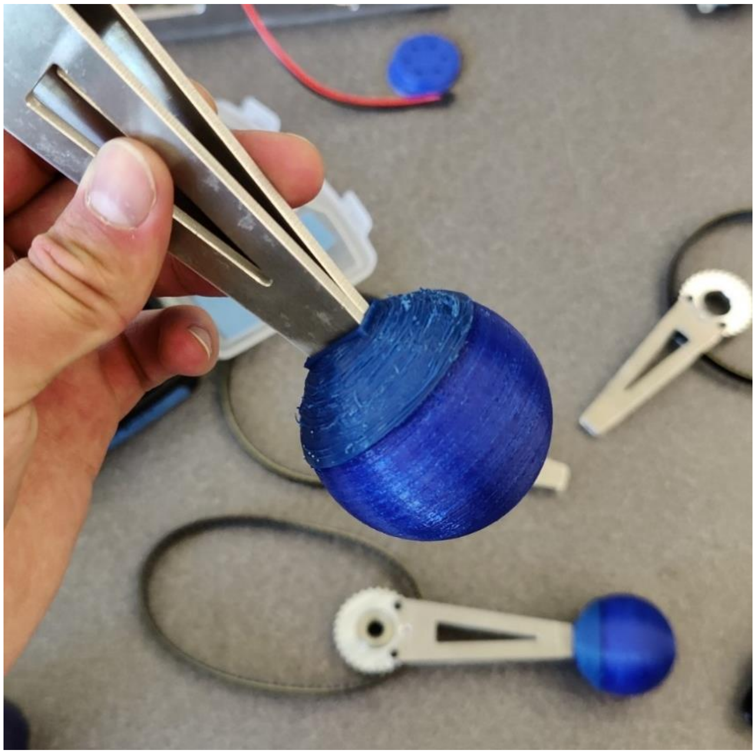


Figure 2: Feet.

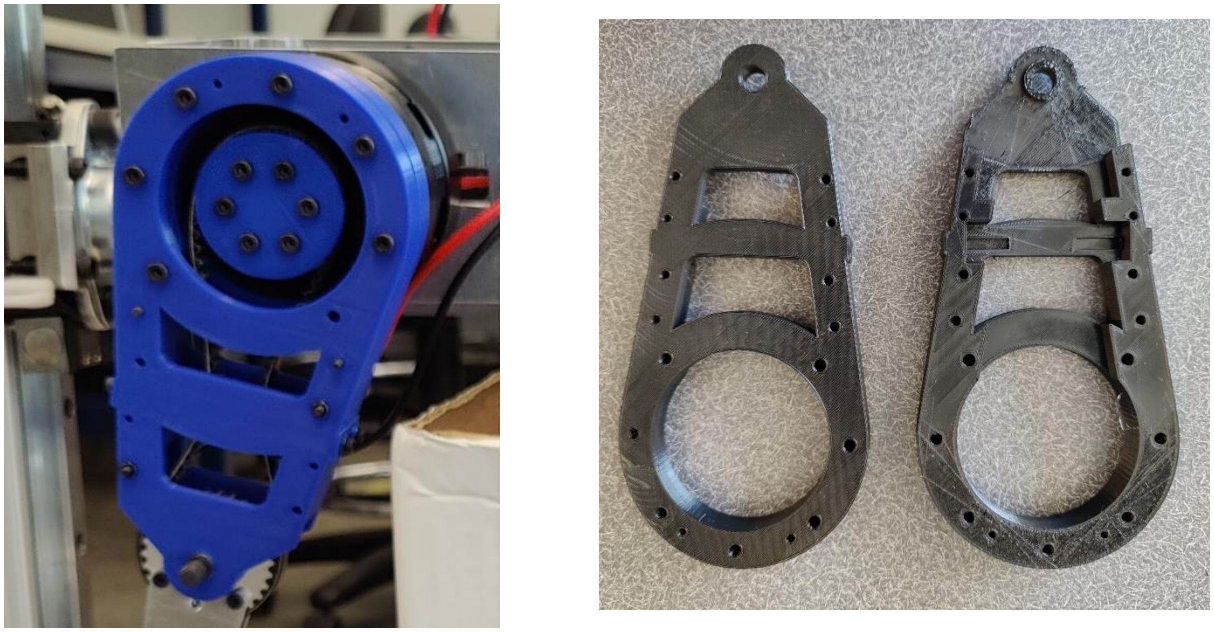


Figure 3: Upper links – PLA on the left and PC on the right (warping not easily visible)

Before the manufacturing of the metal components on the quadruped is discussed, it is imperative to highlight the amount of time spent deburring holes, edges, and any other sharp leftovers of a manufacturing process. This ended up being a time-consuming process but is necessary to ensure that operators of the system are not sliced or cut while assembling our system.

The pulleys in the leg were ordered from Misumi, and post-machined to our system's specifications. Figure 3 displays our hip pulleys; our system's timing belts are 9 mm wide, but the smallest pulley size that Misumi supplies is for 15 mm wide belts. So, we had to machine these pulleys down to a 10 mm width; this operation was done on a lathe for the hip pulleys.

Figure 4: Hip pulleys after being faced to a 10 mm width.

The six holes and center bore in Figure 4 were specified in our order from Misumi.

The knee pulleys also needed to be machined down to a 10 mm width and needed additional machining so that they may interface with the lower link and upper link. We specifically needed a transition fit to put a bearing in the center of the knee pulley and needed three holes in a circular pattern to fasten to the lower links. Figure 5 displays the hip pulleys before R6 bearings were inserted into the center bore.

Figure 5: Knee pulleys after post-processing.

The facing, bearing press fit bore, and three-hole pattern operations were generously done by Colin Reay on the Mustang 60 Haas mill. After Colin's help, the three-hole pattern was tapped on each pulley to interface with a #6-32 fastener. The pulleys were then bathed in isopropyl alcohol to clean the chips and tap oil off them.

The lower links were cut using a waterjet at Mustang 60, then cleaned and deburred as seen in Figure 6. After that the links were then bent in a vice. To bend the lower links to the appropriate angles a jig was used to locate the correct angle and was marked with a scribe. The part was then put in a vice at the line and bent into shape using a rubber mallet. Once bent the angle was checked with a go-no go gauge. The process was then repeated until all lower links were at the correct angle and in a slight z-shape.

Figure 6: Waterjet Lower Links

The belt-tensioner shafts were manufactured from 6 mm rotary shaft stock, which was cut to ~21 mm length with an abrasive saw. The 21 mm sections were clamped in a three-jaw chuck on a lathe, and a 5 mm long, 4mm diameter step was added on either side of the shaft. After adding the steps, we checked the length of the shaft and faced it down to a 20 mm overall length. Figure 7 displays a few belt tensioner shafts before two 696ZZ bearings were pressed onto them, and Figure 8 displays a handful of shafts after bearings were press fit onto them. To press fit the bearings onto the shaft, we drilled a roughly 5 mm hole into a sturdy piece of wood. Place the belt tensioner shaft into the 696ZZ bearing and align its 4 mm step with the 5 mm hole in the wood. Use an arbor press (or rubber mallet if the situation calls for it) to force the tensioner shaft into the bearing. Some of the bearing inner races were a little oversize, so we dabbed some superglue onto the shafts before pressing them into the bearings. Note that the super glue impedes the slip fit significantly and sets quickly, so press with urgency!

Figure 7: Belt tensioner shafts pre bearing press fit.

Figure 8: Belt tensioner shafts post bearing press fit.

2.2.2 Body Frame

The body frame was waterjet from quarter-inch thick 6061 aluminum panels. Any holes that were undersized or need to be tapped we undersized and then drilled out to the proper size with a power drill or drill press. We used 1” x 1” aluminum struts and ¼-20 fasteners and end nuts to fasten the chassis panels together. Charlie supplied us with the 1” x 1” aluminum struts cut to a 3.75” length on a chop saw, and the ¼-20 end nuts. On the long chassis panels, I match drilled a hole to fit with the cable glands that we use for wire harness strain relief. Figure 9 and Figure 10 display the body frame assembled with cable glands and 24 V power harness installed.

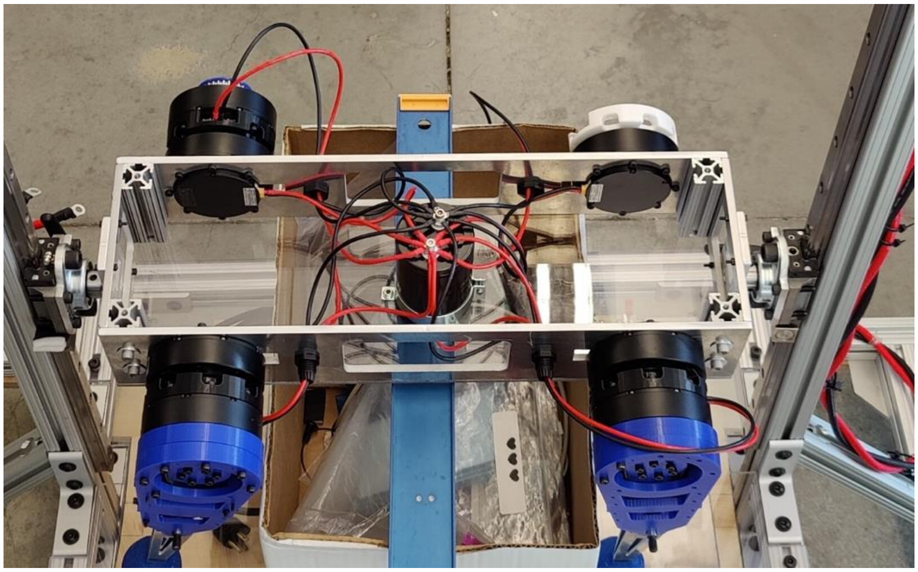


Figure 9: Body frame with 24 V power harness (and some actuators attached).

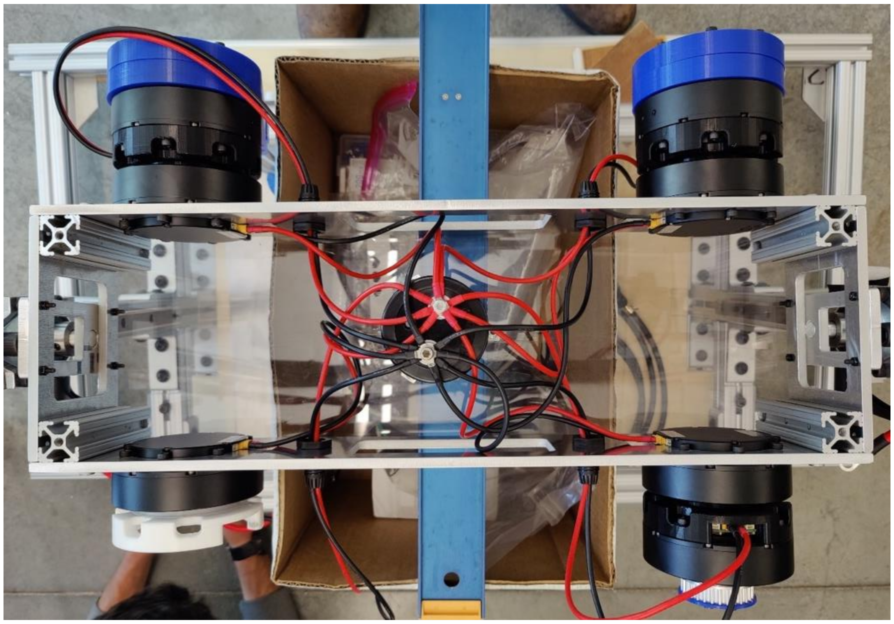


Figure 10: Bird’s eye view of chassis and power harness.

The bottom panel of the body frame was waterjet to match the area of the aluminum chassis; we originally planned to use aluminum, but we had leftover polycarbonate and thought it would look cooler. We match drilled holes into the polycarbonate to fasten to the 1” x 1” aluminum struts, which we tapped ¼-20 threads into. Additionally, we match drilled M4 clearance holes into the polycarbonate to secure the capacitor in the center of the body frame.

The power harness running from the 24 V power supply to the chassis is made from 5-gauge wire, which we crimped 6-gauge #10 stud ring terminals onto for attaching to the capacitor. The internal power harness is made from 14-gauge wire, which was cut to 10” lengths (hip actuators) and 18” lengths (knee actuators). With the supervision of Charlie, 14-gauge #10 stud ring terminals were crimped onto one end, and XT30 connectors were soldered onto the other end. The ring terminals attach to the capacitor and the XT30 connectors plug into the actuators.

The quadruped’s CAN communication harness starts with a 10’ four-conductor wire spliced to a DB9 connector that can interface with the Speedgoat. Consult the Speedgoat CAN I/O datasheet for DB9 pinout information for CAN communication DB9 pinouts. Three of the four conductors correspond to ground (white), CAN H (yellow), and CAN L (green) should be crimped with MOLEX crimps and are inserted into four-hole female MOLEX connectors. The order for this inserting is up to the manufacturer's discretion, if it matches the individual CAN wires that go to the actuators. The CAN wires going to the actuators are comprised of one yellow and green conductor, either 10 or 18 inches long, for the hip and knee actuators respectively. Crimp MOLEX crimps onto one end and insert into a two-pin female MOLEX connector, ensuring to match the convention of the four-conductor wire coming from the Speedgoat. On the other end, splice each yellow and green wire to a wire with a pre-crimped JST connector. Crimping JST connectors is inconvenient because we don’t have the proper crimp tool, and even with the proper tool it is difficult. Insert the yellow and green wires into a GH1.25 connector in the same configuration as Figure 32. Solder a 120 ohm thru-hole resistor between the green and yellow wire, close to the GH1.25 connector, for CAN termination, if possible, do this at the splice between the MOLEX wire and JST wire. Wrap the resistor in electrical tape or heat shrink, and then twist the wire to form a twisted pair – this is easily done with a power drill. To make the perfboard with pinouts for the individual CAN wires, solder two-pin male MOLEX connectors onto a perfboard as shown in Figures 11-14. We are unsure if the 120-ohm resistor in the image is doing anything useful. Solder wire to the pinouts on the bottom as shown, to connect all the CAN H/L and ground wires to the same node.

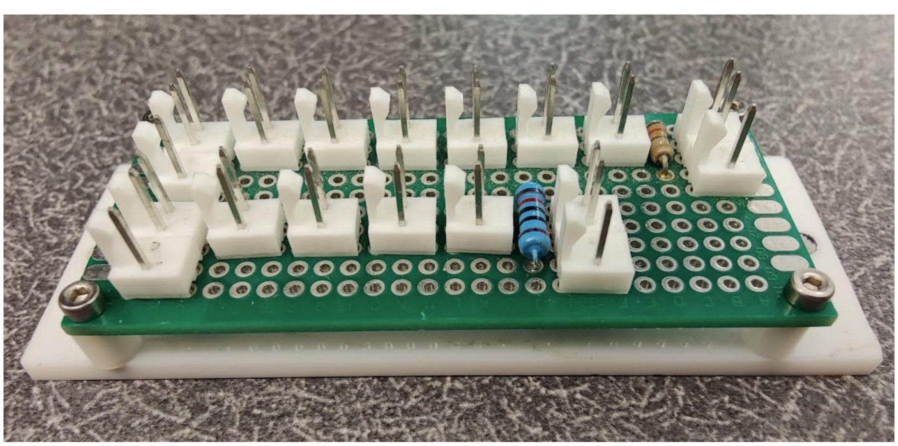


Figure 11: Perfboard configuration.

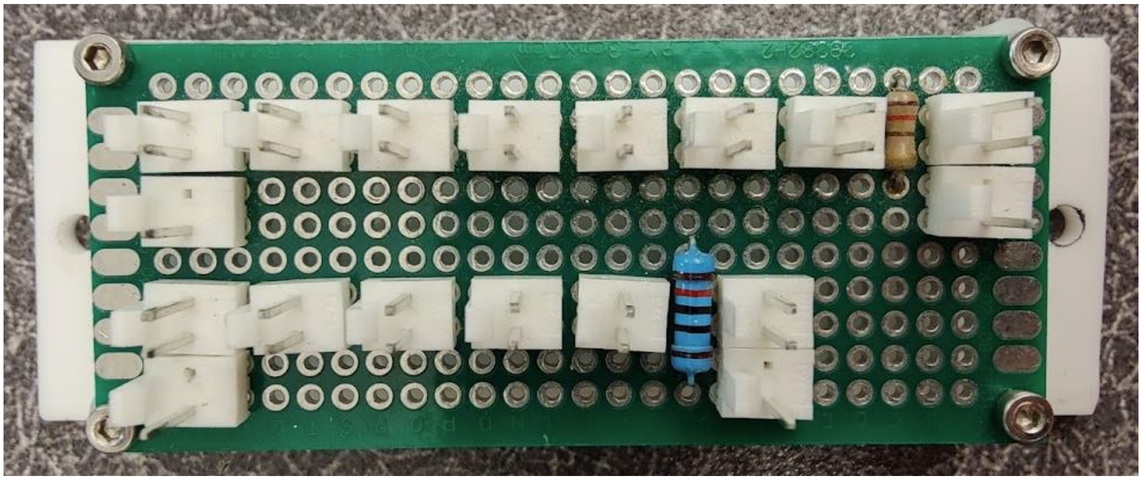


Figure 12: Perfboard configuration.

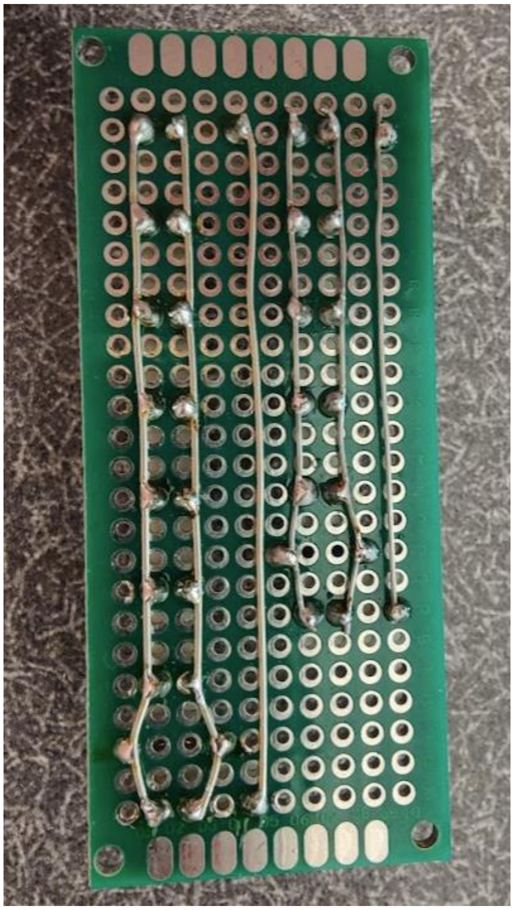


Figure 13: Perfboard configuration.

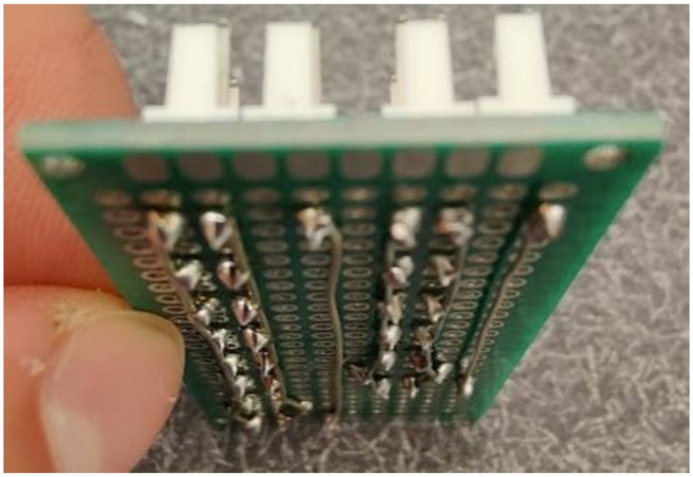


Figure 14: Perfboard configuration.

2.2.3 Test Stand Frame

The test stand frame is made of 1.5”x1.5” slotted 80/20 and is held together by 80/20 brackets. The 80/20s were cut to length. The brackets were waterjet from quarter-inch thick 6061 aluminum panels and clearance holes were drilled out and the part was deburred. Figure 15 and Figure 16 displays the test stand frame and brackets

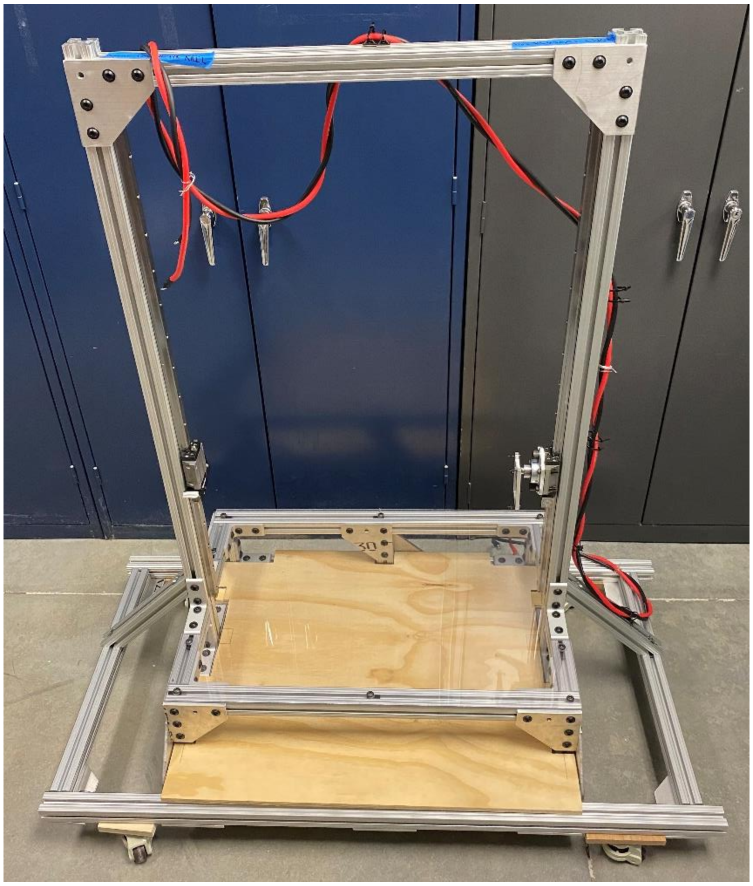


Figure 15: Test Stand Frame

Figure 16: Waterjet T and L Brackets

The quarter-inch polycarbonate jumping platform was originally cut on the waterjet, we had trouble placing the polycarbonate plate onto the test stand this required us to use the jigsaw to add a 1.5” by 1” notch located near each of the linear slider rails. The wooden base was cut to shape with the jigsaw biased on current geometry so it can be placed without interference. Figure 17 displays the polycarbonate jumping platform with the addition of notches and the wooden base.

