

# 2 DEGREE OF FREEDOM ROBOTIC LEG

## FINAL DESIGN REVIEW

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### Team Capy

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## EXECUTIVE SUMMARY

The Cal Poly Mechatronics Department does not have a quadruped robot to use for research and teaching. This robotic technology is developing in private companies and other research institutions, and it will have a large impact on the robotics industry. Professor Xing proposed the project to build a 2 Degree of Freedom robotic leg that can accurately jump 10 cm. The 'hip' will be attached to a stand and only be allowed to move vertically. Team Capy was tasked with taking Cal Poly's first step into the race for quadruped technology by completing the mechanical design of a robotic leg.

This document details Team Capy's entire Robotic Leg design process over the course of one year. This includes the research, the preliminary designs, the further development of those designs, the manufacturing process, and the team's conclusions and recommendations for the project moving forward. This paper details only the first step into building a fully functioning quadruped; there is a lot of work to do in the future. We have given recommendations on how to further adapt the design for a control system and continue this project in the future

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# 1. INTRODUCTION

Professor Xing, an assistant professor at Cal Poly, proposed the 2 DOF Robotic Leg project for this quarter's senior project class. The project is to build a robotic leg attached at the hip to a stand, which will be used as a teaching tool and eventually help develop Cal Poly's very own robotic quadruped. Since this project has multiple uses after its completion, there are multiple customers that it must perform well for: the Cal Poly Mechanical Engineering (ME) Department, the ME Lab instructors, and the students. The Scope of Work (Sections 2 & 3) is composed of 2 main sections: Background and Objectives. The Background covers all research regarding similar products and dynamic systems while the Objectives outline the problem statement and the team's objectives required to complete this project. The following sections are comprised Team Capy's process of achieving those objectives throughout the year-long project. This is described in detail and broken into the following sections: Concept Design, Final Design, Manufacturing plan, Design Verification Plan, Project Management, and Conclusion. This project's scope has significantly changed throughout the year, resulting in a very iterative design process that led to excellent results. This document details every step of that process, leading to the development of the final design and its manufacturing process.

## 2. BACKGROUND

To gain a better understanding of the scope of work for this project, the background research comprised of three main sections: sponsor interviews, product research and technical research. The sponsor interviews were held to learn more about the customer wants and needs. The product research focused on learning about similar products, projects and their successes. The technical research includes patents and literature regarding component advantages and specifications.

### 2.1 SPONSOR INTERVIEWS

Team Capy interviewed the project sponsors, Professor Xing and Charlie Refvem, to obtain a better understanding of their vision for the project, any restrictions the project may face, and the scope of work that needs to be done. During this meeting, Professor Xing clarified that "the goal of the project is to be used at Cal Poly for research and lab education", as well as reassuring the project is "80% mechanical, [there is] not too much coding". Other topics of discussion were:

#### Long Term Goals:

- <sup>1</sup>Create a quadruped robot for research and educational purposes

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<sup>1</sup> This goal extends past this current senior project team.

- Design and produce a 2-degree-of-freedom robotic leg that can repeatedly jump 10 centimeters
- The budget for the project is \$600
- Engineer a stand for safe, repeatable testing

#### Short Term Goals:

- Choose a scale
- Partition and organize future work early

#### Areas of Advice, Research Suggestions:

- Iterate often
- Use 2 motors on top
- Learn from current ‘competitors’
- Avoid bottlenecks by partitioning work
- Look into 3D printing parts

Professor Xing did an analysis of the dynamic forces of a robotic leg with motors at the hip and ended the meeting by noting that a complicated but eventual addition to implement would be variable weight sensors.

## 2.2 PRODUCT RESEARCH

The product research examined products resembling the 2-DOF robotic leg for expanding the list of potential solutions and seeing how previous teams advanced through their project. Reviewed below are some of the products and teams researched, chosen for their fame and/or similarity.

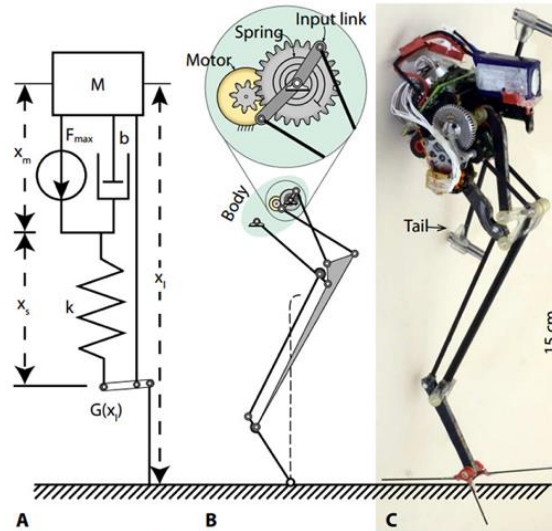
Boston Dynamics is the leading company in the realm of quadruped robots. This company engineered numerous quadruped robots, each with their own purpose and unique design. They engineered the BigDog for combat use with a focus on carrying heavy loads at a slow pace. Spot evolved from SpotMini, which was designed to be lightweight, weighing less than 25 kilograms, and as silent as possible after BigDog was deemed too noisy to use in combat. MIT’s Biomimetic Robotic Lab designed the Cheetah, which can operate at very high speeds, maxing out at 28 miles per hour.



**Figure 1.** Boston Dynamics Robots



UC Berkeley engineered a small, lightweight, jumping and self-balancing robot called Salto. Salto started off with a very simple design and has gone through multiple iterations. The newest versions of Salto can jump off walls and recognize and jump on moving targets. The process through which Salto came to be is very similar to our project as well.



**Figure 2.** UC Berkeley Jumping Robot

Tekno sells an interactive dog toy that can jump and do backflips. While this toy does not have two-degree of freedom legs, it does accomplish a major task set for our project: the interactive dog can repeatably jump, and quite high as well.



**Figure 3.** Interactive Dog Toy

## 2.3 TECHNICAL RESEARCH

The technical research conducted focused on finding advantages and disadvantages to specific solutions. A list of technical journals and patents assessed is provided in the Works Cited section and Appendix A respectively, as well as a table reviewing relevant patents found below. The literature was found using Google Scholar, and the patents using Google Patent using keywords such as “quadruped”, “robot”, and “actuator”.

Following the initial sponsor meeting, Professor Xing decided to supply Team Capy with two joint actuators and their specifications, as seen in Appendix B. With this new information, the scope of technical research currently remains on motor specifications, simulating equations of motion, and finding potential materials.

**Table 1.** Patent List and Useful Qualities

Patent Name	Patent Number	Main Contributions
A Quadruped Legged Robot Driven by Linear Actuators	WO200808448 0A1	<ul style="list-style-type: none"> <li>• Strong claim for linear actuator use</li> <li>• Similar leg design</li> </ul>
Single Leg Mechanism of a Quadruped Robot	CN106627831A	<ul style="list-style-type: none"> <li>• Use of belt and pulley system</li> <li>• Description of accurate gear ratio</li> </ul>
Single actuator per leg robotic hexapod	US6481513B2	<ul style="list-style-type: none"> <li>• Unique, simple design</li> <li>• Better understanding of actuator capabilities and controls</li> </ul>
Walking Mechanism for Four-Foot Robot Driven and Controlled by Cams	CN202038387U	<ul style="list-style-type: none"> <li>• Use of DC Servo motor for high accuracy</li> </ul>
Running Robot Having Four Legs	KR101373740B	<ul style="list-style-type: none"> <li>• Design uses four-bar linkage</li> <li>• Incorporation of gear-pulley system</li> </ul>

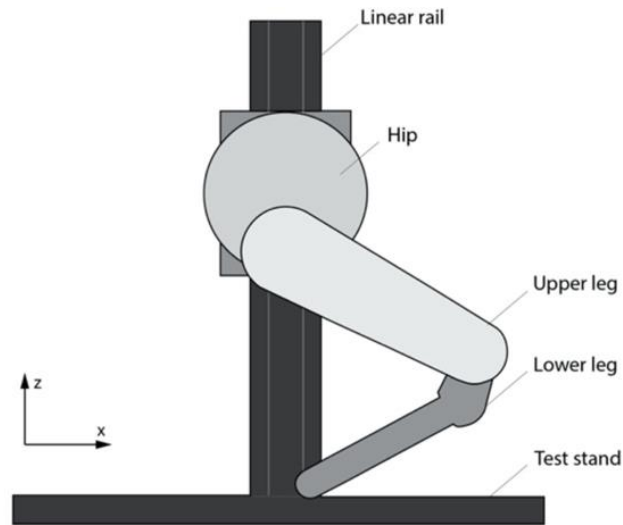
### 3. OBJECTIVES

#### 3.1 PROBLEM STATEMENT

The Cal Poly Mechatronics Department does not have a quadruped robot to use for research and as a teaching tool. To kickstart this massive project, Professor Xing and the department have tasked Team Capy with building a 2 Degree of Freedom robotic leg attached to a stand at the hip. The final product must use two electric motors to accurately jump 10 cm or more, while costing less than \$600.

#### 3.2 CUSTOMER NEEDS & WANTS

Prof. Xing gave Team Capy the project's minimum requirements and provided a sketch of the expected final product (see Figure 2). The leg's motion will be constrained to the x-z plane. It will be composed of two actuated joints, each with their own motor, and encoders to read the angle of each joint. The hip of the leg will be connected to a vertical rail on the test stand. A microcontroller will control the motors, and consequently the motion of the robot. The main goal of this robot is to accurately and repeatedly jump 10 cm on command. The leg must be able to perform several tasks such as kicking and repeated jumping. Table 2 outlines a summary of the customer needs and wants.



**Figure 4.** Expected robotic leg assembly. Sketch was provided by Prof. Xing.

**Table 2.** Summary of customer needs and wants.

Need	Want
x-z plane motion	Easy to use
Fixed to a test stand	Portable
Economic	Durable
Jump minimum of 10cm	Safe
Repeated jumping and kicking	Accurate
Controlled motion by microcontroller	lightweight
2 legs	Noiseless
2 motors	Repeatability

The ‘customer wants’ were developed in meetings with Prof. Xing and during the Quality Function Development process. The requirements provided by Prof. Xing are listed under “Needs,” while wants are not strictly specified. Customer wants will be considered when deciding major design decisions. Some wants will not affect the performance of the final product, such as the following: easy to use, portable, durable, and lightweight.

### 3.3 QUALITY FUNCTION DEPLOYMENT (QFD)

A Quality Function Deployment diagram (QFD) and house of quality connects the customers’ needs and wants with product technical specifications. This technique facilitates the process planning and results in a better understanding of design relationships. This increases customer satisfaction and provides a better idea of how to solve the problem. The QFD can be found in the Appendix B. Table 3 outlines specifications developed in the QFD house of quality. These specifications are quantifiable and can be tested.

**Table 3.** The specifications summary and requirements or target value.

SPEC. #	Specification	Requirement or Target Value	Risk	Compliance
1	Torque	Max-17Nm Ave 6.9Nm	M	A,T
2	Pitch points	Minimize	L	I
3	Hip speed	Variable	M	A,T
4	Total weight	Minimize	L	A,I
5	Variable weight	Variable	L	I,A,T
6	Electrical shock protection	Maximize	M	I
7	Material selection	Strong and light	L	T,A,I
8	Number of motors	2	L	A,I
9	Response time	Minimum	L	A,T,I
10	Impact resistance	100Nm	L	A
11	Vibrations	Minimize	L	A,T
12	General wear	One-year lifetime	L	I
13	Multiple iterations/generations	3	L	A,T
14	Visual feedback	Effective	L	I

Risk: L – Low  
M - Medium  
H - High

Compliance: A – Analysis  
T - Test  
I - Inspection

Each specification is explained in further detail:

1. This refers to the torque that the actuator or motor must achieve. Prof. Xing specified a maximum torque output of 17Nm and a continuous torque of 6.9Nm. The torque requirement is mostly affected by the type of motor: AC or DC, servo or stepper, and of course the cost. A more expensive motor will achieve higher torques and better accuracy, but with more noise. Motors cost must fit the budget, and the entire project cannot exceed \$600.
2. Pinch point was added thinking of the users and their safety. The goal is to minimize the locations where the user can come into physical contact with the leg as the leg is in motion. The final product must pass a safety test developed by team.
3. The speed of the leg must be controlled through a microcontroller. The leg must be program to achieve different speeds desire by the user. This will require the team to test the accuracy of the speed of the hip.

4. The goal is to minimize the total weight of the quadruped leg and test stand. The test stand should weight more than the leg. This is because during operations the test stand cannot move as this will affect the balance of the assembly. This allow the portability of the assembly.
5. There will be a variable weight in the assembly. The goal is to concentrate most of the weight at the hip leg. The leg material selection will also affect the weight variations.
6. Since the leg is going to be power electrically, an electrical shock safety protection must be implemented to the leg. This will improve the overall safe handling of the device.
7. Since one of the goals is to make the device durable, it therefore must be made of high strength material. The material must have lightweight because of the weight considerations. The goal is to optimize the materials.
8. Prof. Xing requested the leg to have two motors. Both located at the hip. This will play a role in scaling the device.
9. The goal it to minimize the time response of the device. When the user wishes to execute a motion, the leg must perform effectively to those commands.
10. The assembly should be able to withstand a drop test. This will be performed via computer software. A 100N force will be applied at the assembly and study the locations of critical stresses. This location can then be reinforced or redesign for superior strength.
11. The vibrations created by the motors are ought to be reduce. This will ensure the durability of the device. To minimize the vibrations the device must operation under the natural frequency.
12. General gear refers to the wear generated overtime. The goal is to minimize wear by studying location where there are rough surfaces in contact and heat generated by frictional contact.
13. Visual feedback is added to allow user to know that the device is safe and ready to operate with a luminous signal.

There are no high-risk specifications. There are only three medium risk specifications, these are the torque requirement, hip speed, and electrical shock protection. Both speed and torque requirement depend upon the quality of the motor. Superior motors mean higher cost.

### 3.4 EDITS MADE TO EXPECTATIONS AND DELIVERABLES

Due to the COVID pandemic and requested design changes late into the senior project timeline, Team Capy drafted an Expectations and Deliverables document. All expectations and specific deliverables are listed, along with due dates and general explanation. The Expectations and Deliverables document was signed by this project's sponsors on October 14<sup>th</sup>, 2020. This document can be viewed in Appendix I.

## 4. CONCEPT DESIGN

After turning in the Scope of Work to Professor Xing, Team Capy received some feedback about the project. The previous budget of \$600 has been extended to \$1100 because of the price of the motors, and this budget does not include the test stand. Additionally, for safety precautions, the stand will have a required emergency stop button. Lastly, Professor Xing proposed that this quarter revolve around the mechanical design, and to focus on the dynamic analysis/modeling in the following quarters. Taking this into account, Team Capy has revised their budgetary plans and begun development of the mechanical design.

Team Capy went through extensive brainstorming and vetting sessions to achieve the 2-DOF robot's preliminary concept design. There were three main functions to develop: the stand design, the upper leg actuator, and the lower leg actuator. The two focuses for Team Capy during brainstorming were safety and quality. After producing multiple ideas for each function, the team had to narrow down options to the best possible cohesive design. The Pugh and weighted matrices used to do this once again focused on safety and quality (shown in Appendix D). Key safety factors considered were pinch points and electric shock potential, while the quality factors revolved around torque losses, impact resistance, and orientation lock.

Looking at the actuator design, Team Capy saw that the lower leg actuator is far more complex than the upper leg design. Because of this, most of the design efforts went toward the lower actuator. After using the Pugh charts to assess all the actuator concepts, three stood out among the rest: the "Belt Drive," the "4 Bar Linkage," and the "Gear, Track and Lever Arm."

The belt drive consists of a small pulley attached to the upper leg, rotating freely of it. This pulley is driven by a motor of its own and runs a belt to a bigger pulley on the lower leg. This provides a large gear ratio, sufficiently locks the orientation through bearing usage, and has few pinch points. A belt drive, such as the concept shown in Figure 5, would have minimal frictional losses and provide the required torque.

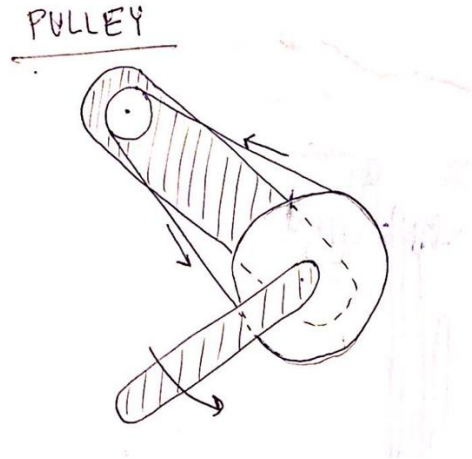


Figure 5: Sketch of Belt Drive Lower Leg Actuator

The second-best design was the “4-bar linkage” (see Figure 6). This system involves having the lower leg motion controlled by a motor that is located at the hip. The motor provides a torque to the gear that is fixed to bar 1. As bar 1 rotates with a radial velocity, it pushes bar 2 to move in the radial direction. In consequence, bar 2 applies a torque to bar 4 which pivots around the joint with bar 3. The torque provided by the motor controls the contraction or expansion of the legs.

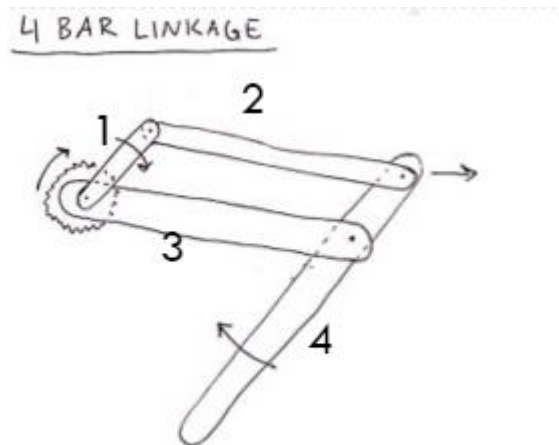


Figure 6: Sketch of 4-Bar Linkage Lower Leg Actuator

This design mainly stands out in material selection, torque required, torque losses, and orientation lock. The design allows the option to select from many materials such as steel, wood, and plastic. A minimum amount of torque is required to cause the system to move because of the minimal torque losses. The design also provides a good orientation lock which is important in maintaining a controlled jump. This eliminates the need to modify the design to only move in the XZ motion.

The “Gear Track and Lever Arm” is a unique design that was brought forward during the first brainstorming session. A gear that is spun by the motor is in contact with a track that runs back and forth as the gear spins. The track is connected at its end to the lower leg knee joint rotates the lower leg as a lever.

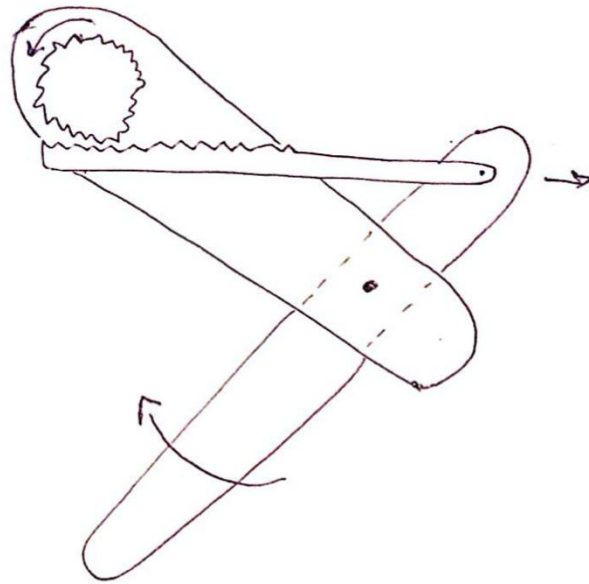


Figure 7: Sketch of Gear Track with Lever Arm Leg Actuator

There are many strengths to this design, including variable design decisions and general aesthetics. However, the design ultimately lost out because of its lack of safety and inability to lock orientation. While the gear track connected to a lever arm looks unique, it generates a lot of pinch points. Team Capy also envisions a difficulty in maintaining contact between the gear and the track as the actuator is operating.

When focusing on the stand, there were a few key design points that had to be met: the stand has to allow vertical motion while restricting all other translation and rotation, it must provide minimal frictional losses, it must be easy to set up, and it must have as few pinch points as possible. Using the Pugh and weighted matrices to help choose the best design, the top contenders were “2 Guide Strings in Tension” in 1<sup>st</sup> place, “Diamond Track with Bearings” in 2<sup>nd</sup>, and “Pole with Keyway and Cylindrical Slider” in 3<sup>rd</sup> (as shown in Appendix D).

The “2 Guide Strings in Tension” design allows for the hip to slide vertically along two tightly wound wires. The two wires negate any unnecessary rotational or translational movement. The connection between the hip to the wires is crucial as it is a potential source of pinch points and friction losses. While a definitive design has not been reached, Team Capy has been



considering this design component. One potential solution brought forward is the use of metal cylinders sliding on greased wire. A sketch is shown below in Figure 8.

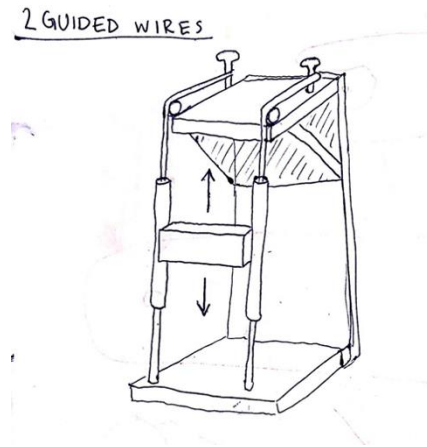


Figure 8: Sketch of “2 Guide Wire in Tension” Stand Design

The “Diamond Track with Bearings” design uses a metal vertical trackway to guide the hip. The hip will be attached to a slider with two wheel-and-bearing assemblies on each end. Because of the diamond shape of the track, there would be minimal rotation or unnecessary translation of the slider experienced. Any frictional losses would occur because of the wheels pressing against the track, which would be intensified by the moment created by the leg. Since this track does not go directly through the hip, there would be a bending moment. This design also has a fair number of pinch points, given that there is slider moving through a vertical stretch of track. A sketch of this design is shown in Figure 9 below.

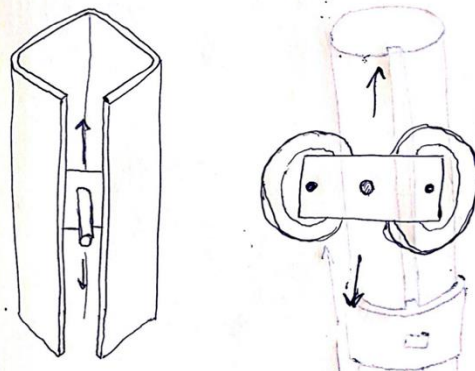


Figure 9: Sketch of “Diamond Track with Bearings” Stand Design

The last contending stand design is the “Pole with Keyway and Cylindrical Slider”. This design uses a cylindrical pole with a keyway as the track for an external cylindrical slider. The keyway would maintain orientation while slider is only allowed to move vertically. Since there would be a large surface area for the slider-pole interaction there would be significant frictional losses. Additionally, there would be more pinch points than the previously mentioned designs. A sketch of this design is shown in Figure 10.

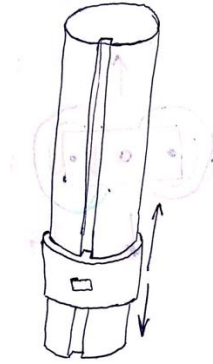


Figure 10: Sketch of “Pole with Keyway and Cylindrical Slider” Stand Design

After thorough assessments of all design options, Team Capy selected a complete concept design to move forward with. The preliminary concept design consists of the “2 Guide Strings in Tension” stand in tandem with a high ratio gear train for the upper leg and the “Belt Drive” for the lower leg actuator. This combination minimizes pinch points and frictional losses while maximizing efficiency and torque output. Team Capy has developed CAD models of these designs using AutoCAD Fusion 360. The stand and leg actuators are shown below in Figures 11 & 12.