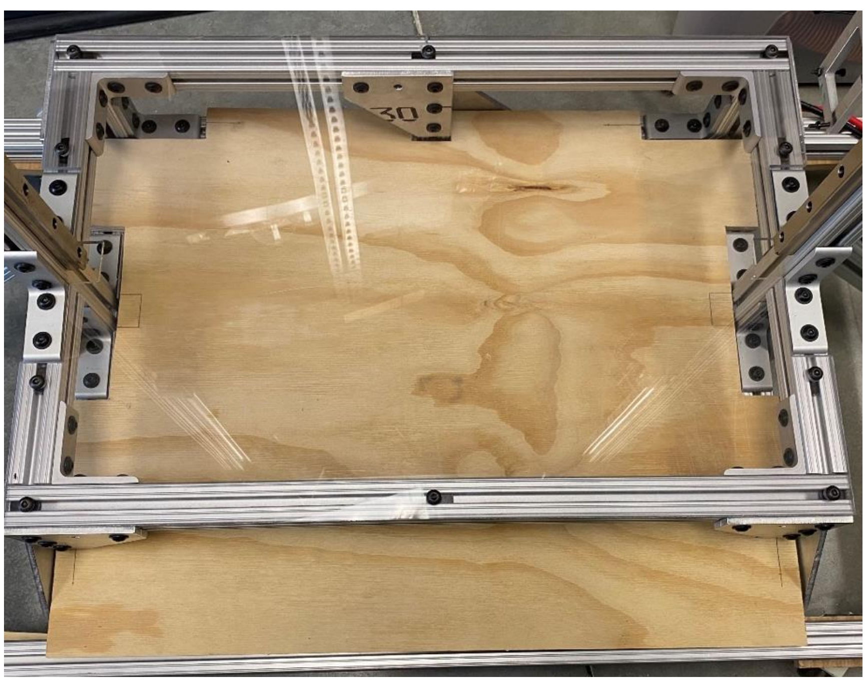


Figure 17: Polycarbonate Jumping Platform and Wooden Base

2.2.4 Test Stand Mount

The test stand frame plates were waterjet from quarter-inch thick 6061 aluminum panels. Two holes were undersized and drilled it out to have a 3 thou interference fit to press fit with the shaft. The shaft was also cut to 1.5 inches and turned down to create this press fit. The holes that mount to the purchased mount were tapped to have a 7/16-14 thread. All the other holes needed to be clearance fits, so they were drilled out to the proper size with a power drill. Figure 18 and Figure 19 displays the detached and fully assembled test stand mount.

Figure 18: Disassembled Test Stand Mount, Body Frame Mount and Linear Slider Mount

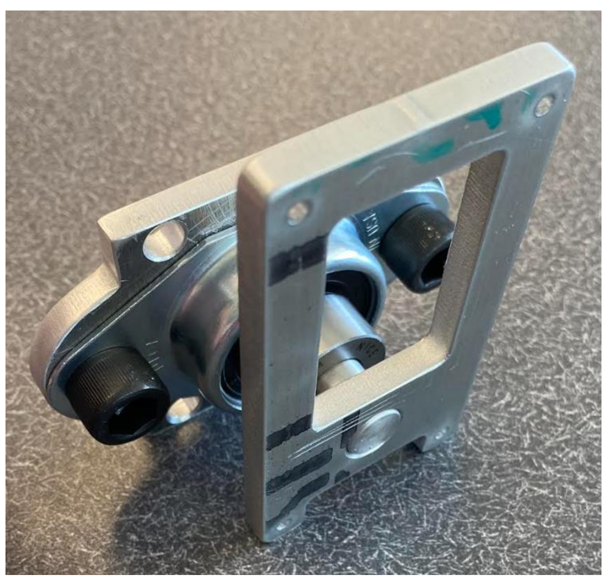


Figure 19: Assembled Test Stand Mount

2.2.5 Wire harness

We manufactured the 24V power harness and the CAN communication harness – with a tremendous amount of assistance from Charlie Refvem. Talk about manufacturing the internal and external harnesses for the power stuff and CAN stuff. Take some pictures?

2.3 Quadruped Assembly

This section outlines the assembly process for the legs, body frame, and electronic harness.

2.3.1 Legs

The leg is comprised of a polycarbonate upper link, aluminum lower link, and two actuators that are couple in series with a polycarbonate adapter.

Actuators and adapter:

1. First screw three M4 12mm FHCS into the three countersunk holes in the center of the adapter. The three holes that are not countersunk mate with the three pins at the output of the actuator (Figure 20).

Figure 20: Hip actuator and adapter before M4 FHCS.

2. Place the knee actuator in the other end of the adapter and fasten it to the adapter with seven M4 12mm SCHS. Be sure to properly align the connectors on the actuator with the slot in the adapter. (See Figure 26 or 27). One needs a short allen key to tighten these fasteners – I angle ground one to the proper length, and it's currently the only tool that works for this part of assembly.
3. Next place the aluminum pulley adapter on the output of the knee pulley; the three through-holes that are not countersunk mate with the knee pulley output pins. Fasten the adapter to the knee actuator with 3 M4 12mm FHCS (Figure 21).

Figure 21: Pulley adapter connected to knee pulley output.

4. Take six M4 20mm SHCS and insert them into the knee pulley flange, and then through the six clearance holes on the knee pulley. These six fasteners thread into the six tapped holes on the pulley adapter (Figure 22).

Figure 22: Knee pulley attached to pulley adapter.

Lower links

1. Align the three-hole circular pattern on the bent aluminum links with the three tapped holes on the knee pulleys. Use a 5/20th SAE allen-key to screw a #6-32 ultra-low-profile FHCS into each tapped hole. One may need to evenly tighten the #6-32 fasteners to properly secure the bent aluminum links to the knee pulley (Figure 23).

Figure 23: Bent links fastened to knee pulley.

2. Before inserting the bent links into the foot, slide a timing belt between the space in the bent links (you might need to open the gap with a light force) and align the timing belt teeth with the pulley teeth (Figure 24).

Figure 24: Lower link with timing belt installed.

3. Insert the narrow side of the bent links into the PLA slot in the foot (Figure 2). To permanently connect the bent links and feet, add superglue, permanent Loctite, or JB weld into the slot before pressing the bent links into the slot.

4. Press R6 bearings into the inner bore of the knee pulley. While this is a transition fit and requires some finagling to properly align the bearing, with a medium force applied on the outer race of the bearing it should tightly slide into the pulley bore. Do this process twice and evenly align the R6 bearings with the pulley (Figure 25).

Figure 25: Two R6 bearings pressed into the knee center bore.

Upper links (and connecting to the lower links / actuators)

1. Place a belt tensioner bearing in each slot of the upper link (Figure 26).

Figure 26: Belt tensioner bearings in tensioner slot.

2. Slide a 5/16 shoulder bolt with a washer through the knee hole in the upper link, and then slide the R6 bearing of the lower link onto that shoulder bolt after it is through the knee hole in the upper link (Figure 27).
3. Mesh the timing belt with the teeth of the actuator knee pulley, so that the timing belt presses the belt tensioners outward and into the upper link structure (Figure 27).

Figure 27: Lower link integrated into upper link.

4. Slide another half of the upper link onto the shoulder bold – be sure that each step on the belt tensioner properly mates with the slot in each upper link half. This might require a bit of finagling.
5. Insert M3 30 mm dowel pins into the four holes indicated in Figure 28. Then add tension to the knee by threading a 3/8” washer and jam nut onto the 5/16” shoulder bolt.

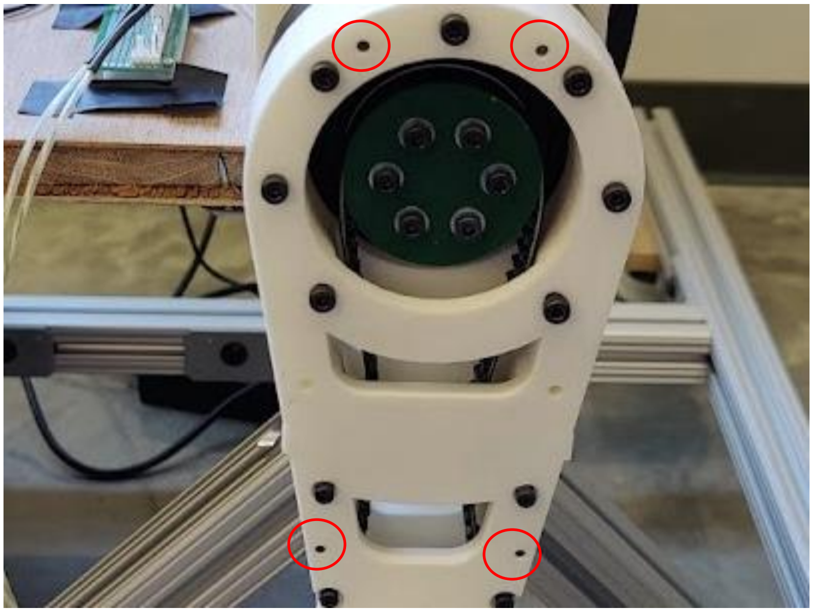


Figure 28: M3 dowel pin locations.

6. Attach the upper link to the actuators via seven M4 35 mm SHCS. It might take a bit of force to properly align the circular hole patterns on the upper link and knee actuators.
7. Further secure the upper links together with 6 M3 35mm SHCS and M3 washers/nuts.
8. Add appropriate tension to the belt by threading two M3 20 mm SHCS into the heat set inserts on each upper link. Gradually thread the fasteners on each side of the leg to ensure that the belt tensioner shaft is not pushed out of its corresponding slot.

2.3.2 Body Frame (Chassis)

1. Start by threading sixteen ¼-20 end nuts onto ¼-20 x 5/8” fasteners that have a washer and are inserted into the corresponding holes on the chassis panels (Figure 29).

Figure 29: ¼-20 fasteners and end nuts in chassis panels.

2. Slide the 1”x1” 3.75” long aluminum framing pieces onto the end nuts to loosely connect the chassis panels (Figure 30).

Figure 30: Loosely connected body frame panels.

3. Gradually tighten the ¼-20 fasteners and ensure that the chassis panels are properly aligned and perpendicular to one another (Figure 31).

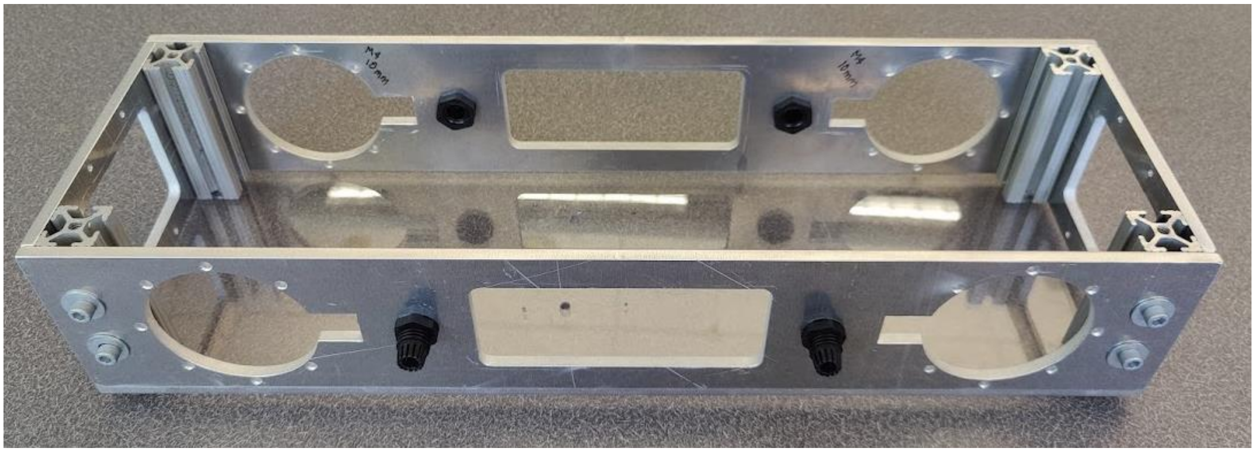


Figure 31: Fully connected chassis.

4. Use four ¼-20 fasteners with washers to attach the polycarbonate bottom panel to the chassis. Thread the fasteners into the tapped holes on the end of the 1"x1" aluminum framing.
5. Use three M4 12mm SHCS and flanged nuts to attach the capacitor to the three holes in the center of the polycarbonate panel.
6. Use two M3 16 mm SHCS and nuts to attach the CAN perfboard to the two holes next to the capacitor circular pattern
7. Attach PG9 cable glands in the two 0.75" diameter holes on each of the side chassis panels. I ordered cable glands with too short of threads and am only able to get ~1 thread to engage – I am considering using a light adhesive to hold the cable glands more securely.

2.3.3 Electronics

1. To integrate the internal 24V power harness, run the ring terminals of the power wires through the cable glands, from the inside to the outside. Be sure to have the removable part of the cable gland loosely threaded, as the XT30 connectors don't fit through the cable gland holes.
2. NOTE: The black XT30 connectors have longer wires and are meant to route to the knee actuators. The yellow XT30 connectors have shorter wires and are meant to route to the hip actuators. Route one black XT30 wire pair through each cable gland.
3. Take all the red wires' ring terminals and attach them to one of the capacitor screw terminals using a #10 machine screw (Figure 10). Repeat this process for the black wires. One must be especially cognizant to ensure that each wire is coming off in a convenient direction to route the wires to their respective actuators.
4. Plug the XT30 connectors into the corresponding connector on the actuators. XT30s are designed to only be plugged in one orientation, so don't worry about mixing up V_{in} and ground.
5. Place adhesive zip tie mounts where convenient to constrain the wire harness. Each time the wire harness is assembled and disassembled, the wires probably won't be in the exact same spot, so don't feel bad if you must remove some zip tie mounts and place new ones elsewhere.
6. To install the CAN communication harness, plug the Molex side of the internal CAN harness into the perfboard Molex pinouts. Be sure to align the CAN H/L wires with that of the external CAN harness that is coming from the Speedgoat (match green wires to green wires and yellow wires to yellow wires).

7. Route the longer CAN wires through the cable glands and plug the GH1.25 connector into the connector indicated in Figure 32. This connector is also labeled “CAN GH1.25” on the back of the actuator. The CAN communication wire is the green and yellow twisted pair.

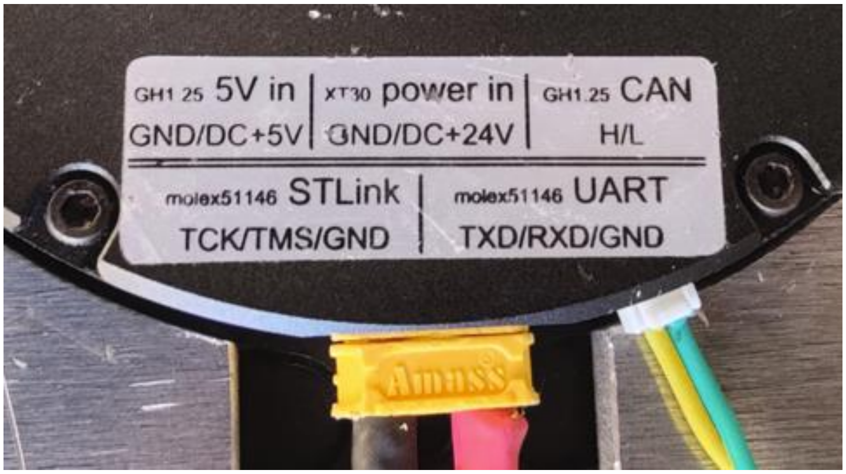


Figure 32: CAN Communication connector.

8. Tighten the cable glands onto the wires so that the strain is relieved but there is not excessive stress on the wires.

2.3.4 System Assembly

To assemble the entire quadruped, fasten the leg to the “front” of the knee actuator via seven M4 35mm SHCS. Ensure that the orientation of the knee actuator connectors is on the same side as its corresponding cable gland to avoid undesirable stress on the connectors and wire harness. Repeat this for all four legs. Attach the “rear” of the hip actuator to the chassis via seven M4 10 mm SHCS. Ensure that the connectors on the hip actuator align with the rectangular slot that is cut into each of the chassis’ actuator holes (Figure 31). Once the legs are attached to the chassis, plug in the power and CAN harness to the actuators.

2.4 Final Budget Status

The total cost of manufacturing the quadruped is just under $3,500. The total cost of the project, including manufacturing the test stand, and other purchases was $5,597. We received a grant from CP Connect that gave us funding to purchase necessary components. Table 1 is a summary table of the budget breakdown for each major subsystem. Reference Appendix B for a complete project budget and bill of materials.

Table 1: Budget Summary Table

Subsystem	Cost
Legs	$568.69
Chassis/Body Frame	$2,720.70
Test Stand	$1,398.94
Test Stand Mount	$428.23
Not in final design	$481.15
Total:	$5,597.71

2.5 Challenges and Lessons Learned

The first difficulty encountered while fabricating the quadruped was with the belt tensioner shafts. We ordered rotary shaft stock because it is great for bearing press fits, but it turns out that rotary shaft stock is made from hardened steel. Hardened steel is harder than tool steel, and this presented a lot of issues when trying to machine the rotary shaft stock. I stalled the Mustang 60 mini lathe while trying to use a carbide parting tool to cut stock to the appropriate length. I then consulted with Brian from the IME department, and he told me to use the abrasive saw to cut the stock; the abrasive saw cut through the shaft stock like butter. To add the 4 mm diameter step to each side of the shaft stock, I had to use the full-size lathes in the Aero Hangar, because the mini lathe in Mustang 60 did not have enough torque and the normal lathe in Mustang 60 was always in use.

The next major was machining the knee pulleys. In theory, a shaft sized for a bearing press fit should be undersized by three tenths (that's three ten thousandths of an inch); the manual machines available to mechanical engineering students on campus simply cannot hit this tolerance. We could have reamed the hole to the correct size, but there were no undersized 7/8" reamers on campus and the only 7/8" reamer on campus has a unique taper that cannot interface with any of the mills on campus. Another option was to bore the hole out to the proper size with a boring bar, but this seemed incredibly tedious and easy to mess up. When I went to manufacture these parts, the quill feed was left unlocked, and as a result the end mill that I was using gradually dipped down into the part as I was facing one side of the part. I did not notice this until the end mill had sunk about 2 mm into my part; this was not only disappointing, but a huge issue that seemed to have no solution. Fortunately, Colin Reay noticed that I was struggling to manufacture this part manually and offered to CNC them for me. He was able to CNC all four pulleys in a few hours and saved me tens of hours of work.

The final manufacturing challenge has been with the 3D prints. The PC and TPU have been very finnicky on Craig's printer and have created many delays since printing parts takes time. With enough attempts Craig should be able to dial in the printer settings and avoid the different issues that have been causing print failure.

3. Design Verification

The design verification chapter describes our testing, data analysis, and what we learned about our design from it.

3.1 Design Specification Verification

The following section outlines our project specifications and describes how our design satisfies these specifications.

1. Vertical Leap Height – 10 cm

Our target leap height of 10 cm was achieved during testing of the quadruped. We measured the vertical displacement of the quadruped from its body frame. We repeated this test several times to collect numerical data to preform error propagation and uncertainty analysis. The quadruped achieved a vertical leap height of 10.02 ± 0.29 cm.

2. Fatigue Durability – 30 minutes of operation

We operated the quadruped for multiple days, multiple hours each day. The quadruped showed no signs of fatigue, and the new knee joint design works exactly as intended. The surface of the knee pin is made of steel and does not transmit torque, so the surface marring no longer occurs. One thing to note is that the fasteners started to loosen over time. The final step for assembly should be to use non-permanent Loctite on all fasteners.

3. Assembly Time – 10 minutes per leg

The original goal of a five-minute assembly time may be unrealistic. However, since the final prototype will not be frequently assembled and disassembled, this rapid assembly is not necessary. A new assembly time of 10 minutes per leg is more reasonable. Currently, the assembly time for the internal electronics is quite time consuming, between 10-20 minutes. However, once the wire harness is assembled it does not need to be disassembled except for maintenance.

4. Weight Management – 10 kilograms

The total mass of the quadruped is 9.95kg. While this is under the weight goal, we do not have the batteries onboard. We do have a heavy capacitor, which might have a similar mass to one of the batteries. With a properly designed PDB, the large capacitor would not be necessary.

5. Center of Mass Position - <0.5 inches from center

The quadruped does not roll when suspended on the test stand in a level position. This indicates that the center of mass of the quadruped is well centered.

6. Compilation Time – 5 minutes

While the STM microcontroller for the quadruped has not been developed, the compilation time for the quadruped MATLAB/Simulink controller takes less than two minute to compile.