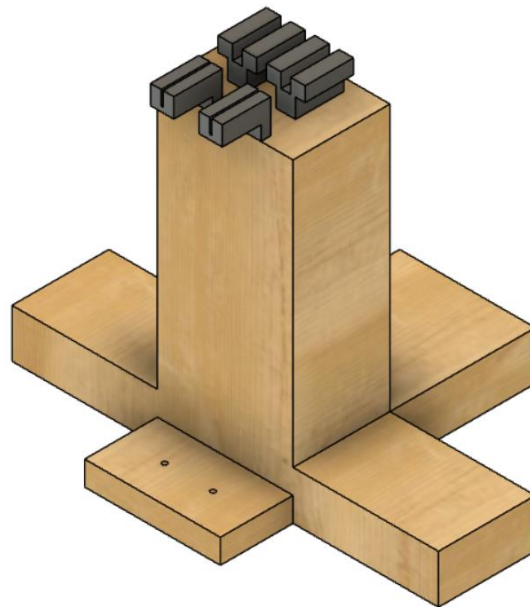


Figure 11: “2 Guided wires in Tension” Stand CAD Model

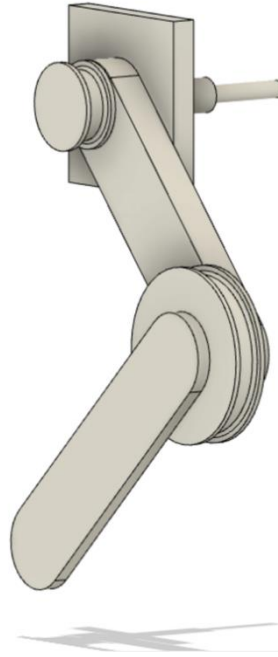


Figure 12: Fusion Model of Leg Actuators

The stand will mostly be made of wood but use metal connectors to guide and hold the wires in tension. Not pictured are tightening mechanisms connected to the Y-shaped metal connectors. Currently Team Capy is thinking of using guitar machine head to tighten the wires. The leg assembly will be printed with plastic, which is be easy to manufacture using 3D Printing. Team Capy can use 3D Printing to manufacture the complex geometries of the leg actuators. The specific plastic has not yet been decided, with more research needed to be performed. Some considerations in choosing the correct plastic include impact resistance, lifespan, and cost.

Not pictured in the CAD models are the strings of the test stand or a connection to the hip to allow for guidance from the strings. The connection to the hip for the strings is not a top priority actively but has been considered by Team Capy. A realistic solution currently brought forward is a flat plate connected at the top of the hip with holes for the guide strings. A potential addition to the scope of the project enabled by this design is the addition of variable weight. With a flat top and guide strings, weighted circular disks can be stacked on top of the hip. This addition would be exciting but would the largely affect the computational simulation.

Shown below in Figure 13 are two captures of the chosen test stand design during a simulated static stress analysis. The study materials were edited such that the lower body has properties similar to pine wood, and the bodies attached at the top have the properties of steel. Contacts were automatically generated as well as a three-way constraint applied to the bottom face. The load arrows seen are all equal to 20 Newtons and represent points where the string applies most stress to the stand.

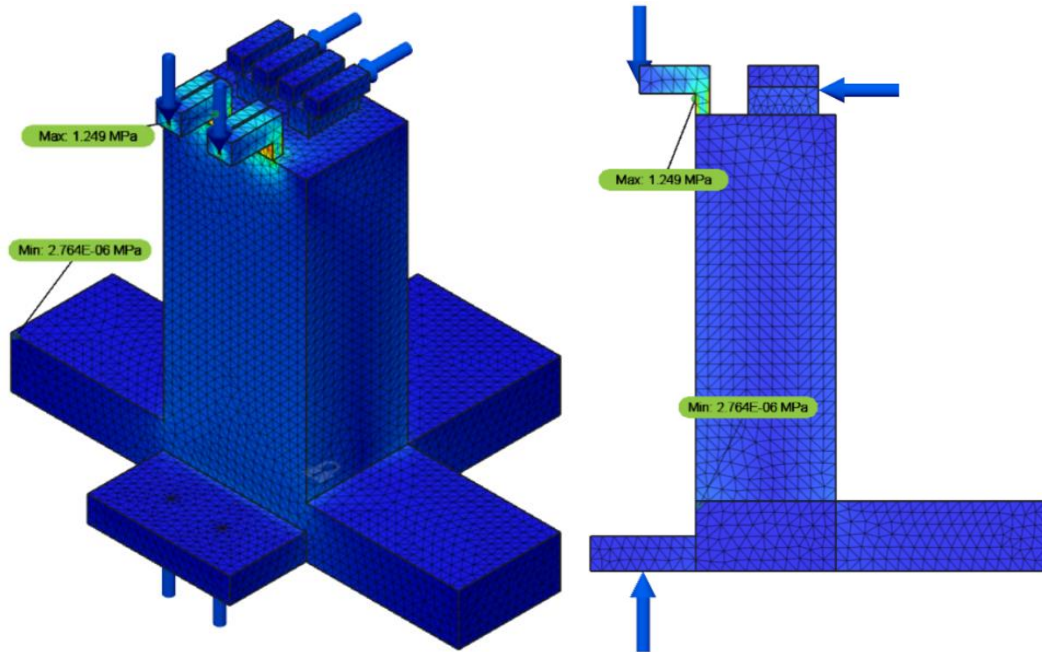


Figure 13: FEA of “2 Guided Wires in Tension” Test Stand

## 5. FINAL DESIGN

EDIT (11/15/20): The final design has been altered for the leg, motor casing, and test stand after the original critical design report was completed. Readers may skip to PAGE 19 for the updated final designs.

### Leg Design:

Team Capy’s final leg design is very similar to that of the concept design. A gear train drives the upper leg while a belt and pulley system drive the lower leg. Using a "shaft inside a shaft" design keeps these systems on the same rotational axis. Bearings between the two shafts prevent significant frictional losses and allow the pulley system to rotate free from the gear system. The motor casing holds the two motors in place, while also allowing vertical movement. A carriage and track system consists of two carriages attached to the motor casing; this system counteracts any moment from the moving parts and the offset center of mass. The carriages also allow for smooth vertical rolling along the stand. The leg design can be seen in Figure 14 below, with an exploded view in Figure 15.

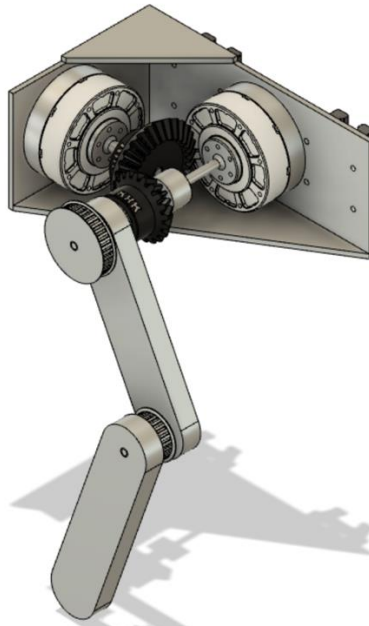


Figure 14: Robot Leg Final Design

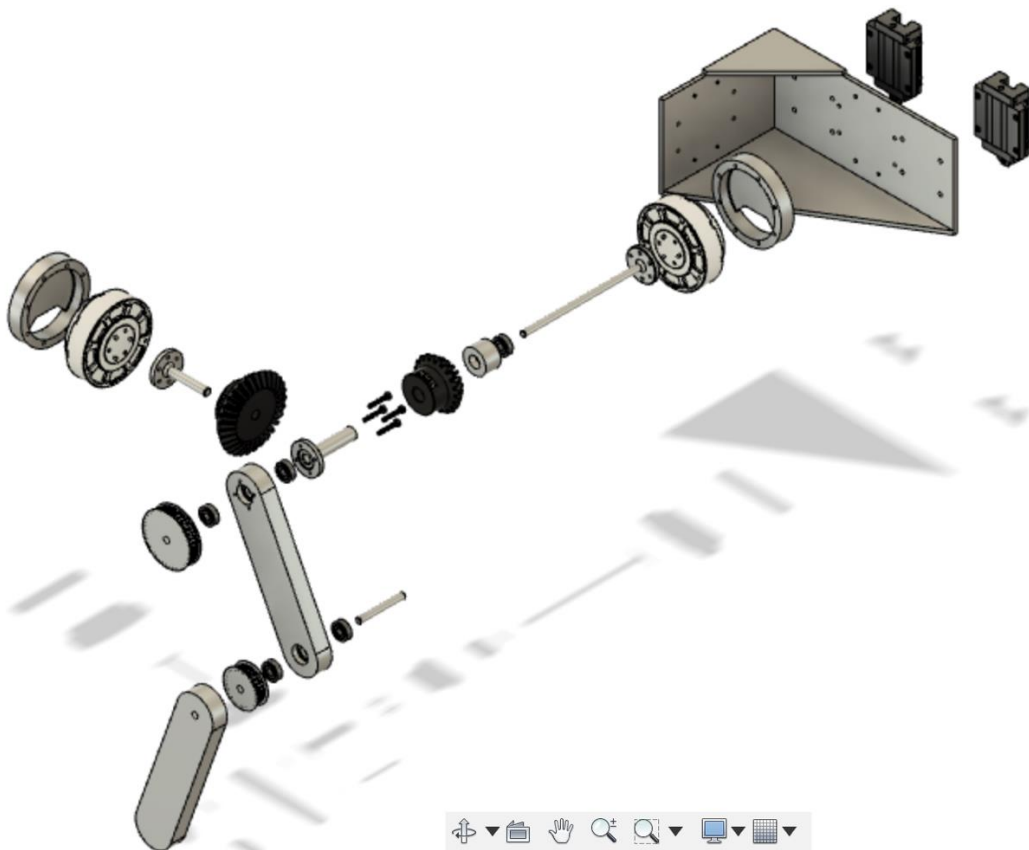


Figure 15: Exploded view Robotic Leg

The significant changes from the concept design are the gear/pulley ratios, the type of pulleys, and the motor casing. After analyzing the pulley setup and the torque output, Team Capy decided to optimize the pulleys to maximize rotational velocity instead of maximizing the torque. The motors have a very high torque output relative to the weight of the system, and our target is hip speed. Hip speed is more important than torque output because the hip needs to reach a critical velocity to jump the desired height. Team Capy settled on a gear ratio of 1.5 for both the pulleys and the gears. Additionally, Team Capy switched from a flat belt drive setup to a timing belt system. Timing belts use teathed belts to reduce friction, allow for more effective direction changing, and prevent slippage in high-stress applications. The concept design had not yet finalized a motor casing design. The final motor casing supports both motors while allowing unrestricted movement along only the vertical axis. This stand design and setup restrict all other five degrees of freedom.

#### Stand Design:

Since finishing the test stand concept design, Team Capy has implemented changes into the final design. After a design change request by the sponsor, the new test stand is now designed to guide the hip via guide rails. These guide rails are mounted on square steel tubing that makes up the frame, as seen below in Figure 15. The implemented changes from a wooden stand to a steel frame exist for two reasons. Primarily, amidst the current pandemic (COVID-19), it is advised that Team Capy pre-purchase as many materials as possible, as discussed further in the next section. Also, the guide rails must be parallel to one another, which will be much easier to



Figure 16. Updated Test Stand CAD

Team Capy did not decide on guide rails for the first concept design, nor were guide rails the first solution after being asked to implement a vertical slider attachment. Initially, Team Capy investigated camera sliders as an option for a vertical slider mechanism. The sliders have minimal friction and can carry an impressive load. What the camera sliders lacked was the capability to attach a non-camera object. Ultimately, Team Capy chose to use guide rails because there would be fewer moving parts and easier, more secure attachment to the carriages.

Not pictured is a secure holding for a power source. Team Capy has received specifications of a current power source that may be used. Since the primary scope of the project remains mechanical design, the securing of the power source will be done after the completion of a mechanical product.

### Safety:

There are many moving parts in this assembly, so safety is a big concern. Team Capy decided to encase the entire robotic leg and test stand in an acrylic box. This will allow users to see the functioning robot but not be able to touch it during operation. The system will be wired so that this box must be in place for the system to run. This simple solution takes care of all possible mechanical injuries.

As for maintenance, the only foreseeable areas to look at are belt wear and bearing friction. These main sources of error come from many cycles of usage under high stress, and external factors such as dirt, etc.. The timing belt we chose has steel cords reinforcing it to provide both short and long-term strength so the belt does not stretch. The source of wear here is the teeth on the belt. After many stressful cycles, these will wear and introduce slippage to the system. The bearings we chose are sealed ball bearings, so they retain their grease and block dirt from entering the system. Although these are a long-term solution, they should also be oiled to remain as friction free as possible.

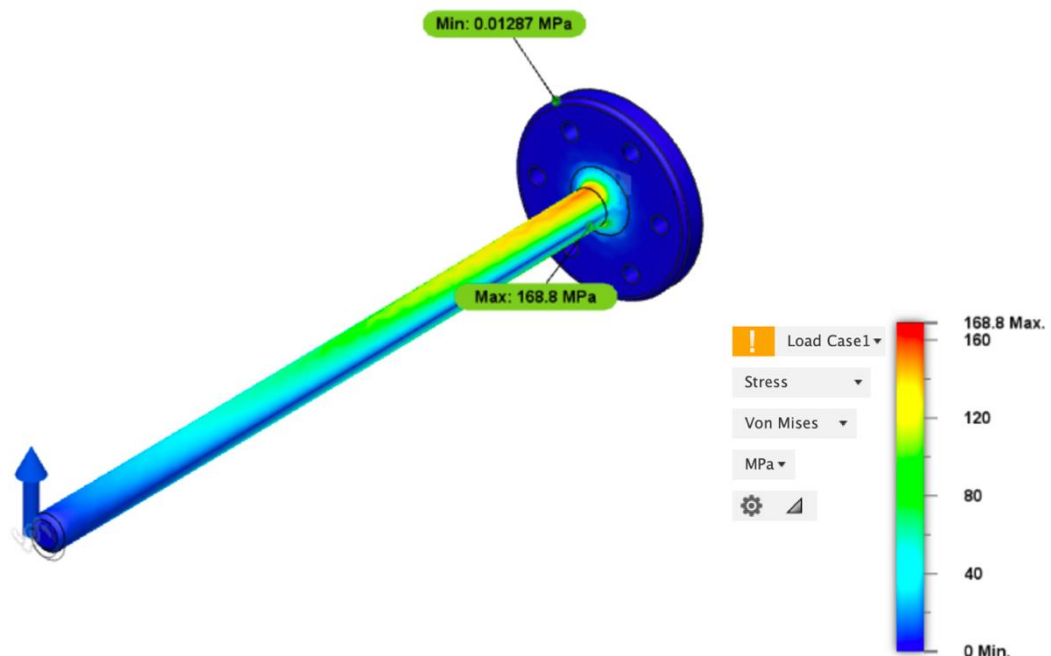


Figure 17: FEA of Inner Shaft



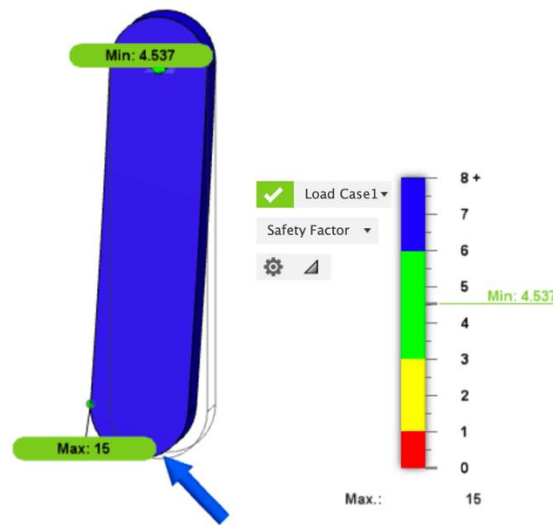


Figure 18: FEA of Lower Leg

Figures 17 & 18 show the Finite Element Analysis of the Inner shaft and lower leg. The lower leg is very thick and is no danger of plastically deforming. The inner shaft, however, is fairly thin and experiences a lot of stress relative to its size. After doing this analysis, Team Capy has decided to reduce the load on the inner shaft by reducing the weight of the legs. We will do this by strategically cutting sections out of the upper and inner leg so it would retain its structural integrity while being a much lighter component. Due to COVID-19 complications, machining the sections on the leg must be delayed.

Attached as Appendix H is the FMEA chart Team Capy created before the PDR. While the design of the legs and test stand changed a few times, with new components added, Team Capy notes that the core functionality of the project never veered off course, in part by understanding the potential areas for failure early on.

The bill of materials is attached as two Excel sheets Appendix I; the first regarding parts for the hip and leg assemblies, the second for the test stand. In total there are over 230 individual parts, roughly 200 of which assemble the test stand. Noticeably, the test stand is much more expensive than the leg and hip assembly, ~\$2500 and \$500 respectively. There are two main reasons why the test stand design is so expensive. First, expensive parts such as the guide rails and carriages are sourced from McMaster-Carr for their high quality. Our sponsor Professor Xing expressed interest in experiencing minimal mechanical friction. The second reason is that the test stand assembly also lists money for an encoder and pressure pad. While \$750 is set aside for these two measuring devices, they are not the primary focus of the scope of the project and will be added after the mechanical product is fully functional.

EDIT: 11/18/20

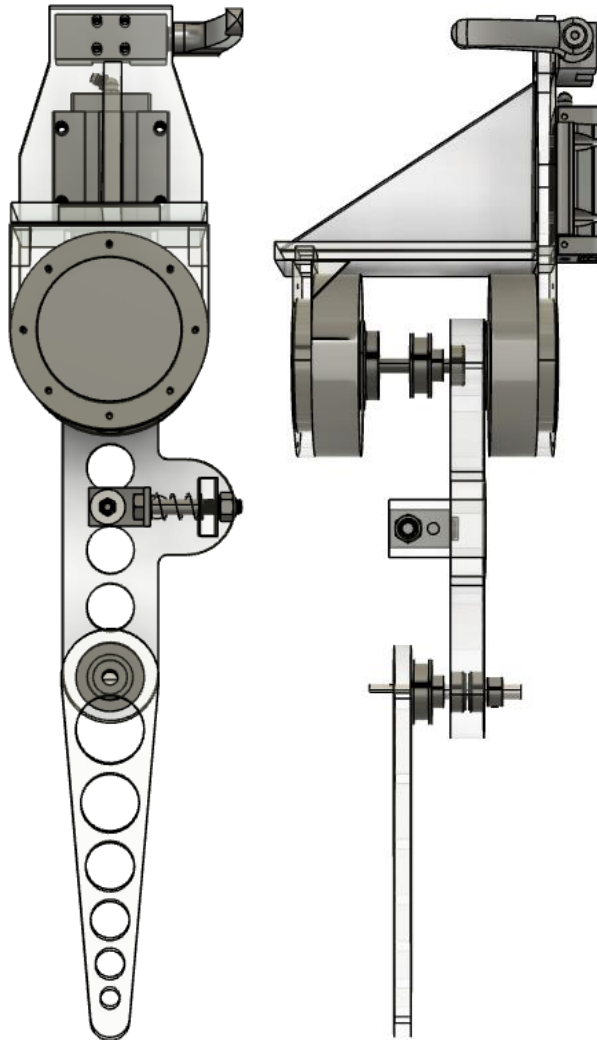
The final leg design evolved over summer to further reduce weight, reduce part count, add a belt tensioning mechanism, and prepare for simpler fabrication and assembly due to the COVID 19 pandemic. A few key changes occurred: a switch from aluminum to polycarbonate for the leg, the addition of lightning holes to, the use of smaller composite pulleys, and the addition of a



custom tensioner. The previous design, while effective, proved to be overly heavy and complicated. Team Capy agreed that the design needed to be lighter, and most importantly, simpler due to the COVID 19 induced rushed conditions of fabrication and assembly.

Each of these changes took considerable design consideration, but ultimately became a far superior product. The upper and lower leg are now made of polycarbonate sheet, adding significantly less weight to the overall design. Lightning holes were added, and the lower leg follows a taper as it approaches the ground. This significantly reduces total weight and the amount of weight that the motors must move. Additionally, composite pulleys of gear ratio 1:1 are now being used, further reducing excess weight. The new lighter model needs less power to generate the same amount of speed in the upper and lower leg. Lastly, the tensioner will provide tension in the belt, giving the team more leeway on belt sizing and accounting for belt stretch as the robotic leg is used.

In summation, these significant design alterations developed a lighter, simpler product that is easier to manufacture and will provide significantly better results than the previous design.



Figures 19: Final Leg Design, CAD Model

**Table 4.** Bill of materials for final leg design.

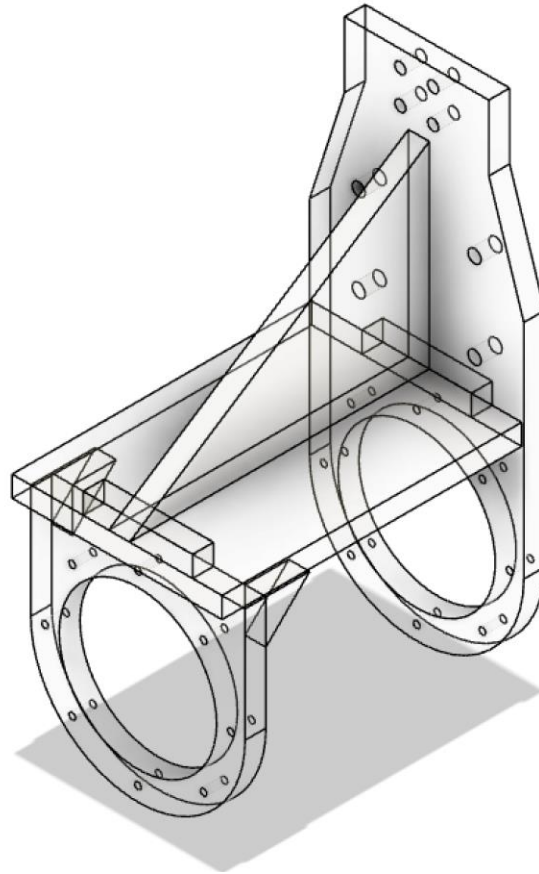
Subassembly	Part Name	Part Vendor	Price	Quantity
Belts & Pulleys	2.03 mm (MXL) Pitch, 48 Teeth, 8mm Bore, Pulley	sdp-si.com	\$11.27	2
	2.03 mm (MXL) Pitch, 224 Teeth, 6mm wide Belt with Fiberglass Cords	sdp-si.com	\$4.78	1
Hip	Ball Bearing Carriage Flanged for 20mm wide rail, 5000 lbs	McMaster Carr	\$140.00	1
	Hand Brake	McMaster Carr	\$140.68	1
	T-Motor AK80-6	T-Motor	\$569.90	1
Legs	Set Screw Collar, 8mm Shaft, Carbon Steel	McMaster Carr	\$1.91	1
	Sealed Ball Bearing, 8mm Diameter	McMaster Carr	\$5.35	3
Tensioner	Idler Pulley 20 Toothless 6mm Bore 10mm Width Timing Pulley Wheel Aluminum for 3D Printer	Amazon	\$2.20	1
	Low-Profile Shoulder Screw; 6 mm Shoulder Diameter, 20 mm Shoulder Length, M5 x 0.8 mm Thread	McMaster Carr	\$6.20	1
	Aluminum Unthreaded Spacer 13 mm OD, 5 mm Long, for M6 Screw Size	McMaster Carr	\$0.77	1
	Compression Springs; 27 mm Long, 13.750 mm OD	McMaster Carr	\$3.47	1
	High-Strength Steel Nylon-Insert Locknut	McMaster Carr	\$13.77	1
	High-Strength Class 10.9 Steel Hex Head Screw	McMaster Carr	\$8.43	1
	High-Strength Steel Nylon-Insert Locknut	McMaster Carr	\$7.14	1
	Low-Carbon Steel 90 Degree Angle, 1 ft.	McMaster Carr	\$4.91	1

Over summer, Team Capy significantly altered the motor casing to reduce both weight and manufacturing complexity. While the previous design used an aluminum housing, bevel gears, and a hollow shaft to actuate each motor separately, the new motor casing uses a polycarbonate housing and in-line motors to accomplish this same task. This design removes any gear losses from the system, increases shaft factor of safety, and significantly simplifies manufacturing. Additionally, this motor casing is designed to fit 2 of the newly purchased motors from T-Motor.

The new motor casing comprises of a series of polycarbonate parts, each with tabs and slots which fit together nicely. These tabs locate the parts relative to one another, provide extra

strength, and allow for an easy and effective gluing process. The new case is designed around in-line motors: one on the carriage-side, directly actuating the upper leg (no shaft), and one on the front-side, actuating the lower leg through a belt and pulley. As this case is made of polycarbonate, it provides strength and rigidity while still being lighter than the previous design.

As a whole, the new motor casing is both simpler and more effective than the previous design. It removes both the bevel gears and the hollow shaft, it is lighter, and it is mostly cut with the waterjet, removing space for manufacturing error.



Figures 20: Final Motor Casing Design, CAD Model

**Table 5.** Bill of materials for final motor casing design.

Subassembly	Part Name	Part Vendor	Price	Quantity
Motor Casing	Clear Polycarbonate Sheet 3/8" x 24" x 48"	eoplastics.com	\$127.77	1
	40 Oz PVC Cement	Home Depot	\$4.87	1

### Final Test Stand Design:

There have been two key alterations made to the final design of the test stand. Primarily, the test stand is now assembled of only 8020 stock parts. The transition to using 8020 beams, brackets, and fasteners was motivated by ease of assembly, and sturdiness. The number of guide rails has also been reduced from 2 to 1. This was done with the understanding that using two guide rails would inevitably be a source of friction unless they are perfectly parallel. A CAD model of the final test stand design can be seen below.