7. Total cost of components – <$5,000

The total cost of the quadruped is ~$3,500. Thus, the quadruped itself is underbudget, but if the test stand is included then we went over budget. Fortunately, we received a grant from CP Connect which gave us the necessary funds to complete our project. The total cost of the project was $5,597

8. Avoid Rolling During Flight – Δt between side impacts < 0.05 sec

The quadruped does not rotate during flight. The feet on each side of the quadruped land at nearly the same time. It may not be exactly 0.05 seconds (we have not determined the exact time of impact for each side), but it is certainly less than 0.25 seconds. The difference in impacts between sides is negligible enough to not impede the quadruped's ability to repeatedly jump. The calculated leg response times were:

Hip Jump: 0.28 [sec]   Hip Land: 0.32 [sec]   Knee Jump: 0.38 [sec]   Knee Land: 0.24 [sec]

9. Leg Response Overcorrection / SSE – < 0.03 radians

The leg response overcorrection was calculated to be around 0.05-0.08 radians. While this is over the steady state error we aimed for, it is still a small value and the steady state error we found did not impact the repeatability of the jump.

Hip Jump: 0.05 [rad]   Hip Land: 0.08 [rad]   Knee Jump: 0.04 [rad]   Knee Land: 0.081 [rad]

3.2 Description of Testing

The following section we discuss our testing approach and the steps we took to achieve a jumping quadruped. Most of our testing ensures that our quadruped operates safely and in the way we expect. Reference Appendix A for images of our Simulink controller; reference Appendix D for our user manual which has detailed instructions for the user of our controller.

All testing took place in ME 192-118. Our sponsors lent us a power supply to power the quadruped and lent us a Speedgoat to command the actuators with a Simulink model. All testing equipment will be held on the modular test stand, other than a development (personal) computer. All tests requiring power will be done with the robot mounted to the test stand. Henry Bouma (c/o 25'), credited with technical assistance, helped our team perform tests that require multiple individuals.

3.3 Single Leg Position Control

Testing the single leg allowed us to adapt the controller to our new leg as well as prove the functionality of the redesigned leg. Figure 33 displays the redesigned leg attached to the test stand.

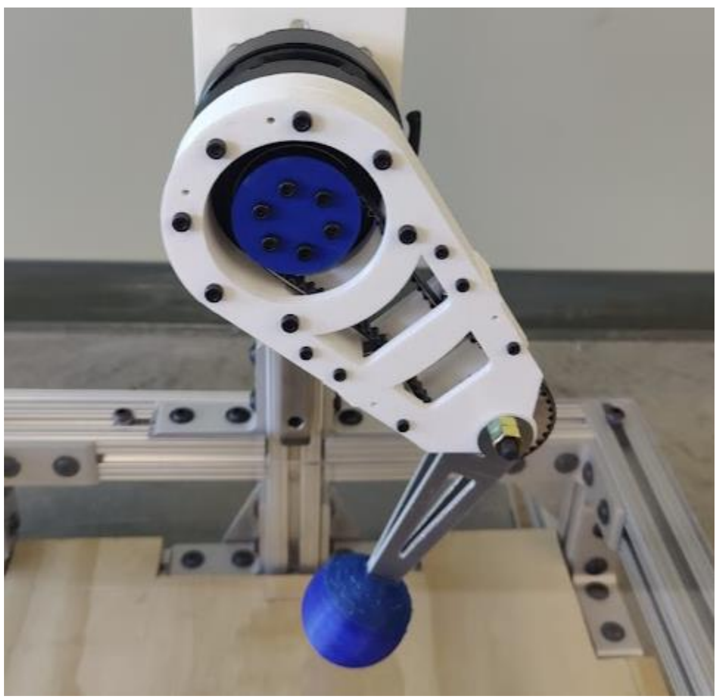


Figure 33: Single Leg Testing

Our quadruped needs to stand sit and hop. We first tested the single leg first to ensure that our controls operate as expected. After creating a functional sit-stand controller for the single leg we used the same logic to create a sit-stand controller for the quadruped, where each leg could operate independently. We choose to start with a sit-stand controller because it is a safe test to prove functionality of the quadruped. Safe testing of the quadruped also allowed us to prove that the power and CAN harnesses were set up correctly.

3.4 Quadruped Assembly Time Evaluation

After completing single leg testing the next step in our testing was to evaluate the quadruped's assembly time and evaluate the position of the center of mass. We timed the assembly of each major component separately, Legs chassis and internal electrics. After the quadruped was assembled, we suspended it to the test stand and assessed its ability to balance.

3.5 Quadruped Position Control

To test the functionality of the test stand mount we made the quadruped tilt left and tilt right. The test stand mount allowed the quadruped to rotate about this axis with ease. Sit, stand, Left-up and Right-up are the four commends we have in our controller. Figure 34 shows the quadruped position control.

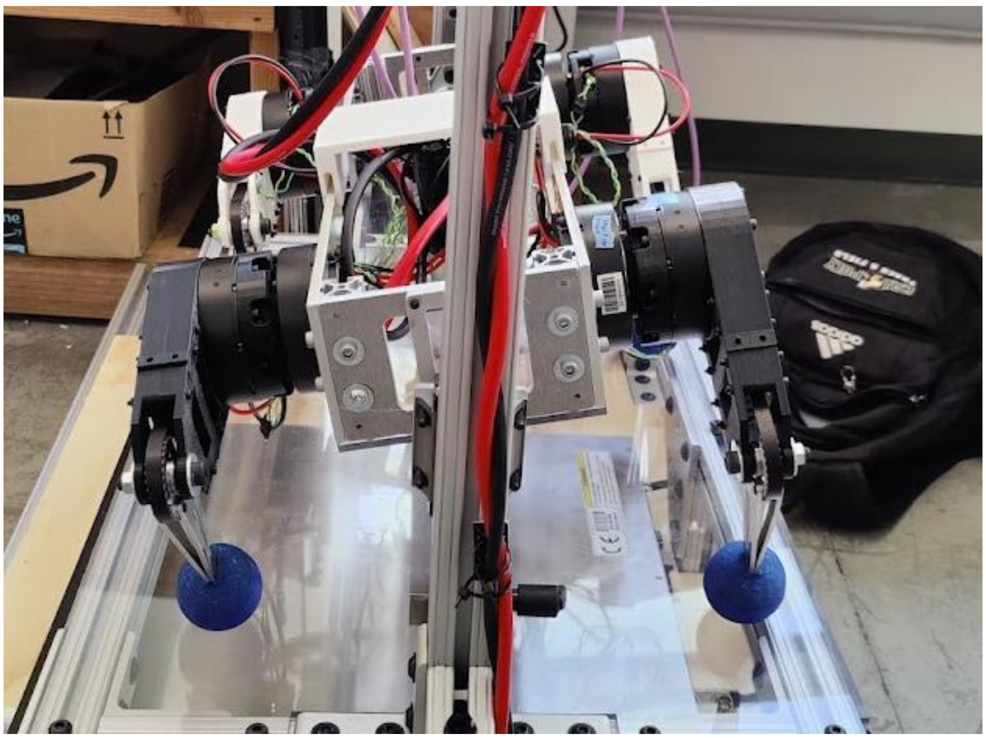


Figure 34: Quadruped in askew configuration

Looking at the DAQ we found that there was some steady state error in our system. This is likely due to the mass of the robot and the use of a positional controller. Figure 35 shows the position error in our system during testing.

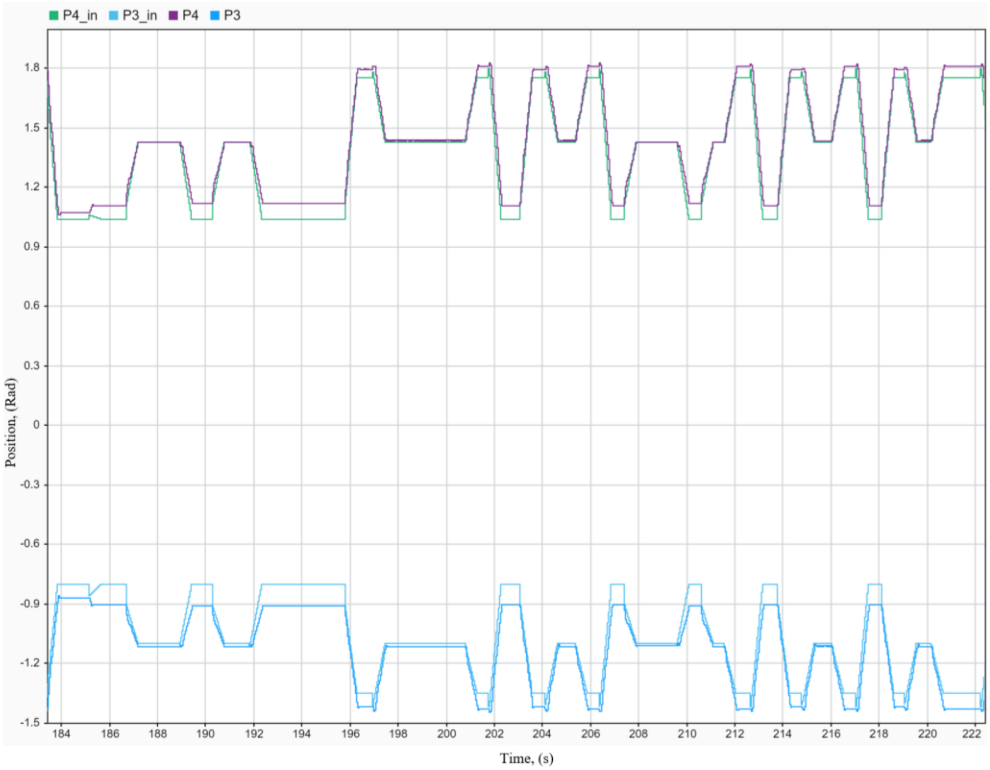


Figure 35: Quadruped Testing Single Leg Data

The data in Figure 35 shows the desired and actual positions during a series of stand sit commands. The variables with the subscript "in" are the desired angles. P3 corresponds to the hip motor and P4 corresponds to the knee motor. We can see that the desired angles are always closer to zero than the actual angle, meaning the leg is always more bent than expected. This makes sense since the robot is fighting the force of gravity to stand and support itself. So, the robot is always going to be a little lower to the ground than what we expect. One change made to decrease this error was increasing the position gain, K_p to 30 from 25; this marginally decreased the error. To fully reduce steady state error an integral gain, K_I would be needed.

3.6 Single Leg Jumping

To ensure our quadruped could safely jump we implemented and tested jumping controls for our quadruped. We used the jump controller developed over summer and adapted the controller to the redesigned leg. Our jumping phase used torque control and our single leg has jumped 7cm off the ground. See Figure 36 for single leg jump.

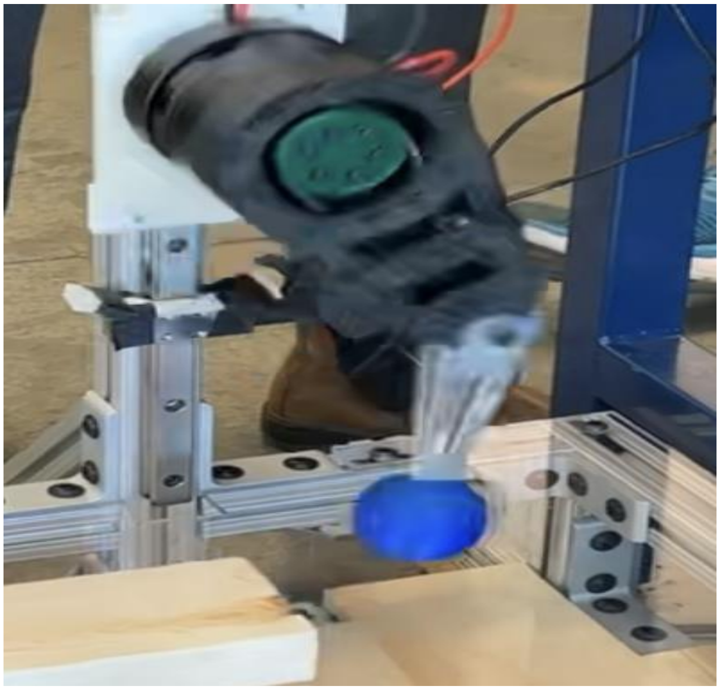


Figure 36: Single Leg Jump Test

The single leg jump test was largely unsuccessful. The jumps that the single leg produced were chaotic and not repeatable. This error is likely caused by flaws in our controller. Mainly the ground reaction force was not calculating correctly, the ground reaction force was calculated to be -15N when the robot was touching the ground. This could have been caused by changes in the leg's geometry. Since our jumps are based on the ground reaction force and the torques were calculated based on a desired force profile, we were not able to create great jumps. Because of these inconsistencies we decided that it would be simpler quicker and more predictable to recreate a jump phase but with position control instead of torque control for quadrupedal testing.

3.7 Quadruped Jumping

The final step in our testing was to evaluate the quadruped's vertical leap, its fatigue durability, and its tendency to roll during flight. Figure 37 displays the quadruped while airborne. By inspection we see that the quadruped is very level during flight and does not roll. In addition, the vertical leap ability of the quadruped is better than we expected.

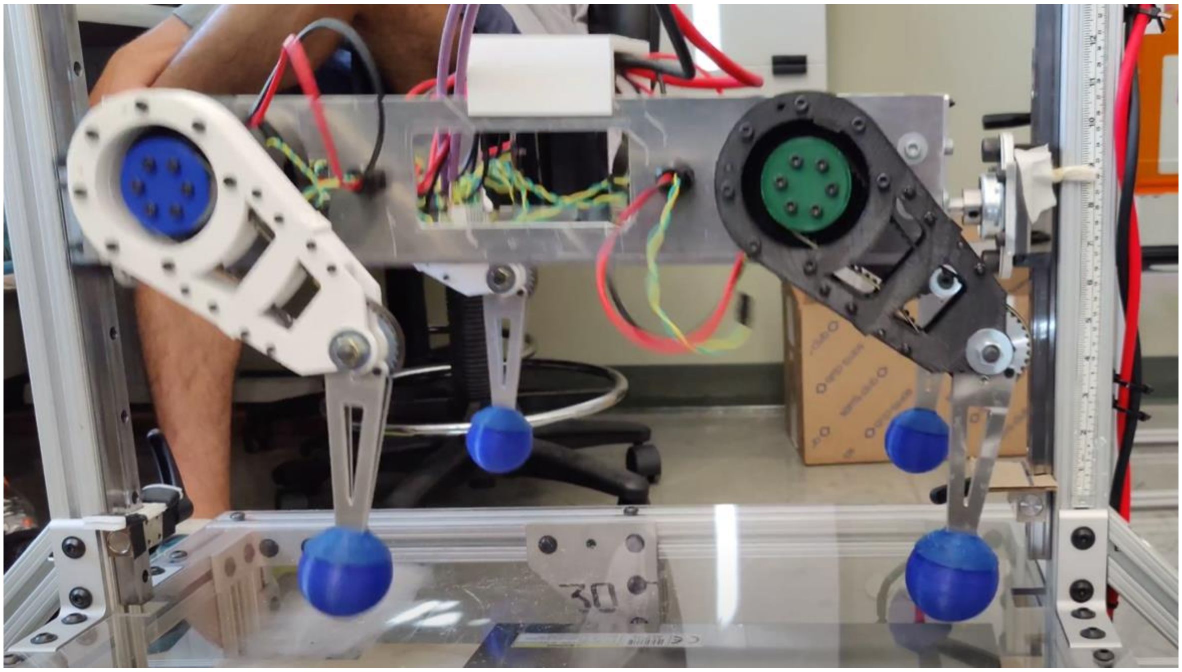


Figure 37: Quadruped Jump Test

As mentioned in the single leg jump testing this controller uses position control. We added two new commands to the controller to help with jumping, called “Jump” and “prejump”. We briefly optimized the controller gains to achieve a desirable jump. We tuned the lift off time and set it to be .12 seconds, any faster lift off time and the feet tend to slip. Once the jump was optimized, we began recording jump heights for an uncertainty analysis. We used the data inspector to analyze the response shape of the jump seen in Figure 38. After completing these dynamic tests, the quadruped was disassembled and checked for any visible signs of fatigue, of which there were none. This verifies that our new knee design is durable enough for continuous operation.

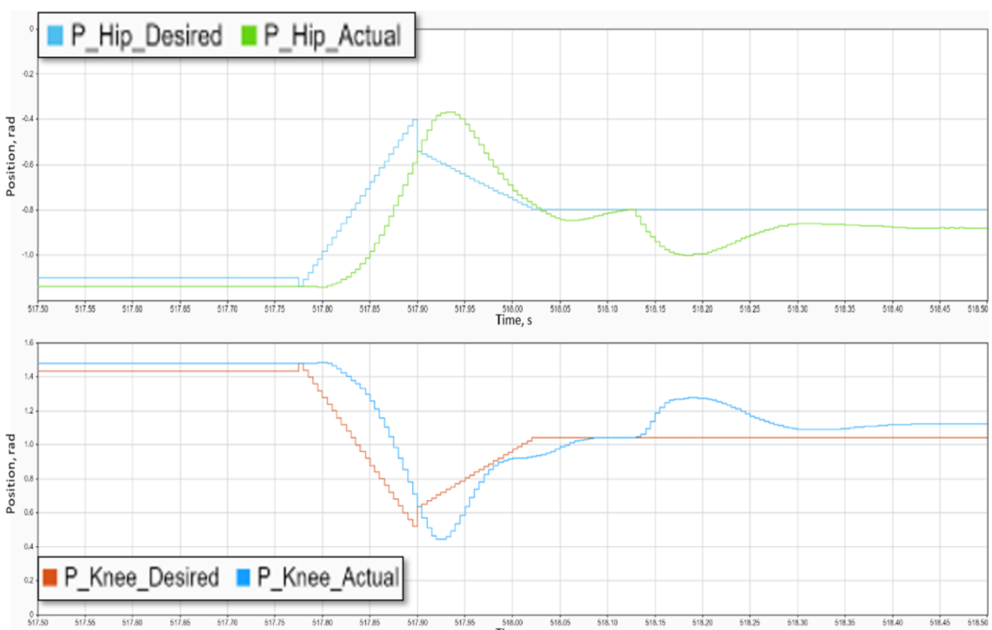


Figure 38: Quadruped Jump Response

3.8 Numerical Data, Error Propagation, and Uncertainty Analysis

The test data in Table 2 was collected from 15 jumps from the full quadruped assembly,

Table 2: Quadruped Jump Data

Jump	Jump Height (cm)
1	10.15
2	10.15
3	9.91
4	9.91
5	10.15
6	10.00
7	10.10
8	10.00
9	10.00
10	10.10
11	9.90
12	10.00
13	9.90
14	10.00
15	10.00

From the collected data an average of 10.02 cm was calculated, with a standard deviation of 0.095. Since the data collected was relatively simple there are no error propagation calculations that needed to be done, but an overall uncertainty was needed. Multiplying the standard deviation by 3 to encompass 99% of the data set gave a statistical uncertainty of 0.28 cm.

To get a total uncertainty the resolution must also be considered. The meter stick used had a resolution of 1mm or 0.1 cm so dividing that by two to get the measurement uncertainty gave 0.05 cm. To calculate the total from the two uncertainties the root mean square was used. After which gave a total uncertainty of 0.29 cm.

3.9 Test Results Summary

Table 3 summarizes our test results of our engineering specification. We achieved the major goal for this project, which was to fabricate a quadruped that can jump 10 cm in the air. Refer to Appendix D for our DVP&R document that has more detailed information regarding our testing results.

Table 3: Test Results Summary Table

Spec #	Specification	Results	Pass/Fail
1	Vertical leap height	10.02 ± 0.28 cm	Pass
2	Fatigue durability	No visible fatigue.	Pass
3	Assembly time	47 minutes for mechanical assembly 10-20 minute for internal electronics 8 minutes per single leg	Fail
4	Weight management	9.95 kg	Pass
5	Center of mass location	Center of mass is close to the geometric center of the chassis	Pass
6	Compilation time	Scope Changed to no longer need a STM microcontroller	NA
7	Total cost of components	$5,597	Fail (Win)
8	Avoid rolling during flight	The quadruped never rolled during flight.	Pass
9	Leg response Steady state error	Hip Jump: 0.05 rad; Hip Land: 0.08 rad; Knee Jump: 0.04 rad; Knee Land: 0.081 rad	Fail
10	Leg response Response time	Hip Jump: 0.28 sec; Hip Land: 0.32 sec; Knee Jump: 0.38 sec; Knee Land: 0.24 sec	Fail

3.10 Missing Tests and Specifications Not Met

3. Assembly Time

   The 10-minute quadruped assembly time was unrealistic. The final prototype will not be frequently assembled and disassembled; thus, rapid assembly is not necessary. Having an hour total assembly time is acceptable. An assembly time of 10 minutes per leg is more reasonable. We achieved a single leg assembly time of 8 minutes which is better than the original leg design.

6. Compilation Time

   The compilation time specification originally was for an STM microcontroller. The scope of our project changed to no longer require an STM microcontroller.

7. Total Cost of Components

Initially we had a budget of $5,000 after applying to the CP Connect grant our budget increased to approximately $8,600. We stayed within our increased budget.

9. Leg Response -Steady State Error

   The Simulink controller uses only a positional gain. The robot is fighting the force of gravity to stand and support itself. Due to the mass of the robot achieving zero steady state error is not reasonable without an integrator gain.

10. Leg Response - Response Time

    Achieving the desired response time was impossible due to slipping. Normally response tests are done with a step function, but we chose to use a ramp function for our controller. The ramp time for our tests was set to be 0.12 seconds, this was the fastest ramp time while still avoiding slipping. Our goal was set to have a response time of less than 0.1 seconds. Since our set jump time is greater than our target response time, we did not achieve this specification. Fortunately, not achieving this specification did not hurt our ability to produce repeatable high jumps.

3.11 Challenges and Lessons Learned

One of the first tests run was the assembly time test, the goal of which was to assemble the quadruped in under 10 minutes. However, during testing the quadruped took around 48 minutes to assemble the body frame, 4 legs and then attach the legs to the body. In retrospect, assembling a complex system such as a quadrupedal robot in under 10 minutes is unrealistic.

Electrolytic capacitors have a positive and negative terminal. Do not mix this up. We did this and blew a capacitor, which delayed us by a few days. Fortunately, no one was injured. An evaluation of our system was done to determine other risks while testing and operating the quadruped, these can be found in Appendix C.