Figure 21: Final Test Stand Design, CAD Model

**Table 6.** Bill of materials for final test stand design.

Subassembly	Part Name	Part Vendor	Price	Quantity
Frame	1-1/2" x 4' T-slotted Framing Rails	McMaster Carr	\$27.30	6
	1-1/2" Extended Corner Bracket	McMaster Carr	\$6.26	12
	1-1/2" Tee Structural Bracket	McMaster Carr	\$9.16	1
	1-1/2"x12" Diagonal Brace	McMaster Carr	\$19.91	2
	1-1/2"x24" Diagonal Brace	McMaster Carr	\$22.77	1
	End-Feed Double Nut, Flanged-Button Head 5/16"-18 Thread	McMaster Carr	\$6.76	6

Carriage Guide	Guide Rail, 20mm wide	McMaster Carr	\$400	1
	M6-1.0 x 18mm Socket Head Cap Screws Metric	McMaster Carr	\$8.49	1
	T-Slotted Framing, End-Feed Single Nut, M6 Thread, for 30 mm Single Rail	McMaster Carr	\$8.06	1

#### Final Resources Design:

Along with the physical deliverable, Team Capy is also handing over some virtual resources and files. For CAD and drawings, Autodesk Fusion 360 was used. Team Capy will be sharing the following folders: “Final Files”, “Subcomponents”, “Non-Final Files”, and “DXF Files”.

- The “Final Files” folder will be all the final models and drawings pertaining to the 2DoF robotic leg. That includes the models and drawings for the final leg, motor casing, and test stand design.
- The “Subcomponents” folder holds all the models for subcomponents used for the leg design; motors, timing belt, ball bearing. (Nested within “Final Files”)
- The “Non-Final Files” folder contains all the models, drawings, and all rough drafts done on Fusion leading up to the final models.
- The “DXF files” are used for cutting parts on the waterjet. The drawings are of the legs, the motor casing parts, and the shaft base.

## 6. MANUFACTURING PLAN

Approaching the end of Spring quarter and Summer months, it became abundantly clear that the COVID pandemic was here to stay for the time being. As such, Team Capy made above the changes to the design with hopes of decreasing fabrication requirements. Following the fabrication section of the manufacturing plan all assembly procedures are listed. Before each procedure there are lists depicting the tools, materials, safety measures, and equipment necessary to advance.

### 6.1 FABRICATION

Team Capy opted for a design that requires very little fabrication and mostly assembly. Most of the fabrication revolve around the leg and casing. The stand had no fabrication except of the landing pad. The leg subcomponents that required fabrication are the tensioner, upper leg motor shaft and lower leg shaft connector. All other leg and motor casing components were cut and assemble. The following lists tools required, raw material used, especial equipment needed, and fabrication procedure.

Leg:

For the leg fabrication the following tools and equipment were crucial for fabricating the leg components.

*Tools list:*

Waterjet, MIG welder machine, circular saw, Bridgepoint mill, chop saw, router, drill press, vise, clamps, grinder, metric drill bits, sandpaper, PVC cement and measuring stick.

*Raw Material:*

90° angle steel bar, Polycarbonate sheet, M8 steel rod.

*Equipment list:*

Wear appropriate clothing, safety glasses, earmuffs, face shield, appropriate welding gadgets and gear.

The fabrication procedure is the following:

1. Use the circular saw and cut the polycarbonate sheet and then glue the free piece to the polycarbonate sheet with PVC cement. Let dry before using. *Note:* The glued piece is where the upper leg will be cut.
2. Make 2D drawings in CAD and then export as DXF file to run in the waterjet. Cut the upper leg and lower leg along with the tensioner and casing components in the waterjet. Polish the edges with sandpaper after the cutting.
3. Use the drill press to drill six M4.5 holes for the motor front attachment. Use the 1/2" Diameter Reduced-Shank Drill Bit to drill three holes where the bearing will be secure in place. Drill 7mm through. Use clamps to secure leg component to the drill table. *Note:* We figure out that low speeds do a better job, leave a better finish, and produce less heat in the drilling process. For exact hole location we recommend printing a 1:1 ratio 2-D template for the hole location and tape or glue it to the part. We recommend starting with a small drill bit and slowly move up in size.
4. For making the slot in the upper leg use a milling machine. Due to tool absence, the slot was shaped using a 1/2in. end-mill. Polish edges with sandpaper when finish. *Note:* We recommend printing a 1:1 ratio template for the slot and tape to the leg. This facilitates machining the component. Allow workpiece to cool off after every pass to prevent material distortion.
5. Use a hand file grind the semi-circle cut in the lower leg. Leave enough clearance for the shaft to go through.
6. Use the drill press to make 10mm diameter hole for the tensioner rectangular component. *Note:* Check that the tensioner guiders can flow with ease.
7. Fabricating the lower leg shaft consists of the following process:
  - a. Use the mill to shape one end of the shaft to a semi-circle. Grind any sharp edges. *Note:* Make sure piece is clamp appropriately to vise and that there is enough clearance for the end mill to not touch the vise. We recommend manually feeding. Use an end mill that is larger than 8mm in diameter.
  - b. Drill a 2mm hole with the drill press on the flat side of the semi-circle. *Note:* Make sure the shaft is clamp properly. Use a punch hole if necessary.
  - c. Use the chop saw to cut the aluminum shaft to length.
8. For fabricating the upper leg shaft:
  - a. Make a 2D drawing for the shaft base and include hole locations. Export the file as DXF and cut part in the waterjet. Grind any sharp edges. *Note:* We found a 1/4 in. steel plate and used to cut our shaft base.

- b. Use the drill press to drill the holes to the correct diameters. *Note:* For the center hole, make a tight fit for the M8 steel rod.
  - c. Attach the M8 rod to the center of the shaft base. Position the shaft so it's only midway through the shaft plate. Use clamps and a vise to secure the components to place. This leaves room for the welding material to fill in. Weld the shaft base side facing the motor. When finish welding, allow workpiece to cool off before handling. Secure shaft to a vise and use a hand grinder to grind the weld and make it parallel to the shaft base. *Note:* We recommend removing any paint or oxide coats in the parts that will be welded for a good weld joint. Practice before welding the part. Adjust the machine for the correct voltage, feeding rate, and gas type for workpiece type and thickness. We set our voltage to 22V.
9. For the tensioner fabrication:
- a. The M8 steel rod and 90° angle steel were cut to length with the chop saw. Grind sharp edges. *Note:* earmuff and face shield are required for this procedure.
  - b. The holes in the 90° angle steel were drill using the drill press
  - c. Weld M8 rod and M8 bolt to 90° angle steel bar. Use clamps to secure components at a 90° angle with the angle bar.

#### Casing:

The motor casing is fairly simple to manufacture, as it is largely comprised of a series of parts to cut on the waterjet. Fabrication procedure goes as follows:

#### *Tools list:*

Waterjet, drill press, vise, belt sander, metric drill bits, sandpaper, file, router

#### *Raw Material:*

Polycarbonate Sheet

#### *Equipment list:*

Wear appropriate clothing, safety glasses, earmuffs, face shield

1. Use Water-jet to cut all provided DXF files
  - a. "Big Bracket", "Little Bracket 1", "Little Bracket 2", "Front-side", "Carriage-side", "Front-side", and "Connector"
2. Use belt sander to flatten the edges of the "Big Bracket", (operation due to taper caused by cutting on waterjet)
3. Drill all spotted holes to clearance fit the screws
  - a. 8 x 3.5 mm for the M3 screws in the "Front-side", holding the motor
  - b. 8 x 3.5 mm for the M3 screws in the "Carriage-side", holding the motor
  - c. 4 x 5.5 mm for the M5 screws in the "Carriage-side", holding the carriage
  - d. 4 x 5.5 mm for the M5 screws in the "Carriage-side", holding the handbrake
4. Sand down the tabs and slots that hold the components together until parts snugly fit together.
5. Use router to carve out space for wires as needed

### Stand:

#### *Tools List:*

Circular saw, electric drill, 1/4" drill bit

#### *Safety Equipment:*

Eye goggles, close-toed shoes

#### *Equipment List:*

3/8<sup>th</sup> thick polycarbonate sheet, 5/16<sup>th</sup>-18 end mill fasteners, end-feed single M6 thread nut, and M6-1.0 x 18mm socket head cap screws.

The only fabricated component for the test stand is the landing pad. The landing pad is was cut of the same material used for the motor casing, a 3/8" thick polycarbonate sheet.

1. Measure and cut a 10"x13" rectangle of polycarbonate.
  - a. Sand the edges that were cut to remove chips and smooth out any sharp points
2. Drill holes to create clearance to fit screws
  - a. Location of holes shown on drawing for Landing Pad (Refer Appendix).
  - b. Confirm the screws have clearance, and the holes align with the beams

## 6.2 ASSEMBLY

The assembly of each component, the leg and stand and motor casing, is done separately before bringing everything together. Below are the steps of assembly, all parts are listed in both the bill of materials and engineering drawings.

### Leg Assembly

#### *Tool List*

M5 & M8 hex ratchet, M3 hex Allen wrench, safety glasses, and rubber mallet.

The leg assembly had the following procedures.

1. Assemble the tensioner.
  - a. Insert the shoulder screw (Tensioner-Part 2) to the idler slider. Add the idler spacer (Tensioner-Part 6) and the idler Tensioner-Part 8). Secure the connection with the shoulder screw locknut (Tensioner-Part 1). Use the M5 hex ratchet along with the M3 hex Allen wrench to hold the shoulder screw from rotating. Note: Overtightening the locknut to the idler will increase friction, we suggest test that idler can rotate freely else loosen the locknut a bit.
  - b. Insert the compression spring into the hex bolt welded to the idle slider. Connect to the tensioner base. Use the M8 hex ratchet to secure the connection.
2. Insert the tensioner base into its proper location in the upper leg. Make sure the bottom of the tensioner base is flat with the back of the leg. Use the rubber mallet if needed.
3. Attach one of pulleys to the motor shaft (Part 8). Add a bearing subsequently. The bearing is press fitted to the shaft. Use the rubber mallet. *Note:* This a very important step. Our team made the mistake in forgetting to add the bearing first. Removing the bearing was a struggle. Luckily the bearing did not get damage.



4. Use the rubber mallet to press fit three bearings to the upper leg. *Note:* One of our bearing had a loose fit. We fix this issue by applying some dry adhesive. We do not recommend using liquid adhesive because it may damage the bearings.
5. Insert the semi-circle shaft connector to the lower leg. Secure the shaft by using a pin.
6. Insert the last pulley to the lower shaft connector. Make sure the flat side of the pulley is in contact with the lower leg. Subsequently, use PVC cement and glue the last pulley to the lower leg. Clamp and let dry.
7. Connect the lower leg to the upper leg by connecting the lower leg shaft through the upper leg double bearings. Use the rubber mallet if needed. Make sure the semi-circle side of the shaft is visible with the front of the upper leg. Use the stop collar to secure the shaft.
8. Lastly, add the belt to the leg assembly.

### **Motor Casing Assembly**

#### *Tool List*

M3 & M5 Allen Keys, safety glasses, Right angle clamps, Standard Clamps, PVC Glue.

1. Fit tabs together and glue parts (taking time to clamp and let dry) in the following order:
  - a. “Connector” & “Carriage-side”
  - b. “Connector” & “Front-Side”
  - c. Both “Little Bracket”s & “Connector” + “Front Side”
  - d. “Big Bracket” & “Connector” + “Carriage-side”
2. Use M3 screws to attach motor to “Front-side”
3. Use M3 screws to attach motor to “Carriage-side”
4. Use M5 screws to attach carriage to “Carriage-side”
5. Use M5 screws to attach hand-brake to “Carriage-side”

### **Stand Assembly**

The test stand is assembly uses only stock parts from McMaster-Carr. The ordered parts are from the same manufacturer, 8020, which are designed for easy and strong assemblies. Below is the procedure to follow to assembly the test stand:

#### *Tools List:*

Metric Hex key set, Philips head driver.