One challenge that we faced while testing was the robot would power off during dynamic tests. We were initially afraid that we were putting too much current through the motors. This was not the case the power supply had the current limit set to be 5 Amps. Each motor of our 8 motors could handle 40 Amps, so a max current of 320 Amps. To allow for more dynamic motion and stronger motor torques we had to increase the power supply amperage limit to 25 amps.

We encountered challenges with the feet of our quadruped slipping. We hypothesize that the infill percent of the foot or the infill pattern are not well chosen, which leads to the foot compressing too much. This has resulted in the leg slipping when jumping and not producing a repeatable jumping motion. Designing the leg with less slippery material would allow improve the legs jumping capability.

4. Discussion & Recommendations

This section summarizes what we learned and goes over recommended changes for improving the project. Refer to Appendix E for the user manual, which contains detailed instructions on how to operate the quadruped during testing. Reference Appendix F for detailed testing procedures and results.

4.1 Lessons learned

We learned that manufacturing a quadrupedal prototype, custom test stand, and creating an entirely new controller from scratch in C or C++ is an incredibly ambitious goal. So ambitious, that we were unable to develop the C/C++ controller and had to expand upon the controller we had developed in Summer 2021. In addition, we learned that bearing press fits are non-trivial to achieve with manual machines and had to change our manufacturing plan and implement CNC machining to fabricate our knee pulleys. We also learned a lot about wire harness design and creation; specifically, the process of creating the hardware to communicate with eight actuators via CAN.

In terms of the goals for this design challenge, we learned that it is possible to make a quadrupedal robot that can jump 10 cm in the air. We spent lots of time analyzing the position of the legs relative to the chassis so that we could attain the largest ground reaction force (GRF). A notable challenge that we faced during testing was that the robot's feet kept slipping while jumping. We addressed this issue by orienting the lower link such that it was nearly perpendicular to the ground. While this fixed the slipping issue, it resulted in the front of the chassis leaping higher than the rear chassis, which could lead to a non-ideal jump.

4.2 Next Steps

Next steps for development of the quadruped include improvement of the foot's friction, attenuation of vibrations sent to internal electronics, and the creation and implementation of the PDB, internal power, and a controller in C/C++. While the vibrations transmitted to the internal electronics did not cause any issues during operation, they are generally undesirable and could lead to reduce lifetime of electronic components.

Further optimization of the Simulink controller can be done to achieve a higher jump height. Suggested tunable parameters can be found in the user manual under the Simulink controller in Appendix D.

4.3 Design Changes

The main design change that would more fully satisfy our sponsors' needs would be attenuating vibrations to the internal electronics. Currently, the internal electronics see lots of vibrations transmitted to them; while this did not cause our system to fail, it is not good practice and could shorten the lifespan of these electronic products. In addition, we need to rethink our approach to attaching the castor wheels to the test stand. The wooden adapter we made broke when we rolled the test stand over concrete with large cracks, so we advise finding castor wheels that directly interface with the t-slot in our aluminum framing.

4.4 Manufacturing Changes

The only component that presented difficulties to manufacture were the knee pulleys. The tolerances that we needed on the bearing hole was too tight to achieve with anything but a reamer or boring bar if manual machining is the route to be taken. Instead, we recommend using CNC to manufacture the knee pulleys. Colin Reay was generous enough to fabricate the knee pulleys on the Mustang 60 HAAS mill and took tens of hours of manual machining and reduced it to a few hours. High-volume production is not the goal for this project; thus, the only recommendation we have is the previously mentioned modification.

5. Conclusion

We were able to fabricate a prototypical 8 degree of freedom (DOF) quadruped and develop a controller that can command the quadruped to leap 10 cm in the air. This was the main goal for our project. In addition, we successfully fabricated a modular test stand that holds the necessary electronics, and facilities the vertical jumping of the quadruped.

We were unable to implement the on-board power supply, PDB, or C/C++ controller which was a major part of our original project scope. Looking back, we should have started months earlier on significant power distribution board development, including the physical layout on a circuit board. In addition, not enough attention was given to properly selecting the batteries and battery management system, which would have interfaced with the PDB. These two issues prevented us from starting on the development of the C/C++ controller, as we have no electronic system for the controller to interface with.

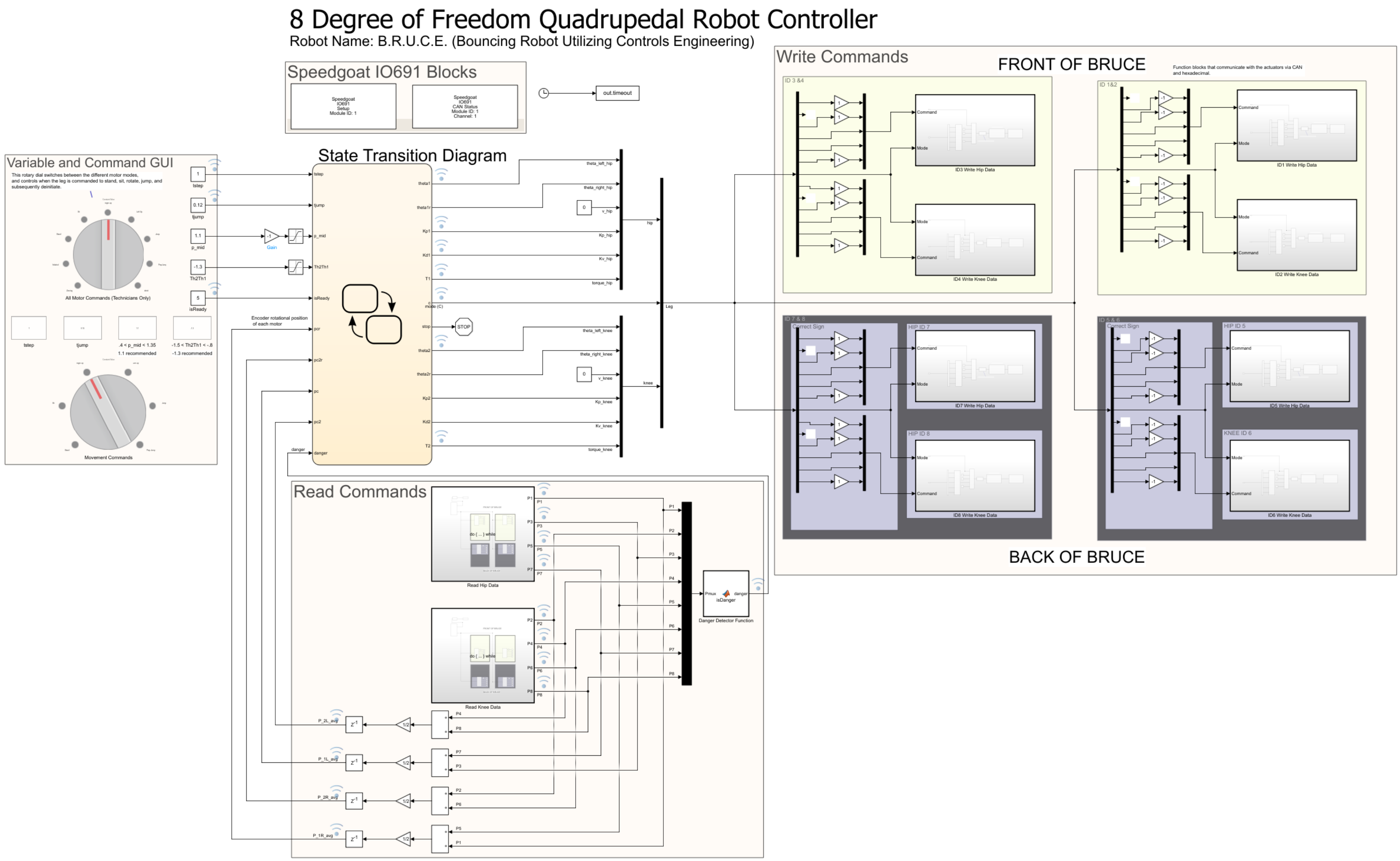
Appendices

Appendix A – Annotated Software

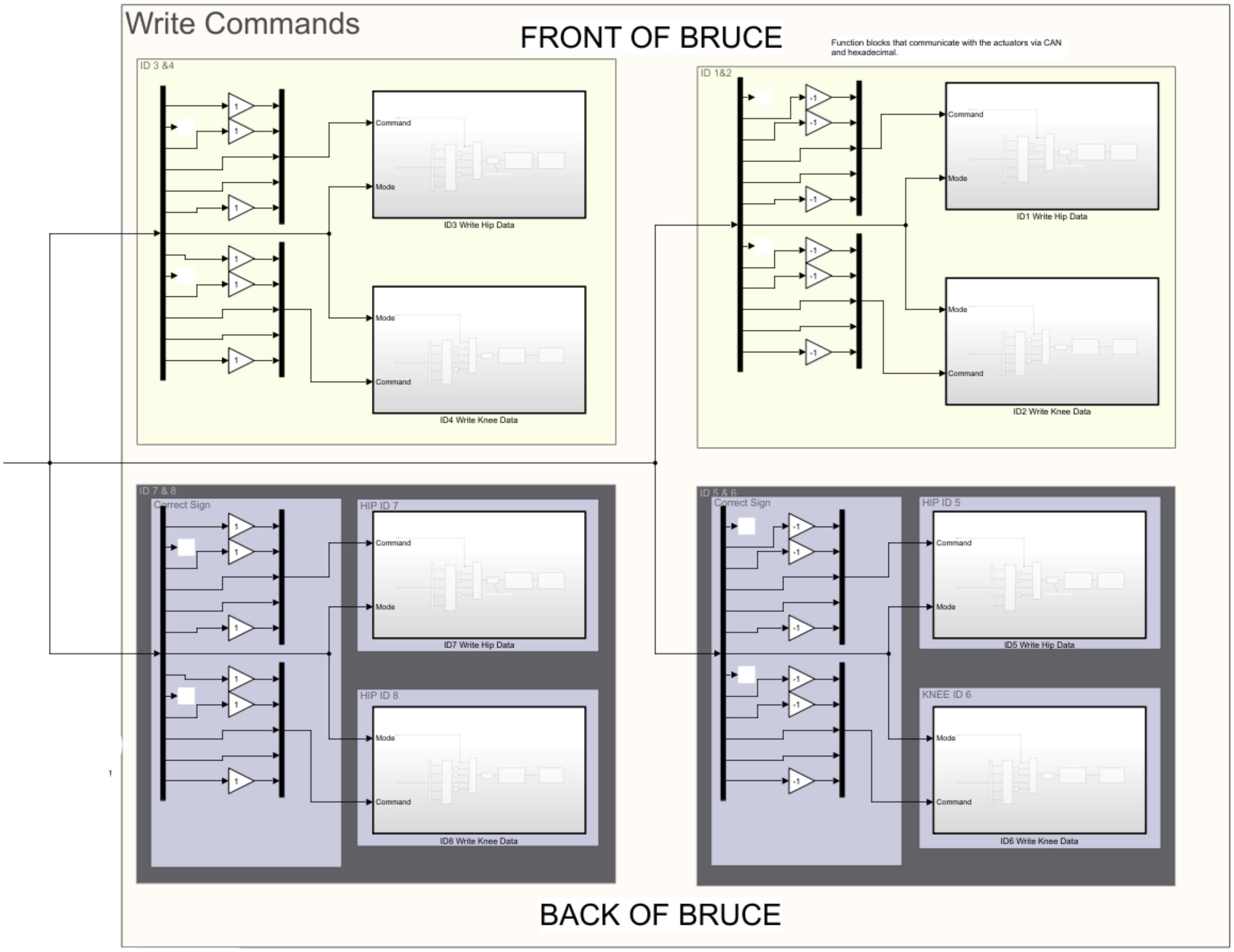
File name: main_quad_rev5_31_315pm.slx

We used a Simulink file paired with the Speedgoat to convert the Simulink file to C++ code that can be run in real time on the actuators. This file is used to command and control a quadrupedal robot through a series of motions using position control. The Simulink controller consists of several sections: write commands, read commands, a state transition diagram in State flow, variable/command GUI, and Speedgoat IO691 setup blocks. Below are images of each section along with their respective subsections.

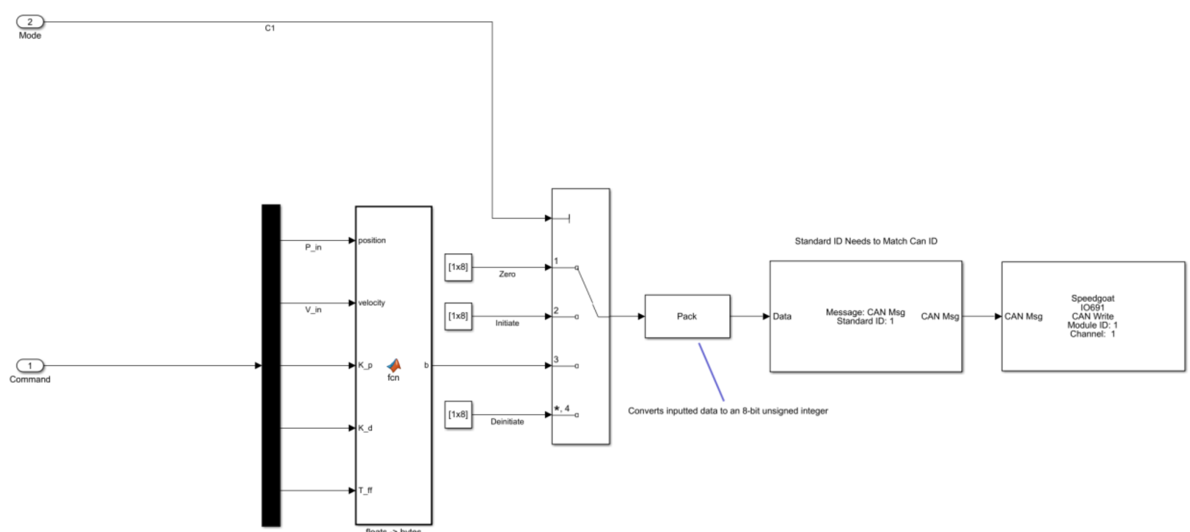
Overall Simulink Controller



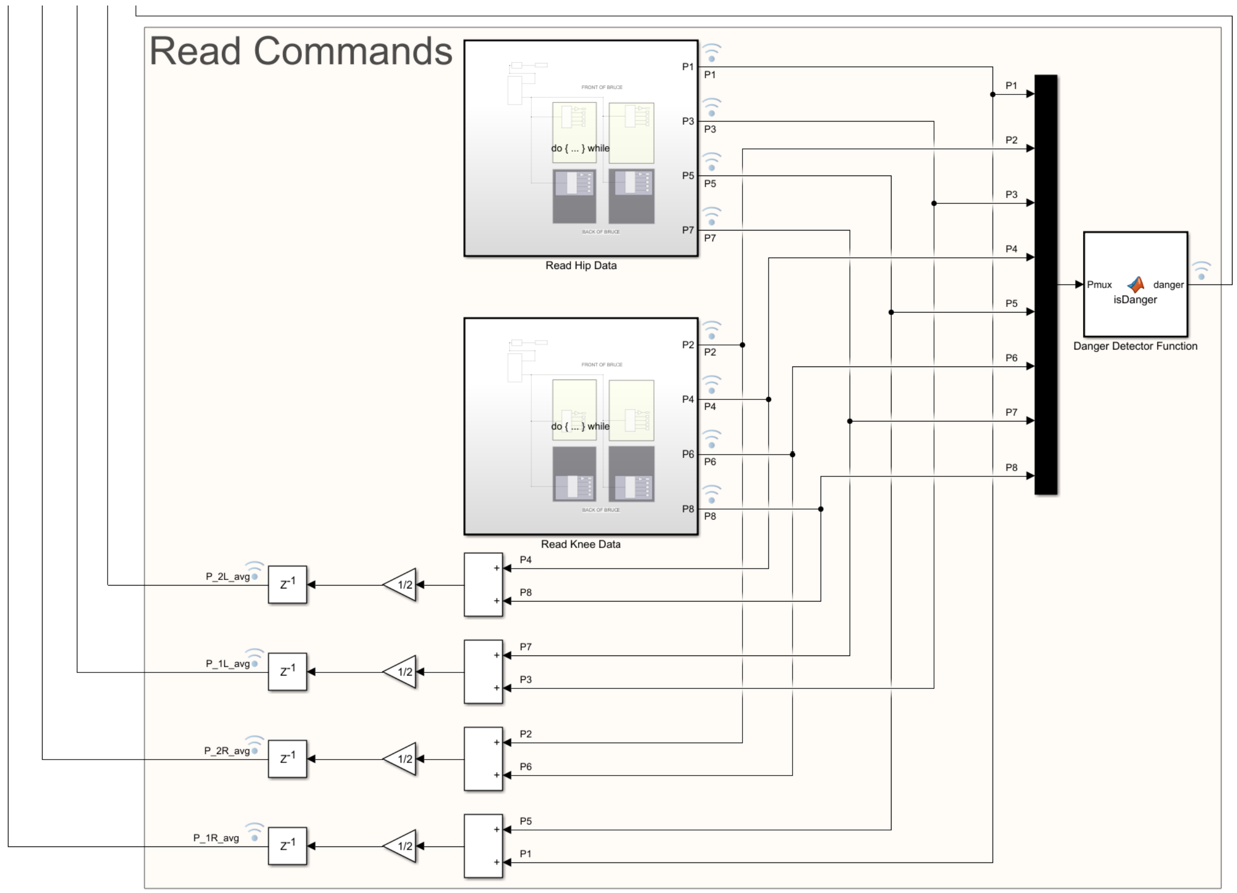
Write Commands Section



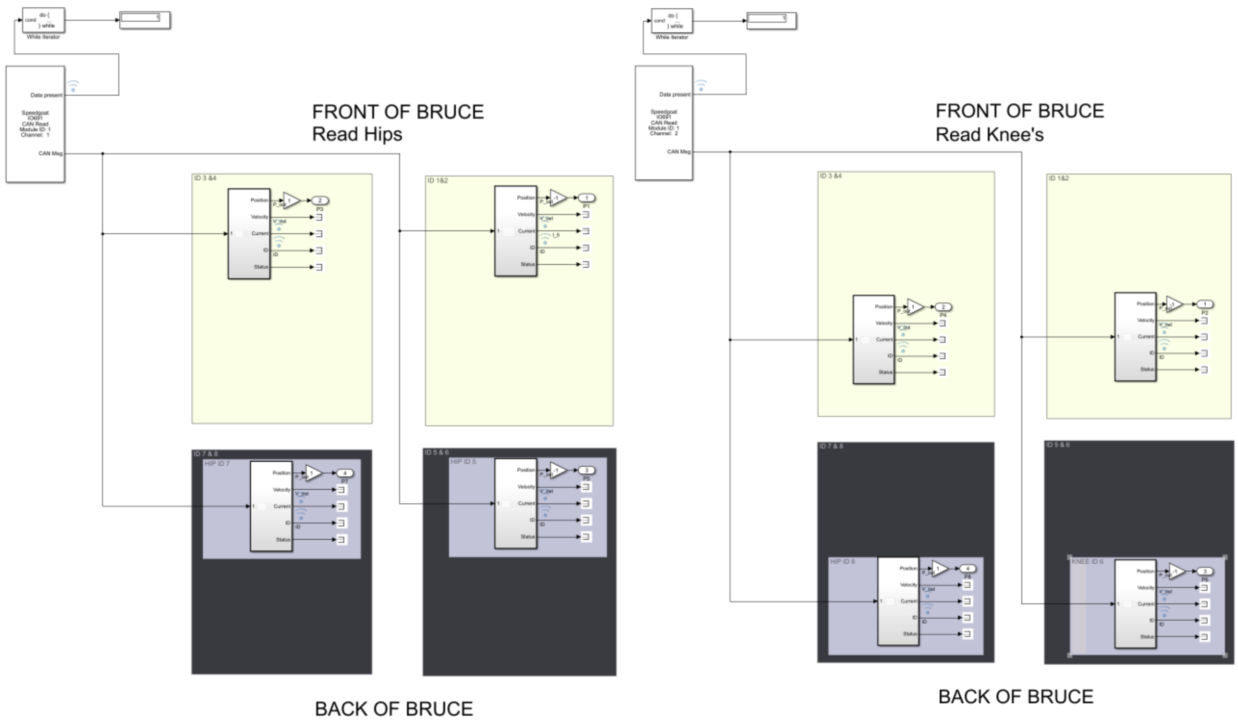
Individual Write Block



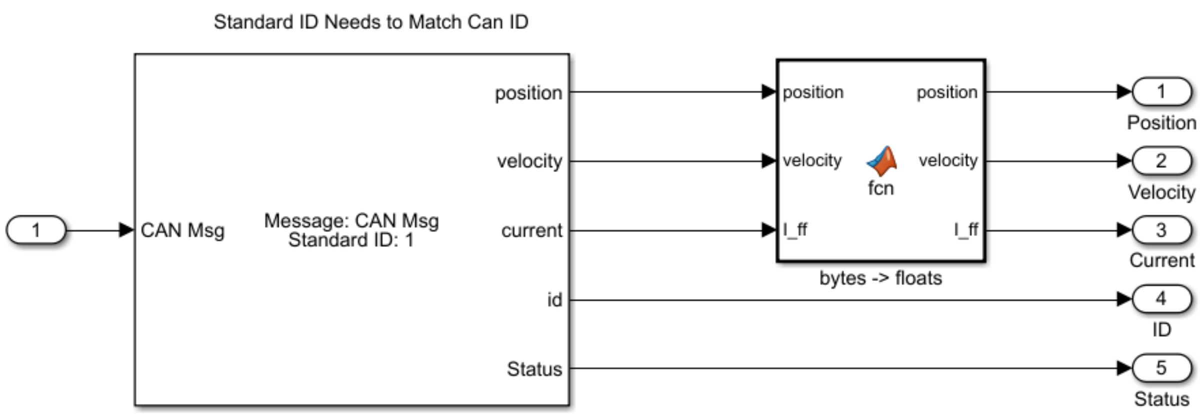
Read Commands Section



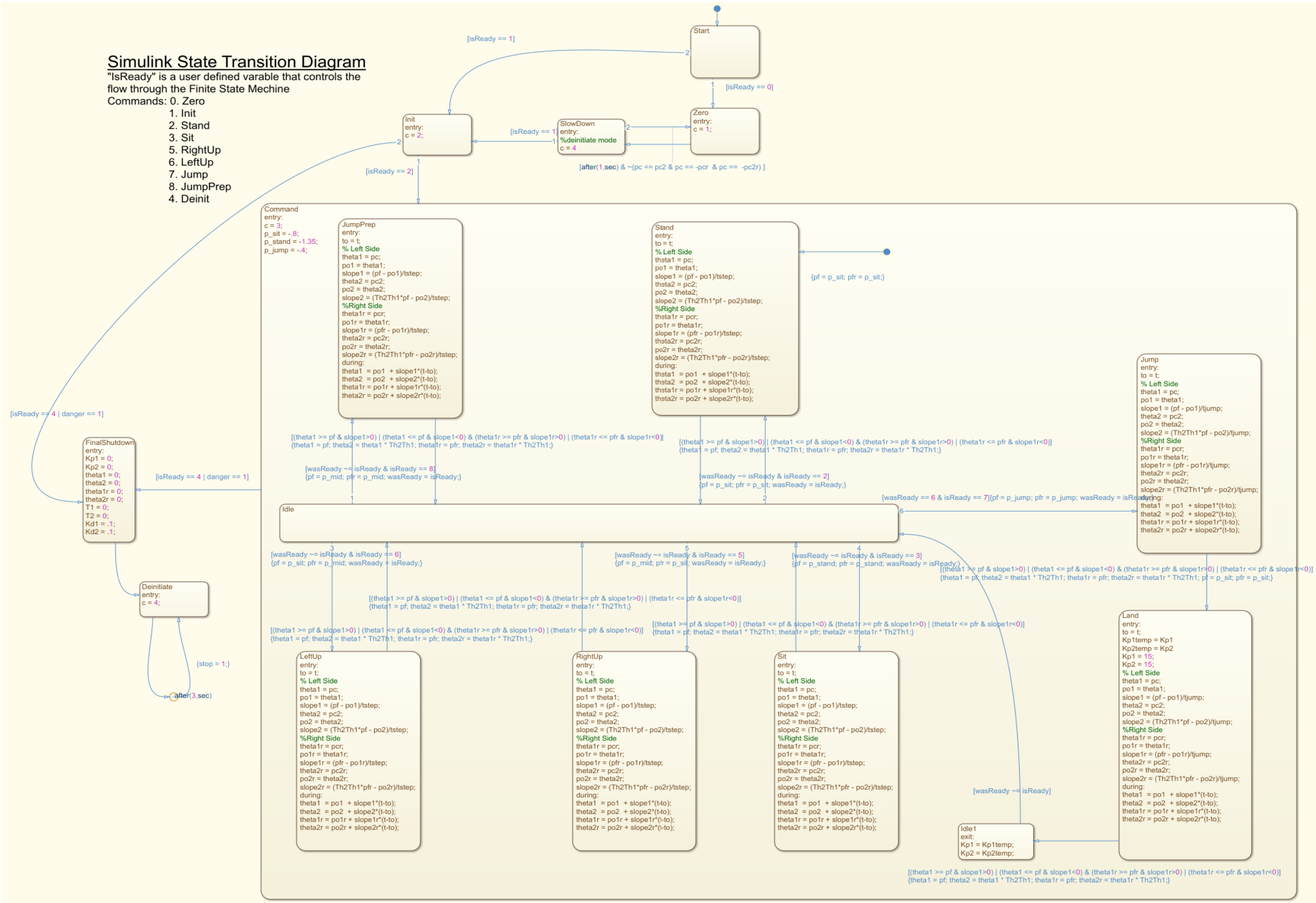
Hip/Knee Read Command



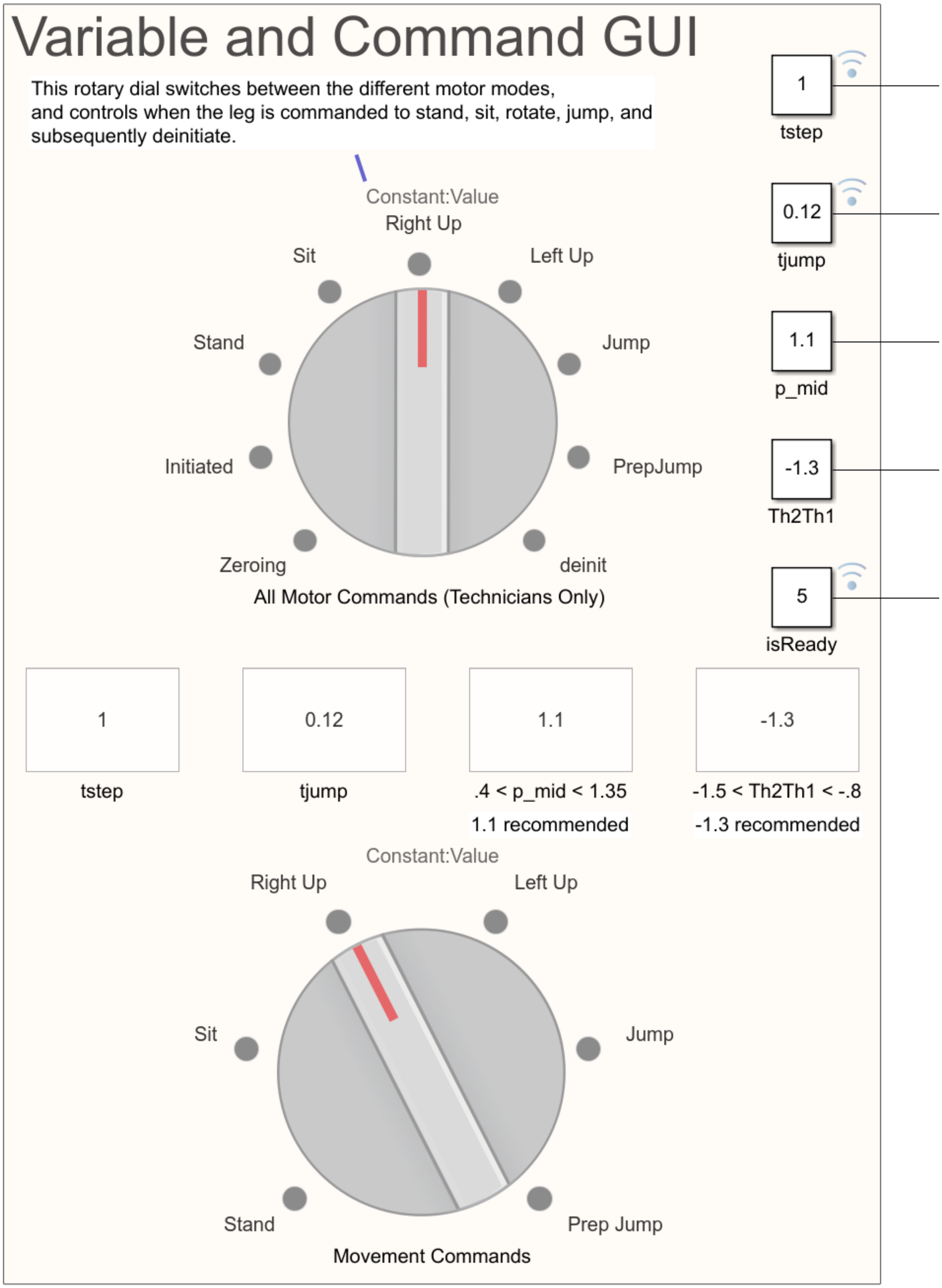
Read Command



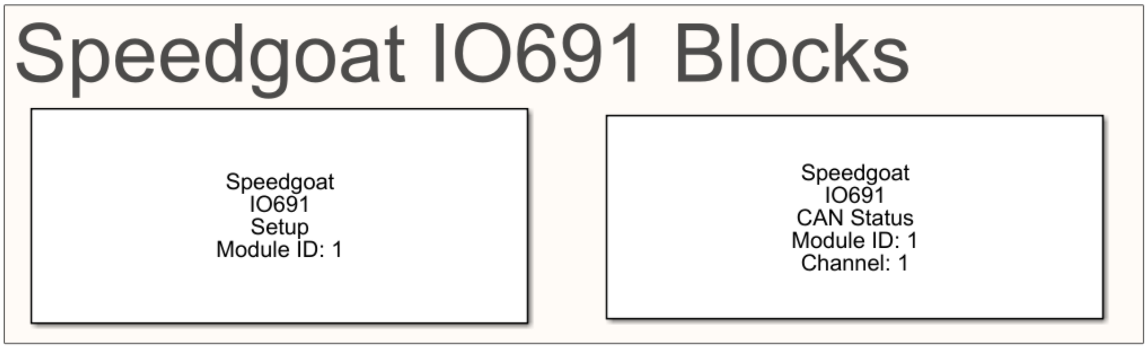
State Transition Diagram in Stateflow



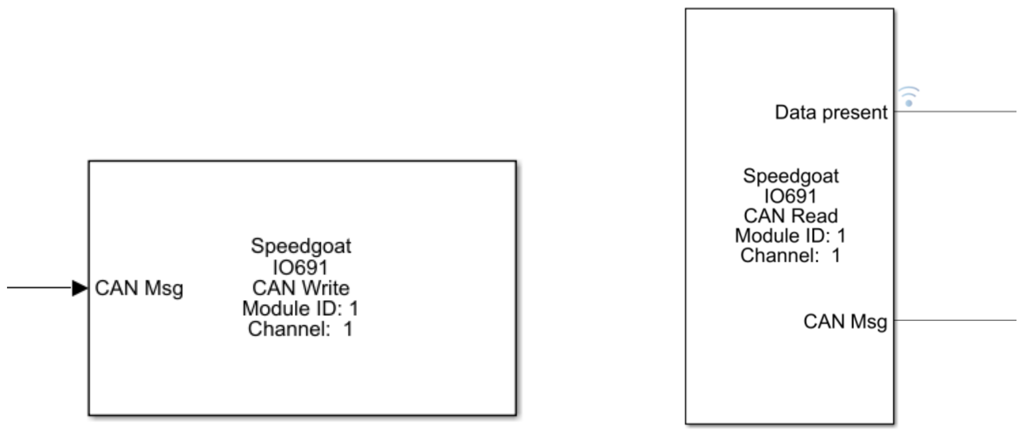
Variable and Command GUI



Speedgoat IO691 Setup Blocks



Speedgoat Read/Write Blocks



Appendix B – Final Project Budget

Assy Level	Design Part Number	Descriptive Part Name Lvl	Qty	Current Qty	Mat'l Cost	Production Cost	Total Cost	About	Part Source/Vendor	Date purchased and location	Procurement	More Info / Vendor Part Number
		0 1 2 3 4										
0	100000000	BRUCE							------			
1	101000000	Leg Assembly							------			
2	101010000	Upper Link					$ -		custom		Sponsor	mold in ABS
3	101010100	Pulleys	4	6	$ 31.00		$ 186.00	Pulleys to drive torque	Misumi		Sponsor	
3	101010200	Timing belt cover	4	1	$ -		$ -	PLA or polycarbonate	Custom		Sponsor	
3	101010300	Link Structure	4	0	$ -		$ -	Polycarbonate	custom		Sponsor	
3	101010400	Actuator-pulley adapter	4	4	$ -		$ -	Aluminum	Custom		Previously manufactured	
3	101010500	Hip-knee actuator adapter	4	4	$ -		$ -	Polycarbonate	Custom		Sponsor	
3	101010600	R6 Bearing	4	0	$ 2.50		$ 10.00	Knee bearings	Amazon		Sponsor	item 23-4509
3	101010700	MR696	16	16	$ 1.00		$ 20.00	Belt tensioner bearing	Amazon		Sponsor	https://www.amazor
3	101010800	M4 35 mm SCHS	56	20			$ 25.80	leg-actuator fasteners	Fastenal		Team reimb	1139530
3	101010900	M4 12 mm SCHS	28	20			$ 6.50	leg-actuator fasteners	Fastenal		Team reimb	https://www.fastena
3	101011000	M4 20 mm SCHS	28	20			$ 9.00	leg-actuator fasteners	Fastenal		Team reimb	https://www.fastena
3	101011100	M4 10 mm SCHS	28	20			$ 9.00	leg-actuator fasteners	Fastenal		Team reimb	https://www.fastena
3	101011200	M4 12 mm FHCS	24	6			$ 8.00	hip Adapter fasteners	Fastenal		Team reimb	1138842
3	101011300	M4 Washer	24	6			$ 3.23	hip Adapter fasteners	Fastenal		Team reimb	https://www.fastena
3	101011400	Pulley Belt	4	0	$ 22.00		$ 88.00	Timing belt to drive to	Royal Supply		Sponsor	https://www.royalsu
3	101011500	M3 30 mm dowel pins	20	6	$ 1.45		$ 20.30	Upper link alignment p	Fastenal? Or Amazon		Sponsor	https://www.fastena
3	101011600	M3 SHCS 35mm	24	24	$ 0.44		$ -	fasteners	Fastenal		Team reimb	https://www.fastena
3	101011700	M3 SHCS 25mm	16	4	$ 0.31		$ 3.72	fasteners	Fastenal		Team reimb	https://www.fastena
3	101011800	M3 SHCS 20mm	16	4	$ 0.31		$ 3.72	fasteners	Fastenal		Team reimb	2139507
3	101011900	M3 SHCS 12mm	16	4	$ 0.31		$ 3.72	fasteners	Fastenal		Team reimb	2139505
3	101012000	M3 Washers	16	4	$ 0.05		$ 0.65	fasteners	Fastenal		Team reimb	https://www.fastena
3	101012100	M3 Nuts	24	24	$ 0.10		$ -	fasteners	Fastenal		Team reimb	https://www.fastena
3	101012200	Flange Nut	5	5	$ 0.10		$ 3.50	fasteners	Fastenal		Team reimb	https://www.fastena
2	101020000	Lower Link					$ -		custom		Sponsor	https://www.fastena
3	101020100	Foot	4	0	$ -		$ -	rubber foot	Custom		Sponsor	vac-formed PET
3	101020200	Calf					$ -		Custom		Sponsor	
4	101020201	Calf Plate	8	0	$ 4.38		$ 35.00	Lower link aluminum p	BB Steel		Sponsor	
3	101020300	R6 Bearing	4	0	$ 2.50		$ 10.00	Knee bearings		item 23-45(	Sponsor	
3	101020400	Pulleys	4	0	$ 31.00			Pulley to receive torqu	Misumi	item 48123	Sponsor	item 48123
3	101020500	#6-32 Ultra low profile mach	24	8	$ 3.83		$ 61.28	Knee fasteners	McMaster			
3	101020600	#6-32 Ultra low profile mach	24	8	$ 3.83		$ 61.28	Knee fasteners	McMaster			
1	102000000	Body Frame Assembly		5							Sponsor	
2	102010000	Body Frame Structure							McMaster		Sponsor	item 48250
3	102010100	Side frame	2	0	$ -		$ -	Body frame chassis	B&B Metals/Custom		Sponsor	
3	102010200	Front/back frame	2	0	$ -		$ -		B&B Metals/Custom		Team reimbursement	
3	102010300	1"x1" 80/20 3.75" L	4	0	$ -		$ -	Chassis connectors	Charlire Refvem		Sponsor	
3	102010400	#10 t-nut	4	0	$ -		$ -	Chassis connectors	Charlie Refvem		Team reimbursement	
3	102010500	M4 Flange Nut	12	0	$ -		$ 3.72	Heat set inserts for ao	Amazon		Team reimb	https://www.amazor
3	102010600	Polycarbonate pa	2	0	$ -		$ -	Electronics panel	Leftover stock		Team reimbursement	
3	102010700	¼-20 Steel washe	16	0	$ 0.06		$ 1.00	Chassis connectors	Fastenal		Team reimb	https://www.fastena

3	102010800	1/4-20 0.75" Cap !	24	0	$ 0.40		$ 3.72	Chassis connectors	Fastenal and Mechatron		Sponsor	2123202
3	102010900	¼-20 Steel washer	32	0	$ 0.08		$ 1.00	Chassis connectors	Fastenal			1133004
3	102011000	M3 16 mm SHCS	8	0	$ 0.10		$ 0.80	Adapter fastener side	Fastenal			
3	102011100	M4 10 mm SHCS	4	0				Adapter fastener top	Fastenal			
2	102020000	Body Frame Layout							custom		Sponsor	mold in ABS
3	102020100	Battery	2	0	$ 125.00		$ 250.00	Deployment battery/b	HobbyKing		Sponsor	https://hobbyking.cc
3	102020200	STM32	1	0	$ 1.30		$ 1.30	Deployment computer	AliExpress		Sponsor	https://www.aliexpr
3	102020300	Power Distribution Board	1	0	$ -	$ 5.00	$ 5.00	step 24v down to 3.3 \	Bay Area Circuits or intl		Sponsor	TBD
3	102020400	Actuators	8	2		$ 359.00	$ 2,154.00	Make robot go brrr	AliExpress	1/25/22; M	CP Connect	https://www.aliexpr
3	102020500	Zip ties	20	20	$ -		$ -	Cable management	Dr. Siyuan Xi	ME 119-11	Sponsor	https://www.amazor
3	102020600	Capacitor	1	1	$ -		$ -	Prevent brownout	Charlie Refv	ME 119-11	Sponsor	
3	102020700	Adhesive zip-tie mounts	26	0	$ 0.19		$ 5.06	For mounting zip ties	Digikey		Sponsor	https://www.digikey
3	102020800	#12 stud 14 gauge ring termi	18	0	$ 0.19		$ 10.00	Power harness	Amazon		Sponsor	Can also find at ACE
3	102020900	#10 stud 5 gauge ring termin	18	0	$ 0.19			Power harness	Charlie		Sponsor	Can also find at ACE
3	102021000	1/4-20 5/8 inch machine scre	18	0	$ 0.19			Power harness	Mechatronics Lab		Sponsor	Can also find at ACE
3	102021100	XT90 Male/Female Connecto	8	0	$ 0.19			Power harness	Charlie		Sponsor	Can also find at ACE
3	102021200	Twisted quad (4 conductor) (	2	0			$ 184.05	Power harness	McMaster		Sponsor	8097T21
3	102021300	Green 20 Gauge wire	8	0			$ -	CAN Harness	Charlie		Sponsor	
3	102021400	Yellow 20 Gauge wire	8	0			$ -	CAN Harness	Charlie		Sponsor	
3	102021500	GH 1.25 Connector	8	0			$ -	CAN Harness	Charlie		Sponsor	
3	102021600	Precrimped JST Crimps	16	0			$ -	CAN Harness	Dr. Xing		Sponsor	
3	102021700	2 Pin Female Molex Connect	8	0			$ -	CAN Harness	Charlie		Sponsor	
3	102021800	2 Pin Male Molex Connector	16	0			$ -	CAN Harness	Charlie		Sponsor	
3	102021900	Molex Crimps	24	0			$ -	CAN Harness	Charlie		Sponsor	
3	102022000	120 Ohm Thru hole resistors	10	0			$ 5.99	CAN Harness	Amazon		Sponsor	
3	102022100	1"x3" perfboard	1	0			$ -	CAN Harness	Charlie		Sponsor	
3	102022200	T3609160101-000	1	0	$ 12.19		$ 12.19	cable glands	Amazon		Sponsor	https://www.amazor
3	102022300	10 AWG Wire [feet]	4	0	$ -		$ -	Wire harness	Charlie		Sponsor	
3	102022400	14 AWG Wire [feet]	8	4	$ -		$ 24.88	For power transmissoi	Digikey		Sponsor	https://www.amazor
3	102022500	5 AWG Wire [feet]	8	4	$ -		$ 33.99	For power transmissoi	Digikey		Sponsor	https://www.amazor
3	102022600	Relays	1	2	$ -		$ -	Regulate power transr	Charlie Refvem		Sponsor	TBD
3	102022700	Fuses	8	0	$ -		$ -	Ensure actuators aren	Digikey		Sponsor	Size TBD
3	102022800	Inline fuse holders	8	0	$ 3.00		$ 24.00	For securing fuses to c	Digikey		Sponsor	Size TBD
1	103000000	Test Stand Assembly										
2	103010000	Test Stand Frame										
3	103010100	80x20 Frame										
4	103010101	11" diagnal	2	2	$ -		$ -	Various 80/20 struts	------		Sponsor	
4	103010102	48	4	3	$ 34.56		$ 129.60	Various 80/20 struts	8020.net		CP Connect	https://8020.net/151
4	103010103	21.5	5	3	$ 15.48			Various 80/20 struts	8020.net		CP Connect	https://8020.net/151
4	103010104	29.5	2	0	$ 21.24			Various 80/20 struts	8020.net		CP Connect	https://8020.net/151
4	103010105	7.5	4	4	$ 5.40		$ -	Various 80/20 struts	8020.net		CP Connect	https://8020.net/151
4	103010106	4	5	5	$ 2.88		$ -	Various 80/20 struts	8020.net		CP Connect	https://8020.net/151
4	103010107	26.5	1	0	$ 19.08			Various 80/20 struts			CP Connect	https://8020.net/151
3	103010200	Corner Bracket	34	12	$ 8.43		$ 185.46	Various test stand stru	McMaster		CP Connect	4301
3	103010300	T Frame Bracket	4	1	$ 12.32			Various test stand stru	McMaster		CP Connect	T-Slotted Framing, Si
3	103010400	L Frame Bracket	22	0	$ 11.80			Various test stand stru	McMaster		CP Connect	https://www.mcmas
3	103010500	M6-1.0 x 18mm	8	54	$ 0.26		$ 3.72	Test stand mount	Fastenal		Sponsor	2139569
3	103010600	End-Feed Single Nut, M6 Thr	186	54	$ -		$ -	T-nuts for test stand			Sponsor	
3	103010700	5/16 X 3/4" BHSCS	186	54			$ 27.41	T-nuts for test stand			Sponsor	
2	103020000	20mm Guide Rail for Ball Bearing Ca	2	1			$ 800.00	Guide rail for ball bear	McMaster		CP Connect	20mm Wide Guide R
2	103030000	wood base	1	0	$ -		$ 26.00	Base for electronics to	Lumber Scraps/Hayward		Sponsor	24x26"
2	103040000	Castor Wheels	4	4	$ 35.99		$ -	Allows movement of t	Sponsor	ME 1119-11	Sponsor	https://www.amazor
2	103050000	Jumping Platform	1	0	$ 90.00		$ 96.75		McMaster		CP Connect	polycarbonate sheet