#### *Equipment List:*

12 extended corner brackets, two 12” diagonal brackets, one 24” diagonal bracket, one flush tee bracket, six 1-½” four-foot beams, end fasteners, M6 socket head screws, end-feed double nut & flanged-button head 5/16”-18, 1000mm Quiet-ride guide rail, M6 thread End-Feed Single Nut

1. Prepare the extended corner brackets
  - a. Use the double nut and 5/26”-18 screws and assemble to each corner bracket.
    - i. There are four holes per bracket, each needing one screw and one fastener
    - ii. The screws are to be on the concave side of the bracket, with the fasteners on the opposing side

- iii. The flat side of the fasteners should face the screw, the side that is not flat should face away
- 2. Connect four of five beams that contact the floor
  - a. Choose one of the beams and slide on the flush tee bracket to the approximate middle
  - b. Using the prepared corner brackets, slide corner brackets onto beams as required
    - i. Three beams have 4 corner brackets
      - 1. Two opposing barren sides of the beam
      - 2. The other remaining sides have two corner brackets each
      - 3. The brackets face away from one another, and be flush with the end of the beams
  - c. Arrange the three beams from above to be parallel and distanced apart from each other by roughly 10", then by roughly 17"
    - i. The beam that has the flush tee bracket should be in the middle
    - ii. The flush tee bracket facing the beam further away
  - d. Connect the one of the two remaining beams on either side of the parallel beams from the step before
    - i. Connect the corner brackets at the ends of the parallel beams to the perpendicular beam using the fasteners
  - e. Tighten the screws on all the corner brackets
    - i. Likely they will need to be loosened and tightened later for beam alignment
- 3. Slide components necessary on the parallel beam from the remaining open side
  - a. On the top side of the middle beam, slide on a 12" corner bracket, the landing pad, and the other 12" corner bracket
    - i. The 1-1/2" corner bracket use end-feed double nut with flanged-button head 5/16"-18 screws.
    - ii. The landing pad uses three end-feed single M6 nuts and M6x1.0 x18mm socket head screws.
  - b. Slide on the remaining fastener side of the landing pad onto the beam closer to the middle beam
  - c. On the top side of the beam further away from the middle beam, slide on the 24" corner bracket
- 4. Connect the other remaining beam on the open side of the parallel beams from step 3
  - a. Connect the corner brackets at the end of the parallel beams to the perpendicular beam using the fasteners
  - b. Tighten the screws on all corner brackets
- 5. Align all components not tightened to the middle of the parallel beams
  - a. Flush tee bracket and landing pad and 24" corner bracket should be have their center points in-line with one another
  - b. The 12" corner brackets are on either side of the landing pad on the center beam, and face inwards to meet the vertical beam
- 6. Connect the vertical beam to the frame assembly

- a. Align the vertical beam where all the components from the step before set
  - b. Slide the vertical beam to be connected to all the components listed, eventually resting on top of the landing pad
    - i. First slide in the fasteners for the 24" corner bracket
    - ii. Then slide in the fasteners on either side for the 12" corner bracket
    - iii. Lastly slide the vertical beam to be connected to the flush tee bracket
  - c. Tighten all the connections to the vertical beam, and on stand
    - i. You may need to loosen and re-tighten a few times to ensure perpendicular alignment at corners
7. Connect the guide rail to the vertical beam
- a. Prepare the guide rail for attachment by connecting M6x1.0 x 18mm socket head screws with end-feed single M6 nuts through each hole on the rail
  - b. Slide the fasteners on the guide rail down the vertical beam, on the same side the landing pad is sticking out.
  - c. Tighten the guide rail to a desired range. Team Capy recommends connecting the guide to come parallel with the top of the vertical support. This gives maximum range for the leg to jump.

### **Full Assembly**

The leg connects to the casing via the front of the motors. The upper leg is screwed in directly and through the shaft with the M4 screws. The leg is then attached to the guide rail. The following list require tools and procedures.

1. Connecting legs to hip
  - a. Use six M4-0.7 X 14mm screws to directly secure the front of the motor to the upper leg. A Phillip drive tool is needed for this procedure.
  - b. Use M4x10mm hex socket head screws and hex Allen keys to connect the upper leg shaft to the front of the motor.
2. Connecting leg & hip to test stand.
  - a. Slide the carriage to the guide rail. Make sure the brake is fully open. Secure the leg by using the brake at any time. *Note:* We suggest cleaning the guide rail with a clean fabric before connecting the carriage.

## **7. DESIGN VERIFICATION PLAN**

Due to the COVID-19 crisis, it was impossible to build a prototype and run testing on a physical model during spring quarter. Therefore, current testing is based on finite element analysis through Fusion 360. Individual finite element analysis will be performed on the robotic leg assembly.

For the leg assembly there are multiple components that must be verified to withstand variable impact load. These components include the inner shaft, and the upper and lower leg. With the

help of FEA, multiple simulated situations were tested on the leg design. These were performed by fixing individual components and applying impact loads one by one. The lower leg was a large focus since there is minimal flexibility and a lot of impact. Similarly, the inner shaft on the upper leg is a potential snap hazard. Members from Team Capy used a spreadsheet generated in a previous class to determine the location and size of bearings needed for the inner shaft. Team Capy did not see any potential failures and expects all components to work properly.

Team Capy was not able to test the stand assembly through FEA. When attempting to auto-generate contacts it became clear that there are too many nuts and bolts for FEA to run and be accurate. There are two concerns relating the test stand: 1) will the weight of the full leg design with motors bend the guide rails, and 2) will the kicking motion cause the test stand to topple sideways. Since the guide rails will be screwed into steel beams, and the whole leg design weighs less than 10 kg, there is no doubt that the steel beams, and as such the guide rails, will remain straight. The test stand itself weighs over 22 kg, not including the power source to be added. Once parts are purchased and the first and last test stand prototype built, testing for sideways toppling will occur. In the real possibility that the test stand topples, perpendicular beams will be connected to the horizontal beams.

Once the legs and test stand are assembled, there are more testing that needs to be. Primarily the 10-centimeter jump test. Discussions with our Sponsor Professor Xing ended at an understanding that we want to test for accurate repeatability. That is jumping the same height, 10 centimeters or more, over and over. Team Capy aims to also add variable weight capability to the hip via a weight rack attached to the motor casing. Similarly, Team Capy wants to investigate the signal response time of the leg as well as its landing pattern. This will help improve the computer simulation for future versions of this project to come.

EDIT (11/5/20): The following sections were added as required by the Expectations and Deliverables document. Before the creation of the document, the project sponsors notified Team Capy that the control simulation will not be ready for the motors. As such, uncertainty testing for the accuracy and success of the leg is not possible. Below we discuss the range of motion of the leg, and in the Conclusion & Recommendations section two recommended ways to track and analyze motion.

The legs and test stand have constraints that limit the possible motion of the system. The current test stand allows the leg to jump a maximum height of 1000 mm. That is the length of the guide rail, which the hip carriage attaches to. The height of the jump will be dependent on the acceleration of the motors and the angles to which the legs rotate. There are angle restraints for each leg. The top leg has roughly 270 degrees of rotation, constrained by the width of the motor casing. The bottom leg has a much larger area of rotation, which is also affected by the angle of the upper leg. At a rough estimate, the lower leg has 300 degrees of rotation, constrained on one end by the tensioner and on the other by the upper leg.

## 8. PROJECT MANAGEMENT

This project will take place over the next 3 quarters (30 weeks), with each quarter dedicated to a different stage of project development. Put simply, the first quarter is dedicated to

research, project planning, and initial analysis and ideation. The second quarter focuses on development of these ideas and production of rough functioning prototypes. The third quarter centers around refining the product and presenting a final design. There are key project deliverables within each quarter that guide the team to achieve these long-term objectives.

#### **Winter Quarter:**

After defining the problem, thoroughly researching it, and creating objectives to guide our process, Winter quarter starts focus on initial product development. For Team Capy, this includes dynamic analysis of the inverted pendulum system, a gear schematic for transmitting torque to the two moving parts of the robot and developing an initial concept model to show the practicality of these ideas.

After the Scope of Work, the team will know their plan of action and complete all a number of tasks before the presentation at the end of the quarter: Preliminary Design Review (PDR). Team Capy will develop the robot's functional design and begin modelling and assessing the concept.

#### **Spring Quarter:**

Spring quarter is focused on “hashing out the details”. This involves reviewing the design, building, testing, and reviewing again. The main goal of the section of Senior Project is to develop the product into something very close to a finished design. By doing detailed analysis and iterating through the design process, Team Capy will develop a functional design of the 2 DOF robot by the end of this quarter.

#### **Fall Quarter:**

The last quarter of Senior project is dedicated to the finishing touches on the robot design, prototyping, and development of the final product. Much of this quarter is focused solely on building the final design and testing it. After this is completed, Team Capy will write the final report and deliver the finished product to the sponsor.

#### **Schedule:**

Table 5 below shows a chronological layout of all deliverables for the entire project. These deliverables will keep the sponsor up to date on the status of the project and give the team achievable goals to strive for within each quarter.

**Table 7.** Deliverable Schedule for 2020

<b><u>Quarter</u></b>	<b><u>Date</u></b>	<b><u>Deliverable</u></b>
Winter	2/3/20	Submit SOW to Sponsor
Winter	2/27/20	PDR Presentation
Winter	3/2/20	Submit PDR to Sponsor
Spring	4/9/20	Interim Design Review

Spring	4/30/20	CDR Presentation
Spring	5/4/20	Submit CDR to Sponsor
Spring	6/4/20	Manufacturing & Test Review
Fall	10/20/20	Confirmation Prototype Review
Fall	11/24/20	FDR Presentation
Fall	11/27/20	Senior Project Expo

#### EDIT- 2/24/2020

Moving forward from PDR, Team Capy will work to develop the project for Interim Design Review and Critical Design Review. This will involve further developing intricate design details and finishing a prototype. Additionally, Spring quarter will involve dynamic analysis of the system and beginning simulation and programming for the final product. This quarter will house a majority of the finer detail development and end with a functional simulation and mechanical design.

#### EDIT – 3/12/20

After presenting and sharing the PDR with the project sponsor Professor Simon Xing, Team Capy received the following feedback. Xing suggested that the hip design for the legs includes some casing for the motors to prevent large impacts. Similarly, Team Capy is strongly encouraged to consider friction effects because of incorrect gear ratios seen as impedance to the motor. Professor Xing has also asked for additional requirements not originally listed in the Scope of Work. These include a force sensor on either the “foot” of the leg or the landing pad of the test stand, as well as a position measurement device to know the hips position and velocity at all times. Sponsor Xing was very pleased with the presentation and the direction of the project thus far.

#### EDIT – 5/12/20

As of early May, there has been a change in the Scope of the project. New requirements were brought to light which led to a complete redesign of the test stand. The leg design remained on the same development path after PDR. This change was unexpected and came very late in the design process, but after a lot of work, ultimately resulted in an improved design.

#### EDIT – 11/19/20

The senior project process worked well for us as a team. While the year was not without flaws for Team Capy, the resources available to us and the direction we were given were a great benefit to completing the deliverables. A specific process that Team Capy found very helpful and used many times over is weighted decision matrices.

Team Capy redesigned the final design of the leg, casing and test stand over summer. That is generally very late for design work to be done. While everything came together in the end, for our next project we have all agreed that there needs to be more communication in the

opening quarter for sponsors to accept, reject or advise on, concept designs. In our next design project, we will focus on increased communication to get designs approved early in the process.

Another element Team Capy did not consider until approaching the end of the senior project experience is testing. The scope of the project deliverables did change drastically in October, however there was no plan in place for testing. As a team we have discussed this as an oversight on our end and noted that a part of designing a project is also designing measurable testing methods.

## 9. CONCLUSION & RECOMMENDATIONS

The Scope of Work is meant to showcase Team Capy's understanding of the problem and goals to move forward on the project. Additionally, it is a tool to correspond with Professor Xing to make sure the team's problem assessment and goals align with his. Our goal over the next year is to develop a 2 Degree of Freedom robotic leg that can accurately jump 10 cm or more, while costing less than \$600. This project is the basis upon which Cal Poly will build a full quadruped robot to use for both research and teaching. After thorough research of quadrupedal robots and general biomimetic-leg mechanics, the design of Cal Poly's 2DOF robot leg has a clear route ahead of it. The next steps are to select a scale based on selected actuator capabilities, develop a mathematical model (Equations of Motion) of the two-bar system, and finish a preliminary design for the product. The results of these objectives will make up the body of our next deliverable, due on February 27: Preliminary Design Review (PDR).

### EDIT- 2/24/2020

Team Capy has developed a preliminary mechanical concept design. This design is composed of a wire-guide stand, gears connecting the motors to the actuators, a gear-set actuator for the upper leg, and a belt-drive for the lower leg actuator. The budget has been raised to \$1100, excluding the stand, because of the motor requirements and costs. Looking toward CDR, Team Capy will further develop the concept design according to PDR critique. The team will build and test a prototype and return to the design phase based on the results.

### EDIT – 11/19/20

The deliverable for the past year was to develop of 2 degree of freedom robotic leg that can accurately jump 10 centimeters while costing less than \$600. Included within that phrasing is a testing mechanism. Team Capy succeeded in developing a 2 degree of freedom robotic leg, while spending much more than \$600 dollars and without confirming whether the leg jumps. Very early in the project process the budget was increased to \$3000, and it became clear that the controls simulation and electronics were not going to be ready for Team Capy to connect to.

Team Capy is very content with the state of the project today. As a team it was understood that we are the first of many projects to be working towards the greater goal of building a quadruped robot at Cal Poly. With that understanding, we are confident that our

project provides clear paths, and abilities to improve on and achieve the goal. Primarily we are proud of the test stand. After many unique ideas and designs, we finally achieved to design and build an easy to assemble, sturdy, long-lasting test stand. We are confident that this test stand will be used to analyze many leg and motor designs.

Team Capy did not achieve to connect electronics and test the leg. In retrospect, the project proposal of designing a leg as well as controls simulation might have been out of reach. We believe that was good for us as a team, because we reached for a goal further than what we eventually reached. While there is the negative viewpoint of not having achieved all we set out to do, the glass half full viewpoint which we choose to see is that we designed and built a better leg and test stand because we knew of the next steps.

Had Team Capy had a re-do with this project, we would increase communication efforts with our sponsors. The design changes that happened late in the process were encouraged by our sponsors, and led to better, more effective designs. While the senior project process is meant as a learning tool for the students more so than a project labor bank for sponsors, our sponsors guided us towards options and design ideas we did not know existed. There is a thin line between the sponsors telling us what to do and suggesting we look for a different solution. During the process Team Capy did not feel our sponsors overstepped in recommending ideas, as such we would have increased communications looking back.

Listed below are recommendations for future teams and our sponsors:

#### Recommended Design of Acrylic Casing:

Team Capy suggests utilizing an acrylic casing for safety when operating the leg on the test stand. While the legs are safe, an additional layer of safety will ensure that during operation it is not possible for a bystander to get pinched or electrocuted. Using clear acrylic will allow operators to still see what is happening. Implementing a switch will require the acrylic box to be in place before movement is possible, forcing the safety precaution to be used.

The following BOM is based on the recommendation made above. Specifically, the amount of acrylic casing calculated for surrounds the entire test stand on all 5 sides (not bottom). The next team leading this project should plan to revisit these measurements and vendor.

Subassembly	Part Name	Part Vendor	Price	Quantity
Acrylic Casing	48" x 96" x 1/8" Clear Acrylic Sheet	Home Depot	\$129.00	5

#### Recommended Methods of Data Collection

Data collection is required in order to complete a feedback loop for the control system. By collecting specific location data, one can extrapolate velocity, acceleration and further displacement derivatives of the specific parts they are looking at. Based on this output, the control system will be able to modulate the motors' torque inputs to the desired specification. Team Capy recommends that the next projects utilize one of two methods to analyze the motion



of the Robotic Leg. The first is by using a slow-motion camera and specific background set up to capture frames of the legs and motor casing at different positions. The second recommendation is to use non-contact encoders. The decision of which method to use should be influenced by the budget of the next team.

Using a camera to capture slow motion videos of the leg in motion is the inexpensive yet complicated way to analyze the motion of the leg. Using rudimentary dynamics equations and treating the legs as rigid bodies, the position, velocity, and acceleration vectors (in addition to further position derivatives) can be extrapolated. This can be done by comparing the different leg angles by stepping time in addition to monitoring motor casing location.

Surprisingly, any modern (iPhone 8 and on) Apple phone camera has the capability to capture slow motion video at 240 frames per second, but may not be able to feed live information to a control system. That framerate is more than enough to be able to accurately analyze the motion of the legs; we recommend finding a way to use the iPhone in this system or purchasing a camera with comparable framerate to capture and send location data to the control system. We recommend using a background with a scale that accounts for the location of the leg relative to the camera, the distance between robotic leg and background, and is easy to read against. An example background is a grid in which the boxes get increase in area proportionally to the distance from the camera's center of view.

A non-contact, optical, linear encoder is another option for collecting the location data of the leg. It would be far more accurate than the camera method but would only give one datapoint: motor casing location. This method would be much easier to incorporate into the control system as it simply outputs a voltage based on the encoder's location. The motor casing velocity, acceleration, and further derivatives could be extrapolated from this datapoint. The input torque from the motors can be modulated based on this single output.

Optical linear encoders are both very accurate and far less expensive than their magnetic counterparts. The price depends on three main factors: accuracy, length, and application. The most expensive ones have industrial applications and are built to withstand much higher loads than are required for our use case. We recommend basing the encoder decision around length, as any encoder that size should provide more than enough accuracy and toughness for this application. The chosen encoder must span the 4 ft length of the guide rail.

The next team's design choice will be between these two options, deciding between the accuracy and the amount of the system they want to define. In an optimal scenario, an encoder would be used to measure the motor casing location while a camera monitors the legs' rotational position (velocity, acceleration, etc.).

### Recommended Part Comparison

Due to restrictions set by the pandemic, Team Capy was forced to fabricate and assemble mostly off campus. As such we did not have access to many measuring devices such as a scale or calipers. We recommend that the next team to take over weigh, measure and compare the

fabricated components against the values the CAD models indicate. Knowing the real weight and dimensions will greatly help in motion analysis.

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## **APPENDICES**

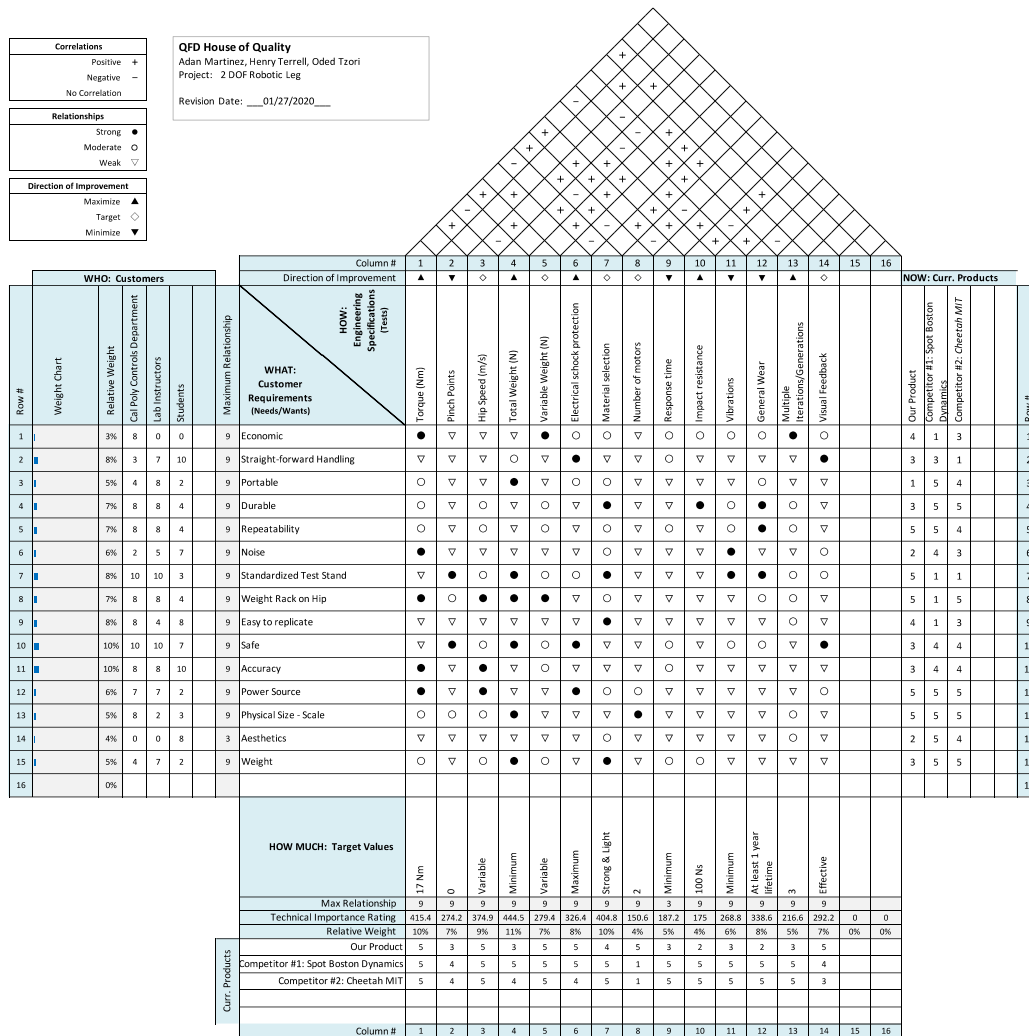
### **APPENDIX A: RELEVANT PATENTS**

Patent Name	Patent Number	Description
A Quadruped Legged Robot Driven by Linear Actuators	WO2008084480A1	The present invention relates to the field of legged robots. More particularly, the invention relates to a quadruped legged robot driven by pneumatic linear actuators.
Single Leg Mechanism of a Quadruped Robot	CN106627831A	The present invention relates to robot innovation and application field, and in particular to a kind of quadruped robot list leg mechanism.
Single actuator per leg robotic hexapod	US6481513B2	The present invention generally relates to robotic devices and, more particularly, relates to a robotic device having six compliant legs, which is adapted to accomplish a wide variety of dynamically dexterous tasks
Walking Mechanism for Four-Foot Robot Driven and Controlled by Cams	CN202038387U	The present invention relates to a walking quadruped robot technology, particularly, to a cam drive controlled quadruped robot walking mechanism.
Running Robot Having Four Legs	KR101373740B	The present invention relates to a quadruped traveling robot. More specifically, the present invention relates to a quadruped running robot that can drive each foot unit with a single drive, simplifying the structure, realizing light weight and reducing costs.
There is the Quadruped Robot of Waist Structure in Parallel	CN104924294B	The present invention relates to walking robot technical field, specifically a kind of quick four-footed machine with waist structure in parallel People.

## APPENDIX B: ACTUATOR SPECIFICATIONS

HT-01四足机器狗电机(整体驱动器性能参数)	
Mass/质量	480g
Dimensions/尺寸	96mm O.D., 40mm axial length
Maximum Torque/堵转扭力	17NM
Continuous Torque/持续扭力	6.9NM
Maximum Output Speed/最大输出速度	40rad/s@24 volts
Maximum Output Power/最大输出功率	250watts
Current Control Bandwidth/电流控制带宽	4.5kHz@4.5Nm; 1.5kHz@17Nm
Output Inertia/输出惯性	0.0023kgm <sup>2</sup>