2	103060000	Speedgoat	1	1	$ -		$ -	Convets MATLAB to C	Dr. Siyuan Xi	ME 1119-1:	Sponsor	
2	103070000	24V/20A Power Supply	1	1	$ -		$ -	External power supply	Charlie Refv	ME 1119-1:	Sponsor	
2	103080000	Capacitor	1	2	$ -		$ 130.00	Keeps current supply s	Mouser Elec	ME 1119-1:	Sponsor	80-ALS70A363MF100
2	103090000	E-Stop	1	1	$ -		$ -	Manual power cutoff	Charlie Refv	ME 1119-1:	Sponsor	
2	103100000	12 AWG?	12	6			$ -	Power transmission ca	Charlie Refv	ME 1119-1:	Sponsor	
1	104000000	Test Stand Mount Assembly									Sponsor	
2	104010000	Body Mount-Shaft	2	0	$ -	$ 5.00	$ 10.00	Need weld to assemble			Sponsor	
3	104010100	Body Mount	2	0	$ -		$ -	Bolts in to Body End F	scrap metal from Body f		Sponsor	
3	104010200	Shaft	2	0	$ 2.51		$ 5.02	Shaft for test stand m	MetalsDepot		Team reimb	https://www.metals
2	104020000	Two-Bolt Flange Mount	2	0	$ 36.55		$ 73.10	Ball bearing that axiall	McMaster		Sponsor	Low-Profile Mountec
2	104030000	Mount Backing Plate	2	0	$ -		$ -	Protects ball bearing c	scrap metal from Body f		Sponsor	
2	104100000	M6x1 Hex Nut	8	0	$ 0.06		$ 7.53	fasteners	Fastenal		Team reimb	210153638
2	104040000	Spacer Plate	2	0	$ -		$ -	Adds extra room for fa	scrap metal from Body f		Sponsor	
2	104050000	Ball Bearing Carriage	2	1			$ 140.00	Slides on guide rail / g	McMaster		CP Connect	Ball Bearing Carriage
2	104060000	30mm M6x1 Fastener	8	0	$ 0.34		$ 3.72	Connects TSM to ball b	Fastenal		Team reimb	11103346
2	104070000	7/16" 3/4in Bolt	4	0			$ 7.53	Connects the ball bear	Fastenal		Team reimb	2123355
2	104080000	Hand Brake for Ball Bearing Carriag	2	1			$ 154.34	Supports ball bearing	McMaster		CP Connect	Hand Brake for Ball E
2	104090000	7/16" Hex Nut	1	0	$ 27.00		$ 27.00	fasteners	Fastenal		Team reimb	36498
		Parts Not In Final Design:	**Need**	**Current**	**Matl. Cost**	**Prod.**	**Total Cost**	**Item Description**	**Part Source/**	**Date purch**	**Procuremer**	**More Info / Vendor**
		24"x6" 22 gauge steel panels	2	0	$ 10.00		$ 20.00	For structural prototyp	Home Depot	2/5/2022; N	Team reimb	Store SKU #333763
		36" Aluminum rod 0.5" OD	1	0	$ 8.92		$ 8.92	For structural prototyp	Home Depot	2/5/2022; N	Team reimb	Store SKU #476935
		R6 ball bearings	1	0	$ 10.00		$ 10.00	For structural prototyp	Amazon	2/5/2022; N	Sponsor	ASIN : B07MWFT32D
		R8 ball bearings	1	0	$ 10.00		$ 10.00	For structural prototyp	Amazon	2/5/2022; N	Sponsor	ASIN : B07MWFZ86K
		0.5" ID steel shaft collar	1	0	$ 13.99		$ 13.99	For structural prototyp	Amazon	2/5/2022; N	Sponsor	ASIN : B0972PM7ZZ
		3/8 SHCS 1-1/4 Length	4	0	$ 0.88		$ 3.50	For structural prototyp	Fastenal	2/5/2022; N	Team reimb	1123307
		5/16 Jam nut	4	0	$ 0.88		$ 3.50	For structural prototyp	Fastenal	2/5/2022; N	Team reimb	1136304
		3/8 flange washer	4	0	$ 0.88		$ 3.50	For structural prototyp	Fastenal	2/5/2022; N	Team reimb	1133008
		Raw Materials			**subtotal**		$ 73.41					
		NinjaTek NinjaFlex Midnight Black TPU Filament - 1.75mm (0.5kg)			$45.00		$ 45.00					https://www.matter
		Raise3D Polycarbonate filament - 1.75 mm (1kg)	1	1	$49.99		$ -					https://profound3d.
		Black MH Build Series PLA Filament - 1.75kg (1 kg)	1	0	$18.99		$ 18.99					https://www.matter
		0.25 Aluminum Sheet stock 24" x 24"	2	0	$135.99		$ 271.98					B&B Metal
		1/8th inch thick aluminum angle stock 36"	1	0	$8.42		$ 8.42					https://www.homed
		0.5" OD aluminum round stock 36"	1	0	$11.88		$ 11.88					https://www.metals
		Tools			**subtotal**		$ 356.27					
		Case for fasteners from ACE					$ 23.91					
		SAE and Metric Allen wrench tools					$ 10.00					
		Loctite					$ 7.56					
		Bad orders										
		T106D1 Diode	1				$ 10.00					
	Total Parts		**1331**	**462**			**$ 5,597.71**					
			1331	462								

Appendix C – Risk Assessment

B.R.U.C.E. Safety 2/15/2022

designsafe Report

Application:	B.R.U.C.E. Safety		Analyst Name(s):	BRUCE Bot Engineers
Description:	Safety Stoof for B.R.U.C.E. Use		Company:	Cal Poly SLO Legged Robots
Product Identifier:	BRUCE		Facility Location:	You already know
Assessment Type:	Detailed			
Limits:				
Sources:	BRUCE Documentation, CDR document, onenote logbook			
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	technician(s) set-up or changeover	mechanical : sharp edges Body Frame	Minor Likely	Low		Minor		On-going [Daily]
1-1-2	technician(s) set-up or changeover	pinch points : Leg Pinch	Serious Likely	High	Pinch point signs	Serious Unlikely	Medium	On-going [Daily] Tyler
1-1-3	technician(s) set-up or changeover	fire and explosives : sparks / flames	Serious Remote	Low		Serious		On-going [Daily]
1-2-1	technician(s) preventative maintenance	None : no hazards	Minor Remote	Negligible		Minor		On-going [Daily]
1-3-1	technician(s) demonstration	struck by/impact : robot Get hit with robot	Moderate Remote	Negligible		Moderate		On-going [Daily]
1-3-2	technician(s) demonstration	struck by/impact : Leg Impact	Minor Unlikely	Negligible		Minor		On-going [Daily]
1-3-3	technician(s) demonstration	mechanical : sharp edges	Minor Likely	Low		Minor		On-going [Daily]

Page 1 Privileged and Confidential Information

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-3-4	technician(s) demonstration	pinch points : Leg Pinch	Serious Likely	High	Pinch point signs	Serious Unlikely	Medium	On-going [Daily] Tyler
1-3-5	technician(s) demonstration	electrical / electronic : burns	Serious Remote	Low		Serious		On-going [Daily]
1-3-6	technician(s) demonstration	electrical / electronic : software errors	Moderate Remote	Negligible		Moderate		On-going [Daily]
1-3-7	technician(s) demonstration	fire and explosives : sparks / flames	Serious Remote	Low		Serious		On-going [Daily]
1-4-1	technician(s) shut down	mechanical : sharp edges	Minor Likely	Low		Minor		On-going [Daily]
2-1-1	engineer(s) trouble-shooting / problem solving	mechanical : crushing / impact	Moderate Unlikely	Low		Moderate		On-going [Daily]
2-1-2	engineer(s) trouble-shooting / problem solving	mechanical : unexpected motion	Minor Very Likely	Medium		Minor		On-going [Daily]
2-1-3	engineer(s) trouble-shooting / problem solving	pinch points : Leg Pinch	Serious Unlikely	Medium	Pinch point signs	Serious Remote	Low	On-going [Daily] Tyler
2-1-4	engineer(s) trouble-shooting / problem solving	electrical / electronic : software errors	Moderate Very Likely	High	Write good and tested code	Moderate Likely	Medium	On-going [Daily] Daniel

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-1-5	engineer(s) trouble-shooting / problem solving	ergonomics / human factors : posture	Minor Likely	Low		Minor		On-going [Daily]
2-1-6	engineer(s) trouble-shooting / problem solving	fire and explosives : sparks / flames	Serious Unlikely	Medium	Appropriate wiring and soldering	Serious Remote	Low	On-going [Daily] Daniel
2-2-1	engineer(s) adjust controls	struck by/impact : Leg Impact	Moderate Likely	Medium		Moderate		On-going [Daily]
2-2-2	engineer(s) adjust controls	mechanical : unexpected motion	Minor Very Likely	Medium		Minor		On-going [Daily]
2-2-3	engineer(s) adjust controls	pinch points : Leg Pinch	Serious Unlikely	Medium	Pinch point signs	Serious Remote	Low	On-going [Daily] Tyler
2-3-1	engineer(s) teach robot	struck by/impact : Leg Impact	Moderate Likely	Medium		Moderate		On-going [Daily]
2-3-2	engineer(s) teach robot	mechanical : unexpected motion	Minor Very Likely	Medium		Minor		On-going [Daily]
2-3-3	engineer(s) teach robot	pinch points : Leg Pinch	Serious Unlikely	Medium	Pinch point signs	Serious Remote	Low	On-going [Daily] Tyler
3-1-1	passer-by / non-user walk near robot	struck by/impact : robot	Moderate Remote	Negligible		Moderate		On-going [Daily]

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
3-1-2	passer-by / non-user walk near robot	struck by/impact : Leg Impact	Moderate Remote	Negligible		Moderate		On-going [Daily]
3-2-1	passer-by / non-user misuse - (add description)	struck by/impact : robot	Moderate Likely	Medium		Moderate		On-going [Daily]
3-2-2	passer-by / non-user misuse - (add description)	struck by/impact : Leg Impact	Moderate Likely	Medium		Moderate		On-going [Daily]
3-2-3	passer-by / non-user misuse - (add description)	pinch points : Leg Pinch	Serious Likely	High	Pinch point signs	Moderate Unlikely	Low	On-going [Daily] Tyler
3-2-4	passer-by / non-user misuse - (add description)	electrical / electronic : burns	Serious Remote	Low		Serious		On-going [Daily]
3-2-5	passer-by / non-user misuse - (add description)	fire and explosives : sparks / flames	Serious Unlikely	Medium	Dont let them touch electronics	Serious Remote	Low	On-going [Daily] Clay

Appendix D – User Manual

D.1 Safety and PPE

There is no PPE required to operate our system. However, one must be careful to remain a safe distance from the quadruped during operation and keep all extremities away from the quadruped to avoid pinching. The actuators can produce significant torques and rotational velocities, so the risk of pinching is high during operation.

Additionally, our system draws high currents and voltages. With eight actuators, our current draw can easily reach tens of amps. There is no risk for fire or burning of electronics, but the screw terminals on the quadruped and power supply should remain covered and out of reach when the system is powered on.

D.2 Assembly and Repair Procedures

Refer to the manufacturing summary for detailed assembly guidelines.

While repair is unlikely, if it were to be necessary it would be due to fatigue in the 3D printed components. To replace one of the 3D printed components, reprint the damaged part using the appropriate STL file in the Quadruped CAD GrabCAD.

D.3 Operation of the System

The following section outlines the operation of the controller, the test stand, and the various pre-purchased electronics that our subsystem uses.

D.4 Simulink Controller

The Simulink controller is saved in the file main_quad_rev5_31_315pm.slx. See Appendix A for documented Simulink script. This file allows us to manually cycle through each phase of set up at a safe pace. The phases are Zeroing, Initiated, Stand, Sit, RightUp, LeftUp, Jump, PrepJump, and de-initiate. These phases are controlled by the rotary switch seen in Figure D.1.

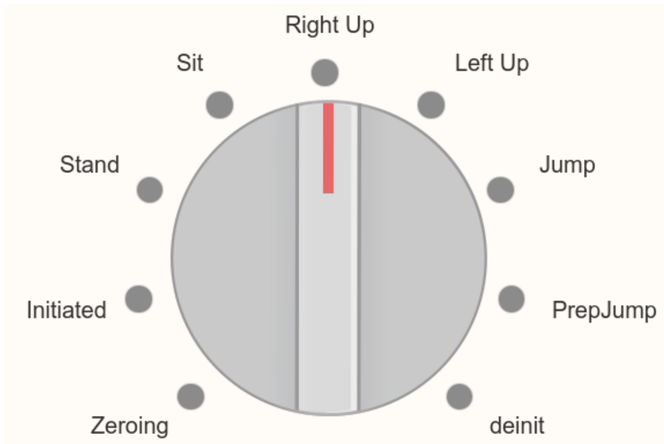


Figure D.1: Rotary Switch in Simulink file. Nine Phases of operation

There is a second rotary switch that just controls the motion commands, see Figure D.2. This switch is recommended to be used to avoid accidentally de-initiating during testing.

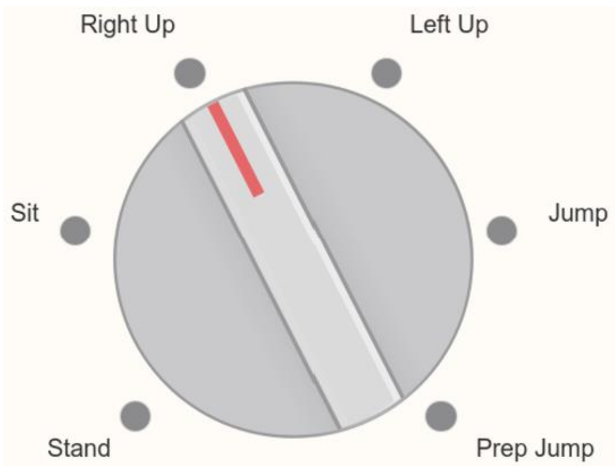


Figure D.2: Rotary Switch in Simulink file. Motion Commands only

The flow of phases is managed in a Stateflow block, shown in Figure D.4. The Stateflow is set up to limit the changes between states in a way that makes sense. One cannot set the rotary switch to jump then hit run on the simulation, an incorrect command will put the robot in an idle phase until a correct command is given. The commands are generally in the order seen on the switch moving left to right, With the exception that we can move between all movement commands, we could skip zeroing, and we can go to de-initiate from any phase.

D.5 Tunable Parameters

There are several parameters that can be adjusted to change the operation of the robot. This section will discuss what parameters are and where they should be tuned. Reference Figure D.3 for variable locations.

Variable	Symbol	Description
Movement Time	tstep	The time it takes to move from one position to the next
Jump Time	tjump	The time it takes for the robot to push of the ground
Hip Initial Jump angle	p_mid	The angle the hip actuator will be set to before each jump
Leg Angle Ratio	Th2Th1	Theta 2 (knee angle) over Theta 1 (hip angle). The angle ratio should place the be the angle that places This parameter is used to
Landing Actuator Gain Parameters	Kp1, Kp2, Kd1, Kd2	Landing actuator gains which are different to flight gains. Kp is the positional gain, Kd is the velocity gain. 1 represents the hip actuator and the 2 represents the knee actuator.
Jumping Actuator Gain Parameters	Kp1, Kp2, Kd1, Kd2	Jumping actuator gains which are different to landing gains. Kp is the positional gain, Kd is the velocity gain. 1 represents the hip actuator and the 2 represents the knee actuator.

The majority of these variables can be tuned during testing without de-initiating from the variable and command GUI, see Figure D.3. All the Kp and Kds can be changed in stateflow the jumping gains can be edited in the symbol panal and the landing gains can be tuned in the block named “land” located inside the block named “command” this is circled in red on the Stateflow diagram.

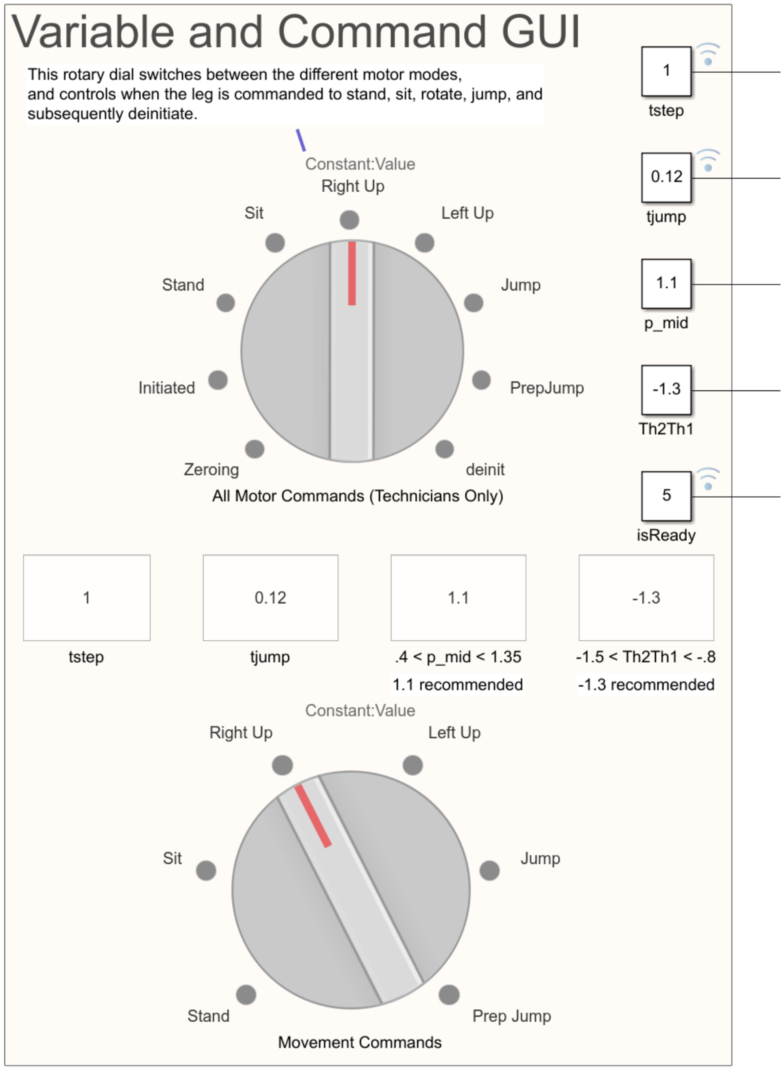


Figure D.3: Variable and Command GUI

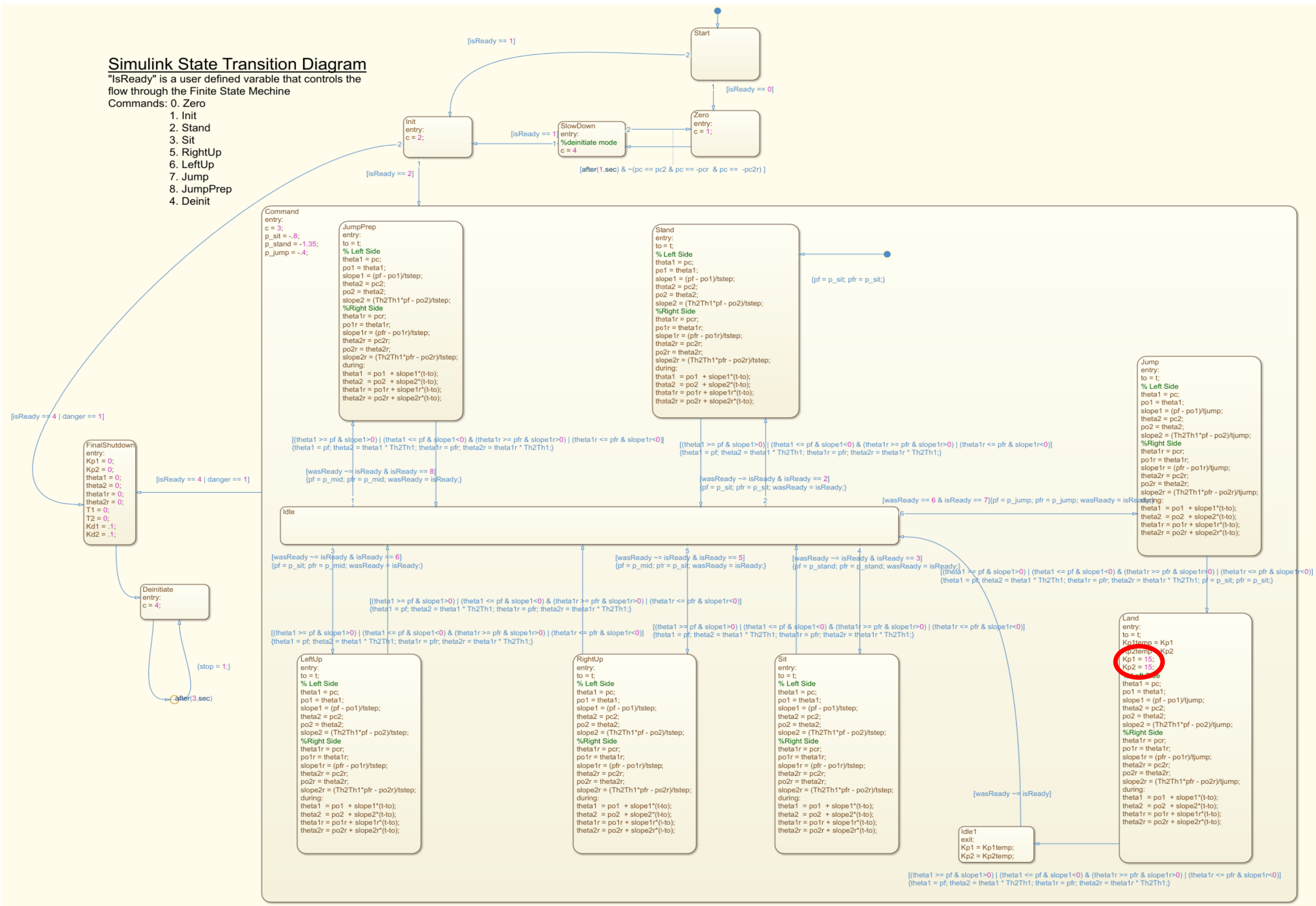


Figure D.4: Simulink State Flow diagram

D.6 Initial Startup and Zeroing Instruction

Note every time the robot loses power and is rebooted for any reason the robot must be zeroed (i.e. power cycle to actuators).

1) Suspend the robot and adjust the quadruped's joints so that they extend downwards. The legs will be stretched out in a neutral orientation forming a zero angle for our testing.

2) Before running the Simulink file, set rotary switch to Zeroing.

3) Run the Simulink file, wait until code has compiled and code is running (roughly 1 minute), then set the rotary switch to initiate.

4) After robot is initiated unsuspend the robot and set it on the jumping platform in an orientation that in a crouching or sitting position.

D.7 Standard set up between tests

Note use this set up when the quadruped does not need to be zeroed since power was never lost.

1)Before running Simulink file, make sure the robot is in a neutral/squat position resting on the test stand and the rotary switch is set to initiate.

2)Run file the initiate Robot

D.8 Command phases (Stand and Jumping)

Note if anything seems is wrong you can either switch the rotary switch to de-initiate or hit the Estop

1) Before switching from initiate to stand make sure that there is one person holding the Estop. This person should be watching the robot and prepared to press it if anything fails.

2) Once ready for the stand phase, turn the rotary switch to stand. The robot will slowly begin to stand wait until the stand movement is complete. You will not be able to proceed to any other command phase until the stand phase is complete.

3) All movement commands except for jump can now be used. As before you will not be able to proceed to any other command phase until the current command is complete.

3) When jumping, the prep-Jump phase must be active before switching to the jump phase. The robot will perform a jump. The person on the Estop should be extra alert for this phase.

4) After testing is complete the robot should be set to sit and once it sits. de-initiate the robot.

D.9 De-initiating

Unlike the other phase which can only be selected in a specific order the de-initiate command on the rotary switch will always de-initiate the motors. When de-initiated the robot will not lose power but it will stop executing commands and will collapse. Since power was never lost, we can go straight into the standard set up.

D.10 Using the Test Stand and Quadruped

The quadruped and test stand can be used in two configurations, single leg testing, and full system testing. Each configuration has its own mount, power, and CAN harness.

To begin testing, first place the test stand in an appropriate location. Once situated lock all caster wheels at the base to ensure the stand does not move while testing. Next plug in all systems such as the Speedgoat, power supply and other testing equipment.

To initiate single leg testing, first detach one leg from the B.R.U.C.E. quadruped. Then get the single leg testing mount and attach it to one of the slider rails, which one does not matter. Release the slider brake and put it in a lower position for now. Mount the leg with the appropriate fasteners and apply the slider brake such that the leg still has full motion, but the motors will not hit the ground in case of failure.

To initiate full system testing, first ensure all legs are attached accordingly and all motors are plugged in. Next lower the brakes on the sliders until they are at the base of the platform. Next align the B.R.U.C.E. system with the slider mounts and fasten accordingly. Ensure there is no binding then gently lift the quadruped and re-engage the slider brakes in a position that will allow the robot to jump but stop it in the event of a failure.

D.11 Using the Actuators

The relevant connectors on the actuator are the XT30 connector, GH1.25 connector, and MOLEX 51146 Buckle connectors. The XT30 connectors provide the 24 V power to the actuator. The GH1.25 connector is for the CAN communication. The MOLEX 51146 Buckle connector is for the UART communication, which is used to set relevant parameters of the actuator such as the device CAN ID, and other useful parameters. Reference Figure D.5 and D.6 for connector images [1]. Reference open-source documentation about the actuators at this link [1]:

https://docs.google.com/document/d/1QIEI6IdHOcW4N1cRyucb33io4LriNYafIMs1sjLfTQU/edit

Figure D.5: CAN connector (GH1.25) and 24V power connectors (XT30). We did not use the 5 V power.

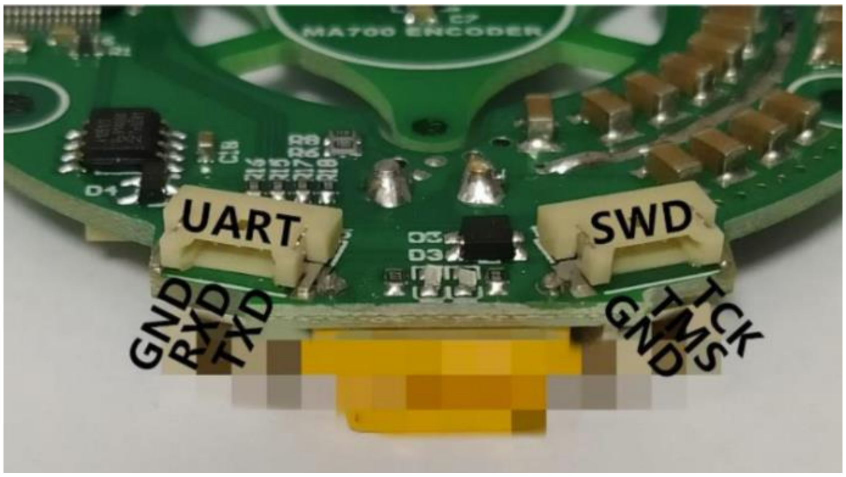


Figure D.6: UART connector (MOLEX 51146). SWD not used.

D.12 Using the Speedgoat

How does one setup and interface with the Speedgoat? What MATLAB/Simulink toolboxes does one need to use the Speedgoat? Add links to useful Speedgoat websites and documentation and downloads.

D.13 What is a Speedgoat

Simulink Real-Time™ and Speedgoat takes simulation to rapid control prototyping (RCP) and hardware-in-the-loop (HIL) testing in a single click. The products connect to electronic control units and physical systems with MATLAB® and Simulink®

D.14 Speedgoat Required Files

To run our simulation, you need to download the newest version of MATLAB and download several MATLAB toolboxes.

Toolbox/Software	MATLAB Description
Simulink	Simulation and Model-Based Design
Stateflow	Model and simulate decision logic using state machines and flow charts
Simulink Real-Time	Perform rapid control prototyping and hardware-in-the-loop testing
Simulink Desktop Real-Time	Simulink Desktop Real-Time supports real-time performance up to a 1 kHz sample rate with Simulink, and up to 20 kHz with Simulink Coder™.
Vehicle Network Toolbox	Communicate with in-vehicle networks using CAN, J1939, and XCP protocols
Simulink Coder	Generate C and C++ code from Simulink and Stateflow models.
MATLAB Coder	Generate C and C++ code from Simulink and MATLAB models.
HDL Coder Integration Packages	HDL Coder Integration Packages enable you to run Simulink models on your Programmable FPGA I/O module using the HDL Coder™ workflow.
I/O Blockset (IO691)	Simulink block library allowing you to use Speedgoat hardware.
Configuration Files for Configurable I/O modules	Configurable I/O modules allow you to define and redefine required I/O functionality and channel count.

The blockset used for our application is blockset IO691. See Appendix A for Simulink model with IO691 blocks

D.15 Hardware Set Up

For our application we have two connectors on the “back” (Figure D.9), the host link and power input, and two DB9 connectors on the “front” (Figure D.8) I/O Module 2 Ports A and B. Once all the cables are plugged in, press the power button on the Speedgoat.

Figure D.8: Front of the Speedgoat with Labels

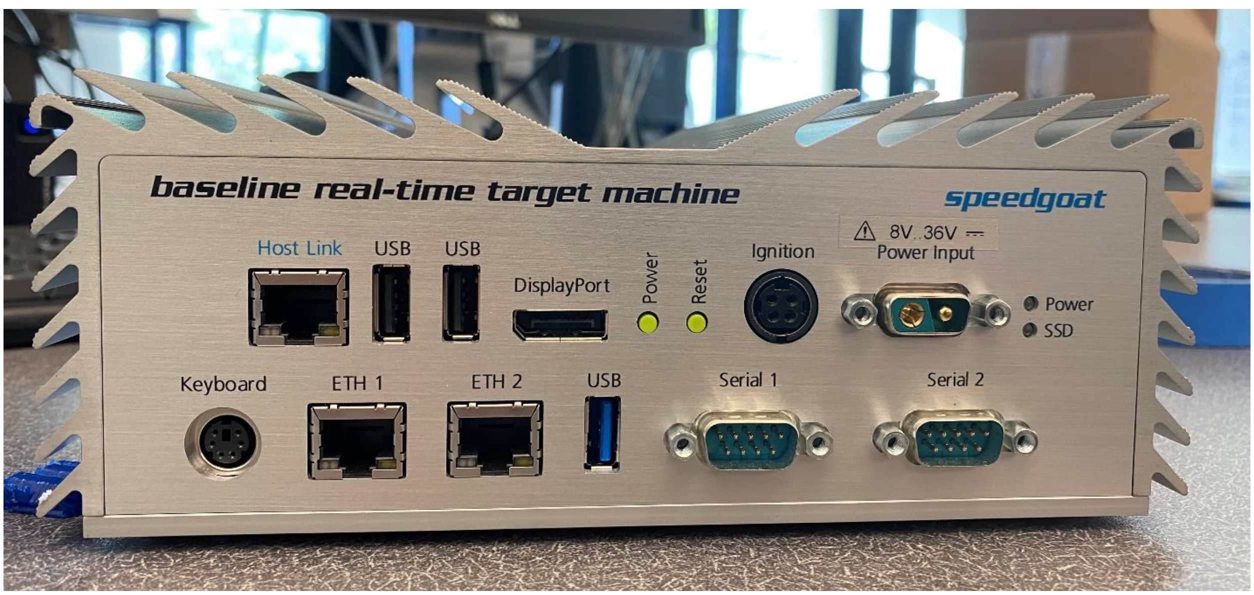


Figure D.9: Back of the Speedgoat with Labels

D.16 Software Set up

Initial set up begins with setting up the target computer Ethernet connection. The static IP address for the Speedgoat is 192.168.7.5. Also set the target computer IP address to something different then the static IP address (recommend 192.168.7.4) and set Subnet mask address to (255.255.255.0). To get to the view in Figure D.10 click on the down arrow above disconnected in Figure D.11, then click on SLRT Explorer.

If the target computer and the Speedgoat MATLAB versions do not match hit the update software button to make the MATLAB versions match. If you want to change the IP address of the target computer hit the "change IP address button".

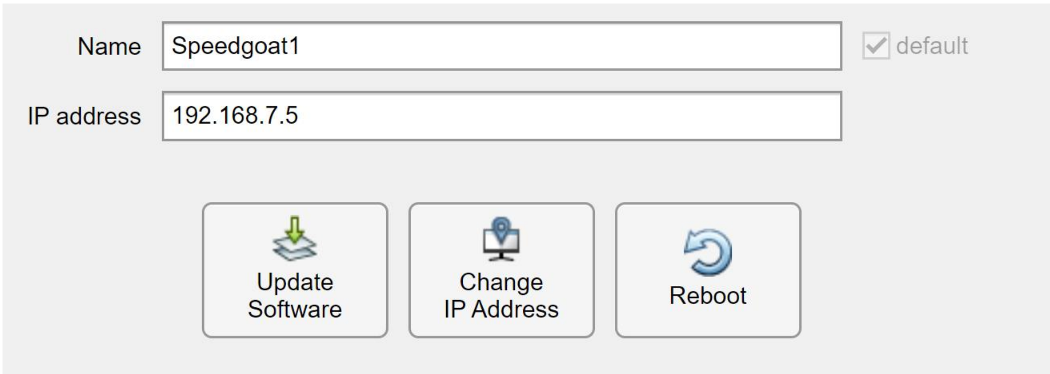


Figure D.10: Simulink Real-Time Explorer

Once a connection is established open Simulink real-time tab then hit the disconnected button to connect to the speedgoat. Once the button says connected, we can run the Simulink files by hitting the start button.

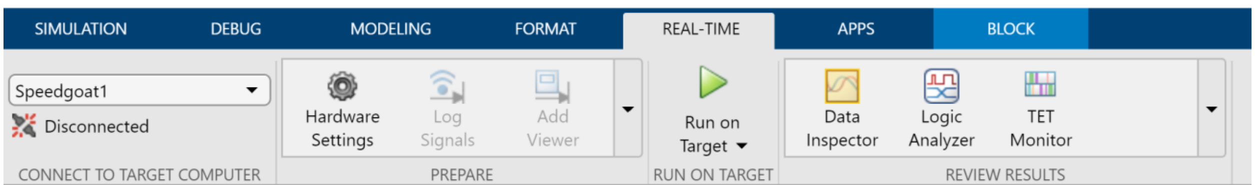


Figure D.11: Simulink Real-Time Tab

For trouble shooting and toning the controller we recommend using the Data Inspector to analyze and record data while running. The Data inspector is a great way to record and observe what the controller/quadruped is doing.

D.17 More information

https://www.mathworks.com/help/slrealtime/ug/command-line-pci-bus-ethernet-setup-multiple-target-computers.html#:~:text=Connect%20Ethernet%20Cables%20To%20configure%20the%20target%20computer,computer%20Ethernet%20card%20by%20using%20Simulink%C2%AE%20Real-Time%E2%84%A2%20Explorer.

D.18 Using the KEPCO 24 V Power Supply

The 24 V power supply is simple to operate. Plug the KEPCO's power cord into a wall outlet, and then flip the large black I/O switch to the "I" position. Set the power supply's voltage by pressing the "V" button and turning the white dial, for current press the "A" button. To switch between constant current and constant voltage on the power supply, press the "shift" button and then press either the "OVP" (overvoltage) or "OCP" (overcurrent) buttons. To send power to the actuators, press the green button labeled "OUT" (Figure D.12).

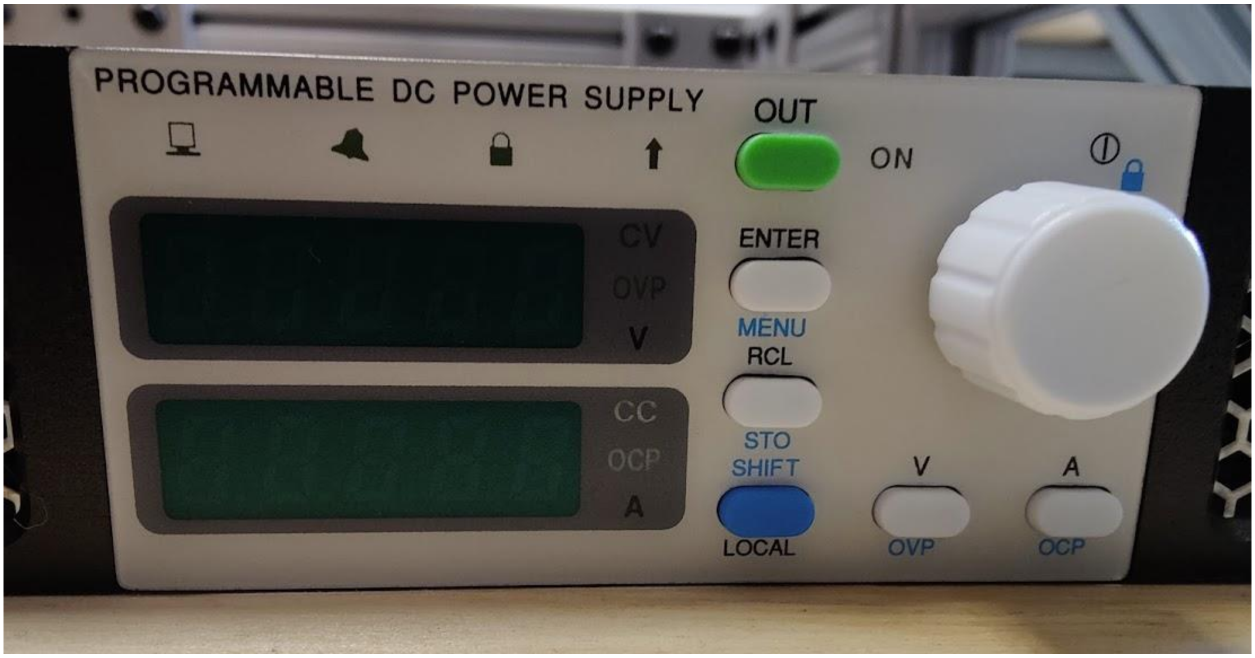


Figure D.12: KEPCO Power supply user interface

The actuators in our quadruped use 24 V so there is no reason to change the power supply's setting from 24 V constant voltage. If the robot is doing dynamic motion that requires a large torque value, then increasing the current limit might be required to maintain constant voltage. We ended up having to set the limit at 25 A to operate the quadruped, but we never saw the current rise above 10 A on the power supply's current display.

D.19 Parts List:

KEPCO 24 V Power Supply
Speedgoat Real-Time Target Machine
Modular Test Stand
Single Leg Testing Mount
B.R.U.C.E. Quadruped

Appendix E – DVP&R

DVP&R - Design Verification Plan (& Report)

Project: F72 8DOF Quadrupedal Robot | Sponsor: Dr. Siyuan Xing and Charlie Refvem | Edit Date: 2/4/2022

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	Finish date	Numerical Results	Notes on Testing
1	Vertical leap height	Measure the height that the ball bearing carriage is displace when the quadruped is executing a vertical hopping motion. Alternatively, measure the hieght that the foot reaches off the ground	Vertical displacement of the ball bearing carriage and foot of robot	10 cm vertical displacement	24V power; large open space	Quadrupedal prototype and modular test stand	Clayton	3/22/2022	5/31/2022	10.02 ± 0.29cm Standard Deviation: 0.095	Front of chassis jumped higher than rear of chassis likely due to foot position.
2	Fatigue durability	Cycle the quadrupedal robot and single leg redesign through >1000 cycles. Evaluate and inspect if any fatigue or wear has occurred at any points of the robot. Specifically inspect the knee joint in the leg, and the brackets/fasteners on the body frame	Number of jumping cycles the leg has executed	>1000 cycles	24V power supply; large open space; either a Nucleo (if C/C++ controller is ready) or Speedgoat (if C/C++ controller is not ready)	Modular test stand (for quadruped); summer test stand (for single leg) supply	Clayton	3/22/2022	5/31/2022	N/A	No visible fatigue. Previous knee joint assembly issue is no longer present
3	Assembly time	Assemble the quadruped (excluding the test stand). This includes the legs, body frame, and setting up the various cable harnesses and installing necessary electronic components	Time to assemlble quadruped	<10 minutes	Variety of allen keys, large open space and table to assemble at (likely in 119-118)	Quadrupedal prototype	Clayton	3/21/2022	5/17/2022	47 minutes for mechanical assembly time	We assembled the different subsystems of the quadruped individually, as well as the time to put the subsystems together, and then added up all the individual times
4	Weight management	Measure the total weight of the quadrupedal robot when fully assembled	Weight of the quadruped	<10 kg	Large plate scale or spring scale	Quadrupedal prototype	Clayton	3/21/2022	5/17/2022	9.95kg	Mechanical mass with capacitor included

DVP&R - Design Verification Plan (& Report)

Project: F72 8DOF Quadrupedal Robot | Sponsor: Dr. Siyuan Xing and Charlie Refvem | Edit Date: 2/4/2022

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	Finish date	Numerical Results	Notes on Testing
5	Center of mass location	Examine the behavior of the quadruped during flight; does it roll to the left or right? If so, the COM is poorly located. To measure the robot's tendency to pitch, we may examine the COM of the body frame/internal electronics in SOLIDWORKS, and verify the numerical values with hand calculations of the COM location	X, Y, X coordinates of the COM	<0.5 inches from the body frame's geometric center	24V power, large open space	Quadrupedal prototype and modular test stand	John	3/21/2022	5/17/2022	N/A	Center of mass is close to the geometric center of the chassis. We suspended the quadruped on our test stand mount that allows rolling, and observed that the quadruped only rolls from equilibrium when subjected to an external force.
6	Compilation time	Record the amount of time it takes for the controller to run once compilation begins	Time to compile controller code	<5 minutes	STM microcontroller	None	Daniel	4/20/2022	Scope Changed to no longer need a STM microcontroller		
7	Total cost of components	Total the cost of the components for quadruped and test stand	Cost of components	<$5,000	None	None	Tyler	2/24/2022	5/27/2022	Total expenditures for test stand, quadruped, and parts not in assembly is approximately $5,500. Exact number will be determined 6/3/2022	CP Connect grant gave us an extra $3,600. So the new budget is $8,600.
8	Avoid rolling during flight	Examine the quadruped's tendency roll during flight (film the flight of the robot too); if the left and right side legs of the quadruped do not impact at the same time, then the robot has rolled.	Time difference between left and right side leg impacts	Time difference between left and right sides <0.05 seconds	24V power; large open space	Quadrupedal prototype and modular test stand	John	4/1/2022	6/1/2022	N/A	The quadruped never rolled during flight; the response time for each leg was nearly identical and produced a very repeatable flight.

DVP&R - Design Verification Plan (& Report)

Project: F72 8DOF Quadrupedal Robot | Sponsor: Dr. Siyuan Xing and Charlie Refvem | Edit Date: 2/4/2022

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	Finish date	Numerical Results	Notes on Testing
9	Leg response overcorrection / steady state error	Observe the steady state error of the angular position of the leg upon landing after a jump. Angular position will be inspected on a plot of angular position versus time with data collected from the motor encoders.	Angular position error between desired and measured steady state values	Steady state error < 0.03 radians	24V power, large open space	Summer test stand and/or modular test stand. Single leg prototype (for initial controller tuning) quadruped prototype (for final controller tuning)	Tyler	4/2/2022	6/1/2022	Hip jump: 0.05 rad; Hip Land: 0.08 rad; Knee jump: 0.04 rad; Knee land: 0.081 rad	SSE and response time for the quadruped was reasonable. The quality of the hopping motion could certainly be further optimized, but it's not a bad start!
10	Leg response time	Observe the time required for the leg to move from fully extended (immediately after liftoff) to the desired landing angle. Angular position versus time plot will be inspected to determine these values	Time to move from fully extended position to desired landing position	Response time of < 0.1 seconds	24V power, large open space	Summer test stand and/or modular test stand. Single leg prototype (for initial controller tuning) quadruped prototype (for final controller tuning)	John	4/3/2022	6/1/2022	Hip jump: 0.28 sec; Hip Land: 0.32 sec; Knee jump: 0.38 sec; Knee land: 0.24 sec	

Appendix F – Test Procedures

Test Procedure

Test Procedure #1

Test Name: Quadruped Vertical Leap Height Evaluation

Purpose: The purpose of this test is to evaluate the height that the quadruped can jump. We will measure the vertical displacement of the body frame to measure the jump height of the robot.

Scope: The test evaluates the performance of our controller. A small vertical displacement indicates a poor controller, while a higher jump indicates an effective controller.

Equipment:

1. Quadrupedal prototype
2. Modular test stand for quadruped
3. 24 V DC Power Supply (initial quadruped testing only)
4. SpeedGoat Real-Time Target Machine
5. High-speed camera / phone camera
6. Tripod (Tech rentals)
7. Yardstick (Engineering building)
8. Tape

Hazards:

1. Pinch points near robot's legs
2. Rapidly / suddenly moving parts

PPE Requirements:

The test is performed in an enclosed environment away from experimenters and requires no PPE.

Facility: ME 192-116/117/118

Procedure:

1. Set up test stand with backdrop
   a. Ensure backdrop is perpendicular to test stand base
2. Mount B.R.U.C.E. to test stand
3. Set up high speed camera on tripod
   a. Ensure that body marker is visible and is eye level to the camera
4. Calibrate test stand
   a. Lift body marker to 10cm while also recording on the camera
   b. Ensure camera recording of body marker is at the 10cm mark of the backdrop
   c. If mismatched, move/adjust camera and redo
5. Record initial offset of body marker
6. Initiate testing
   a. Execute single hopping motion while camera is recording
   b. Check high speed footage for body marker height
   c. Repeat until 10 samples have been recorded
7. Disassemble test stand and camera
8. Analyze acquired data

Results/Data Table:

Vertical Leap Height Data Table		
Test Number	Vertical Height	Correct Landing Position?
1	10.15 cm	Yes
2	10.15cm	Yes
3	9.91cm	Yes
4	9.91cm	Yes
5	10.15cm	Yes
6	10.00cm	Yes
7	10.10cm	Yes
8	10.00cm	Yes
9	10.00cm	Yes
10	10.10cm	Yes
11	9.90cm	Yes
12	10.00cm	Yes
13	9.90cm	Yes
14	10.00cm	Yes
15	10.00cm	Yes

Results	
Average Vertical Height	Percent Correct Landing
10.02cm	100%

Test Date(s): 5/31

Performed By: __Tyler McCue_

Test Procedure #2

Test Name: Single Leg Mechanical Durability Evaluation

Purpose: The purpose of this test is to evaluate the mechanical durability of the redesigned single leg before it is implemented into the full quadruped system assembly.

Scope: The test specifically evaluates the mechanical durability of the redesigned knee joint. We will be repeatedly cycling the redesigned leg through many hopping motions, and checking for material wear, surface galling, and ensuring that the knee joint may be disassembled after operation (this was an issue with the original knee design).

Equipment: (List of equipment necessary)

1. Redesigned single leg
2. Modular test stand for single leg
3. 24 V DC Power supply
4. SpeedGoat Real-Time Target Machine
5. Camera for documenting before and after condition of leg components

Hazards:

1. Pinch point at knee joint
2. Rapidly / suddenly moving parts

PPE Requirements: (e.g., safety goggles, respirators)

/No PPE is required; experimenters must simply be sure to keep hands away from the single leg when the actuators are initiated, and the MATLAB/Simulink controller is running.

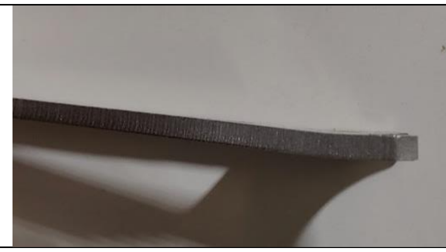
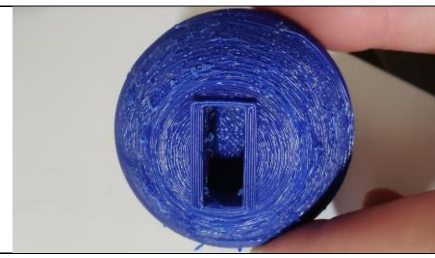
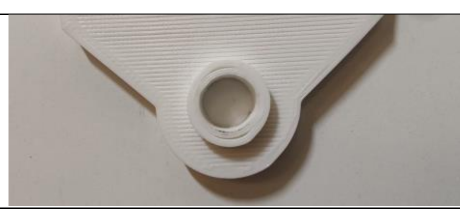
Facility: ME 192-116/117/118

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

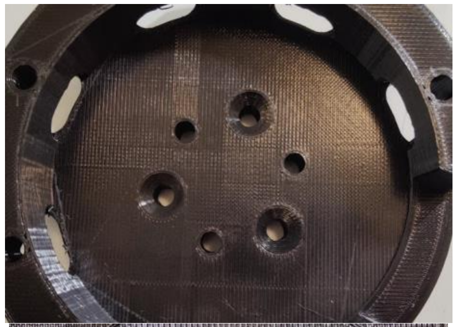
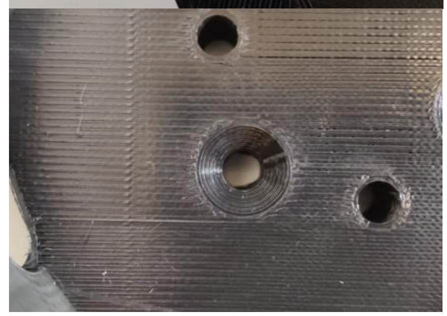
1) Photograph redesigned leg components before assembly
    a. These datum conditions will be compared to the part condition after cycling
2) Assemble the redesigned single leg
3) Affix hip actuator of leg to ball bearing carriage via a 3D printed adapter
    a. Use single leg test stand from the summer
4) Connect 24 V power and CAN harnesses to the actuators
    a. Turn on the 24 V power supply; then press green button to send power to actuators
5) In MATLAB/Simulink, set desired number of jumps to >1000 or cycle leg until 30 minutes have elapsed.
    a. Run controller and monitor leg to ensure it is executing a repeatable hopping motion (should not be an issue as we have already tuned the controller somewhat well)
6) After cycling, disassemble redesigned leg and examine/photograph components for any wear/galling/fatigue

Results:

Photographs of part components before and after operation

Component	Before	After
Lower link sheet		
Lower link fasteners		
Foot/foot adapter		
Knee pulley		
Knee pulley bearing		
Knee shoulder bolt		
Upper link structure		

Belt tensioner shaft		
Belt tensioner bearing		
Hip pulley		
Hip pulley adapter	 	
Timing belt		
Hip actuator		
Knee actuator		

Hip-knee actuator adapter	 	 

Test Date(s): 5/31

Performed By: ________Clayton Elwell____

Test Procedure #3

Test Name: Assembly Time Evaluation

Purpose: The purpose of this test is to evaluate the ease of assembly for the full assembly.

Scope: The test specifically evaluates the ease of assembly of the whole quadruped assembly. For the single leg prototype assembly was not easy and took an excessive amount of time. A goal for the redesign single leg and the overall quadruped is to make assembly as easy as possible. Our goal is to be below 10 minutes.

Equipment:

1. Redesigned legs
2. Body frame
3. Other components and fasteners
4. Variety of A]]]]][][]]][[][]]][]]]][][]]][][][][]][\]]]]]]]]]]][]llen keys
5. Large open space and table to assemble
6. Timer

Hazards:

1. Damage to loose components
2. Pinch point while assembling

PPE Requirements:

No PPE is required

Facility: ME 192-116/117/118

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

1) Layout all necessary components in large open space in a way so that all components are readily available when assemble begins. (Legs, body frame and electrical components as well as fasteners)
2) Start Timer
3) Use Allen keys to fasten together and completely assemble robot
4) Stop timer once completely assembled. Record time in table below
5) When it is time to disassemble the robot follow the same steps as above and record the disassembly time.
6) Repeat assembly test if assembly time is greater than 10 minutes

Results:

Record times to assemble and disassemble robot if anything goes wrong or needs to be noted add them to the comments.

Assembly-Time Table		
Date	Total Time	Comments
5/17	49:15	No Wire Harness Assembly
5/17	52:21	No Wire Harness Assembly

Test Date(s): 5/17

Performed By: __________Tyler McCue____

Test Procedure #4

Test Name: Weight Management Evaluation

Purpose: The purpose of this test is to evaluate the total weight quadruped to ensure we are within our weight requirement.

Scope: Our quadruped needs to be relatively light to satisfy of jump height requirement. The heavier the quadruped is the harder it will be for the robot to jump. The mass constraint for our project is 10kg.

Equipment:

1. Full Quadruped Assembly
2. Scale

Facility: ME 192-116/117/118

Procedure:

1. Set full quadruped assembly on scale. Record total weight. Convert to kilograms if needed.
    a. If components are too large for scale separately add their individual weights together then sum them to find the weight of the assembly.

Results/Data Table:

Total Weight of Quadruped		
Date	Total Weight	Comments
5/24/2022	9.95 kg	
5/24/2022	9.95 kg	

Test Date(s):

Performed By: _____Clayton Elwell____

Test Procedure #5

Test Name: Center of Mass (COM) Location Evaluation

Purpose: The purpose of this test is to evaluate the center of mass location relative to the mid plane of the robot. If the COM is poorly located this will result in a poor flight phase and make our controls header to debug. We will repeatedly check then adjust the center of mass until the robot is balanced.

Scope: The test evaluates the mass distribution of our internal components. A robot that is reluctant to tilt indicates a well-placed COM, while a robot that flips immediately indicates a poorly placed COM.

Equipment:

1. Quadrupedal prototype
2. Internal electrical components
3. Weights and tape
4. Modular test stand for quadruped
5. Level
6. Camera and sharpy for documenting/ marking component locations

Hazards:

1. Damage by loose components

PPE Requirements:

The test requires no PPE.

Facility: ME 192-116/117/118

Procedure:

1. Mount B.R.U.C.E. to test stand with rotating mount
    a. Power will not be used for this experiment.
2. Hold robot in level position
    a. Determine the robot tilts
3. Adjust Mass Distribution
    a. If an internal electronic component can be adjusted adjust move these first.
    b. Then add small weights with tape to the inside of the body
    c. Do this step until the level on the robot shows it is optimally balanced.
4. Record the exact locations of each internal electrical components and weights added to the body frame.
    a. Take a picture/ mark component that will be secured with sharpie
5. Disassemble test stand and remove loose internal electrical components.
6. Prepare to permanently secure internal components and weights into the body.
    a. This test can be repeated until all components are secure

Data Table:

Component Location Data Table		
Component Name	Mounting Location	Additional Description of Location
PDB	No longer in design	
Capacitor	Center	
Microcontroller	No longer in design	
Batteries	No longer in design	
BMS	No longer in design	

Notes: Since our internal electronic configuration now only consists of the capacitor and a perfboard to split the CAN wires to each actuator, the capacitor only impacts the center of mass of the quadruped, since the mass of the perfboard is negligible. The leg design is the same for all four legs, and the chassis is symmetrical, and thus the COM of the quadruped should be centered if the capacitor is positioned well. Our quadruped jump tests and balance tests verify that the center of mass is well located.

Test Date(s):

Performed By: _______________John Bennet____

Test Procedure #6

Test Name: Compilation Time Evaluation

Purpose: The purpose of this test is to evaluate the time it takes to compile controller code. Since we Switched to using the Speedgoat we need not perform this test procedure.

Scope: The compilation time is no longer a super relevant criterion as the controller will be run on a Speedgoat and not a microcontroller, however for testing purposes the compilation time of the Speedgoat should be evaluated and optimized if necessary.

Equipment:

1. Robot controller (STM microcontroller or Speedgoat)
2. Timer

Facility: ME 192-116/117/118

Procedure:

1) Prepare controller to begin compilation.
2) Start Timer then hit run to begin compiling.
3) When the controller is done compiling. Stop timer and record time in table below
4) Hit the stop button and unplug controller

Results:

Record times to compile code robot if anything goes wrong or needs to be noted add them to the comments.

Compile-Time Table		
Date	Total Time	Comments

Test Date(s):

Performed By: _____Clayton Elwell____

Test Procedure #7

Test Name: Total Cost of Components

Purpose: The purpose of this test is to evaluate the total cost of the components for quadruped and test stand. To ensure we are within our budget.

Scope: Our project budget cannot be more than $5000 this test is to check we are within our budget. However, after getting the CP Connect grant for $3,600 we now may purchase up to $8,600 worth of parts.

Equipment:

1. Excel document IBOM.xlsx

Facility: Excel

Procedure:

1. Open IBOM.xlsx excel document
2. Look at total cost in IBOM
    a. Record total cost and date of the total cost table
3. If components that are purchased change and the total cost changes add a new row to the total cost table and record the change. And add a description of what changed

Results/Data Table:

Total Cost of project		
Date	Total Cost	Comments
2/28/2022	$ 4,172.24	First Check of Total Cost
5/27/2022	$5,500	Cost estimate after testing
6/03/2022	$5,597.71	Final Project Budget

Test Date(s): 2/28/2022, 5/27/2022

Performed By: __John Bennett____

Test Procedure #8

Test Name: Avoiding Rolling During Flight Phase Test

Purpose: The purpose of this test is to evaluate the quadruped's tendency to roll during flight and to debug our code to improve the controls in the legs.

Scope: If the COM or the code is poorly done, it will be noticeable when the quadruped begins to tilt in the flight phase. This test will help to debug our code and any further center of mass issues. We will repeatedly check then adjust our code or center of mass until our results are repeatable. We will use the time difference between the impacts between the left and right side to measure rolling during flight. We decided to check

Equipment:

1. Quadrupedal prototype
2. Modular test stand for quadruped
3. 24 V DC Power Supply (initial quadruped testing only)
4. SpeedGoat Real-Time Target Machine/ DAQ Software
5. High-speed camera / phone camera
6. Tripod (Tech rentals)

Hazards:

1. Pinch points near robot’s legs
2. Rapidly / suddenly moving parts

PPE Requirements:

The test is performed in an enclosed environment away from experimenters and requires no PPE.

Facility: ME 192-116/117/118

Procedure:

1. Mount B.R.U.C.E. to test stand
2. Set up high speed camera on tripod
    a. Ensure that of body frame is visible and is eye level to the camera
    b. The camera should also me mounted to the axis of rotation.
3. Set up DAQ to record leg impact times.
    a. Use the GRF function to check when impact time occurs for each leg.
    b. Set these values to be outputted after each jump.
4. Initiate testing
    a. Execute single hopping motion while camera is recording.
    b. Check high speed footage for finding the body frame tilt angle. Record Angle.
    c. Use DAQ to record impact times for each leg. Average left and right impacts and take the difference.
    d. If adjustments need to be made to the code, make needed adjustments and then restart data collection.
    e. Repeat until 15 successful samples have been recorded
        i. Average less than 15-degree tilt and impact time difference less than .05 seconds
5. Disassemble test stand and camera
6. Analyze acquired data

Data Table:

Rolling During Flight Data Table								
Test Number	Front Left Impact Time	Back Left Impact Time	Average Left Foot Impact Time	Front Right Foot Impact Time	Back Right Foot Impact Time	Average Right Foot Impact Time	Impact Time Difference	Tilt Angle
1	Every single test we ran, the four legs landed evenly each time							
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-

Results	
Average Impact Time Difference	Average Tilt Angle
Negligible	Less than 1-2°

Test Date(s): 5/31/2022

Performed By: ___John Bennett____

Test Procedure #9 and #10

Test Name: Leg Response Overcorrection / Steady State Error Test / Leg Response Time Test

Purpose: The purpose of this test is to evaluate and observe the time required for the leg to move from fully extended to the desired landing angle. As well as observing the steady state error of the angular position.

Scope: The time requirement, steady state error, and the overshoot are all important components of evaluating response. A proper response to a sudden change in position will allow the robot to catch itself and propelling itself upward. These parameters that define the response of the leg can be tuned biased on several parameters positional gain, Kp, and velocity gain, Ki. We will test to ensure that our selected Kp and Kv produce a steady state error less than .05 radians and a response time of < 0.1 seconds. Angular position versus time plot will be inspected to determine these values.

Equipment:

1. Quadrupedal prototype
2. Modular test stand for quadruped
3. 24 V DC Power Supply (initial quadruped testing only)
4. SpeedGoat Real-Time Target Machine/ DAQ Software

Hazards:

1. Pinch points near robot's legs
2. Rapidly / suddenly moving parts

PPE Requirements:

The test is performed in an enclosed environment away from experimenters and requires no PPE.

Facility: ME 192-116/117/118

Procedure:

1. Mount B.R.U.C.E. to test stand
    a. Suspend Bruce using the hand breaks on each linear slider.
2. Set up DAQ to record Angular response data.
    a. Extend leg in position that we expect to be a lift off angle for the leg. Record initial leg orientation.
    b. Determine final orientation that would put the robot in a crouch position ready to fall safely.
3. Initiate testing
    a. Select a Kp, and Kv
    b. Input initial leg orientation. Allow robot to go to that position
    c. Then input the crouch leg position. As a step response.
    d. Record the response data and Kp and Kv for the test in the response data table below.
    e. Restart test and select different Kp and Kv if the response does not meet the minimum requirements. A steady state error less than .05 radians and a response time of < 0.1 seconds
    f. Repeat test 14 more times to check for repeatability ensure the robot can meet the minimum requirements for the same Kp and Kv. Record tests in compute averages and if this test fails then restart step 3.

g. Analyze acquired data
4. Disassemble test stand

Data Table:

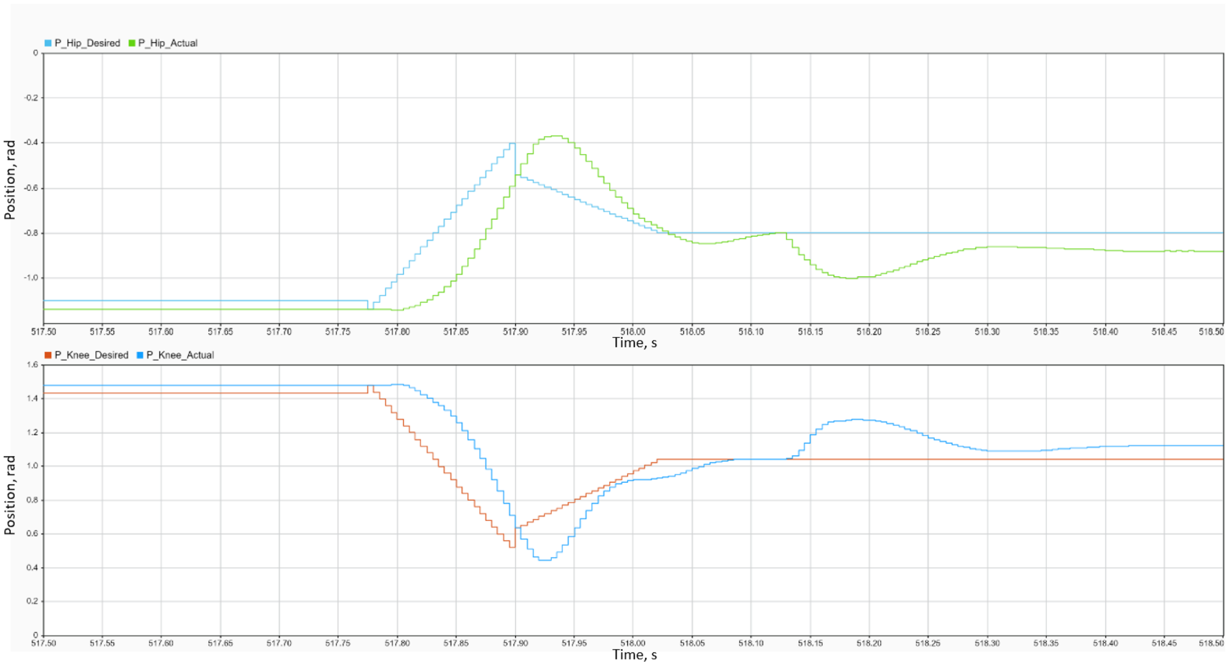


Figure 1: Jump and Landing Data, Desired and Actual positions for the Hip and Knee

Test Number	Positional Gain, Kp	Velocity Gain, Kd	Steady State Error, e_{ss} [rad]	Response Time T_r [sec]
Hip Jump	30	0.2	0.05	0.28
Hip Land	15	0.2	0.080	0.32
Knee Jump	30	0.2	0.04	0.38
Knee Land	15	0.2	0.081	0.24

Test Date(s): 5/31/2022

Performed By: __John_Bennett____