# APPENDIX C: QUALITY FUNCTION DEPLOYMENT



## APPENDIX D: DECISION MATRICES

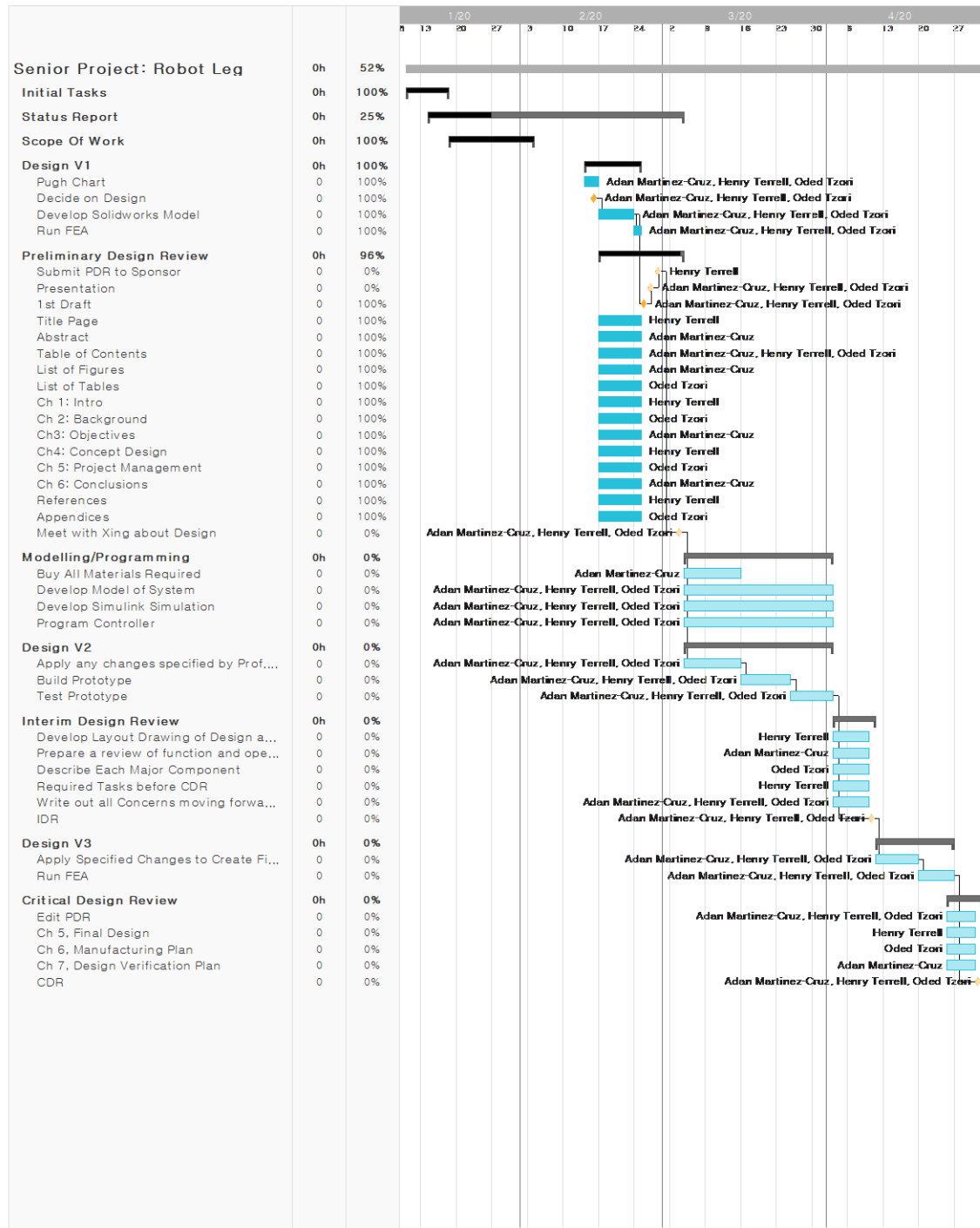
Stand																
	Factors	Pinch Points	Total Weight	Variable Weight	Material Selection	Friction	Electrical shock protection	General Wear	Vibrations	Portability	Compactability	Set-up Ease	Visual Feedback	Aesthetics	Orientation Lock	Total
2 Guide strings in tension	Weights:	5	2	2	4	4	2	2	1	2	1	4	3	2	4	
	Unweighted	4	5	5	5	2	3	2	1	5	3	4	5	4	5	53
	Weighted	20	10	10	20	8	6	4	1	10	3	16	15	8	20	151
Rectangular Track with Bearings	Unweighted	5	3	1	3	2	2	4	4	2	2	4	3	3	4	42
	Weighted	25	6	2	12	8	4	8	4	4	2	16	9	6	16	122
Pole with Cylindrical Slider @ Hip	Unweighted	3	4	1	4	4	3	3	4	5	5	5	4	3	1	49
	Weighted	15	8	2	16	16	6	6	4	10	5	20	12	6	4	130
Diamond Track with Bearings	Unweighted	5	3	1	3	5	2	4	4	2	2	5	4	4	5	49
	Weighted	25	6	2	12	20	4	8	4	4	2	20	12	8	20	147
Pole with Cylindrical Slider With keyway @ Hip	Unweighted	3	4	1	4	4	3	4	4	5	2	5	4	3	5	51
	Weighted	15	8	2	16	16	6	8	4	10	2	20	12	6	20	145
Guide string in tension with track for knee	Unweighted	3	5	5	5	3	3	3	1	4	3	3	5	3	5	51
	Weighted	15	10	10	20	12	6	6	1	8	3	12	15	6	20	144

### Weighted Decision Matrix for Stand Design

Lower Leg Actuator																
	Factors	Pinch Points	Total Weight	Cost	Material Selection	Torque Required	Maintainence	Torque Losses	Portability	Response Time	Impact Resistance	Visual Feedback	Aesthetics	Orientation Lock	Vibrations	Total
Gear, Track and Lever Arm	Weights:	5	3	3	4	4	2	4	1	3	3	1	2	4	3	
	Unweighted	2	4	4	5	3	4	2	3	4	2	4	4	2	3	46
	Weighted	10	12	12	20	12	8	8	3	12	6	4	8	8	9	132
Belt Drive	Unweighted	4	5	5	3	4	3	3	5	4	4	2	2	4	4	52
	Weighted	20	15	15	12	16	6	12	5	12	12	2	4	16	12	159
Drive Train	Unweighted	4	2	3	2	2	5	5	2	5	4	2	3	1	2	42
	Weighted	20	6	9	8	8	10	20	2	15	12	2	6	4	6	128
Bike Chain	Unweighted	1	1	3	2	3	3	3	2	4	4	3	4	3	1	37
	Weighted	5	3	9	8	12	6	12	2	12	12	3	8	12	3	107
Gear Train	Unweighted	1	3	4	4	2	3	1	2	2	2	4	5	3	1	37
	Weighted	5	9	12	16	8	6	4	2	6	6	4	10	12	3	103
4 bar linkage	Unweighted	1	3	3	4	4	5	4	4	4	2	3	4	4	4	49
	Weighted	5	9	9	16	16	10	16	4	12	6	3	8	16	12	142

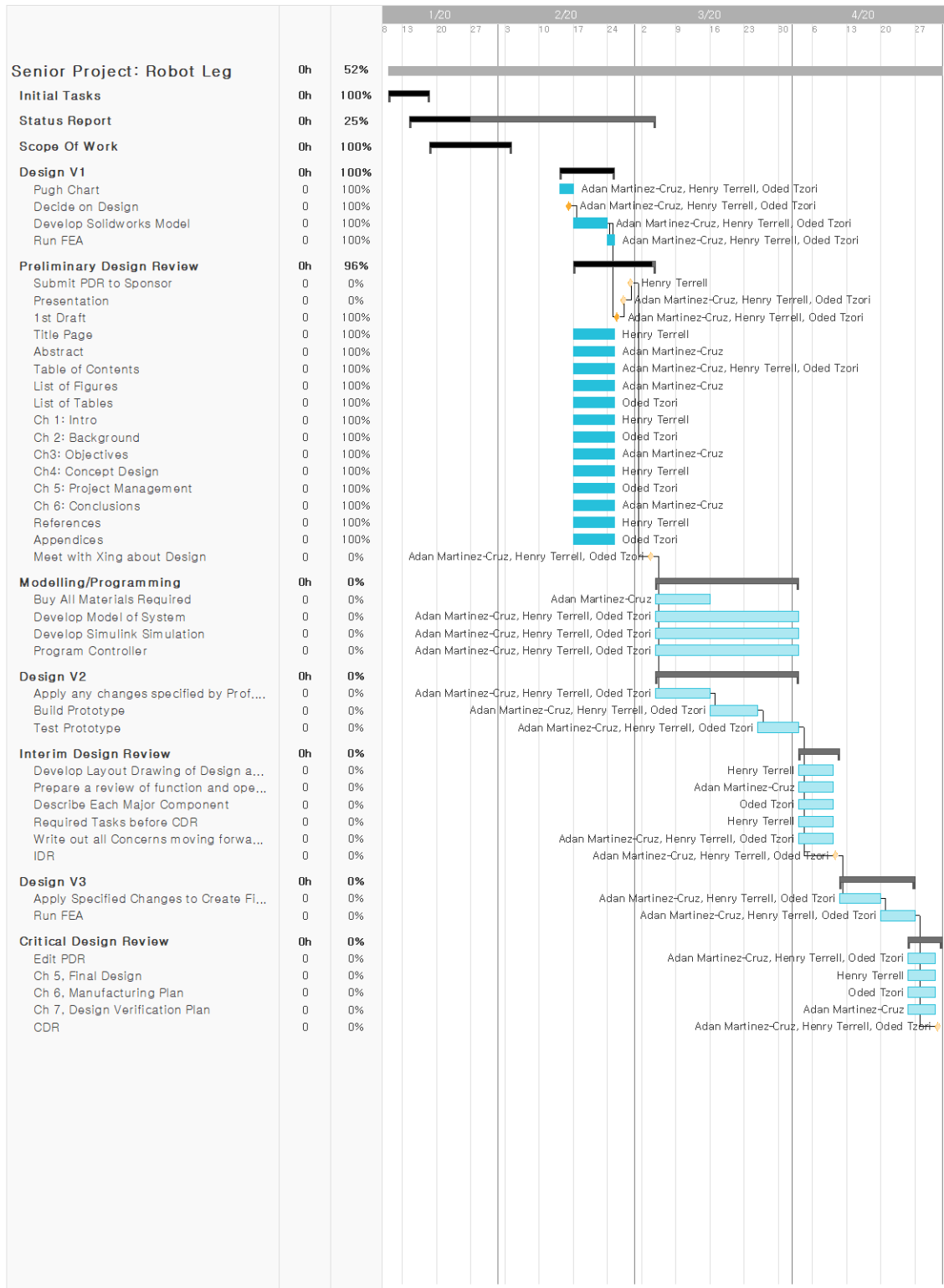
### Weighted Decision Matrix for Lower Leg Actuator.

## APPENDIX E: GANTT CHART



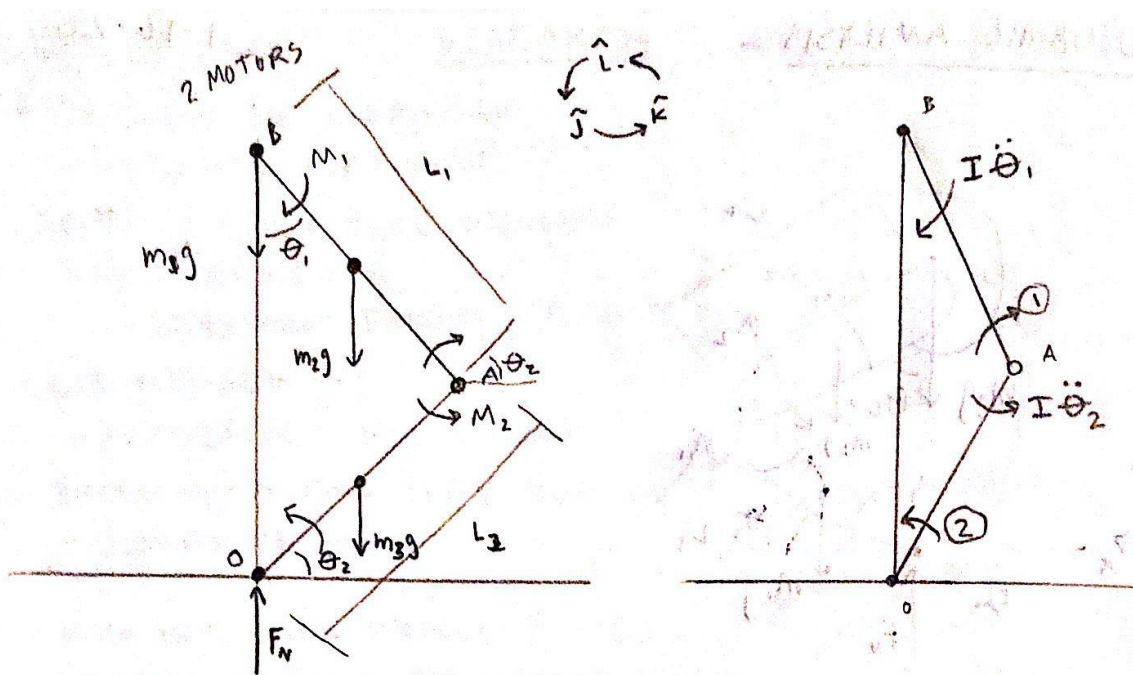
Gantt Chart 2-3-20





Gantt Chart 2-24-20

# APPENDIX F: PRELIMINARY ANALYSIS



$$\vec{V}_B = \vec{V}_A + \vec{V}_{B/A}$$

$$V_B \hat{j} = \vec{\omega}_{OA} \times \vec{r}_{OA} + \vec{\omega}_{AB} \times \vec{r}_{B/A}$$

$$V_B \hat{j} = \omega_{OA} \hat{k} \times L_2 (\cos \theta_2 \hat{i} + \sin \theta_2 \hat{j}) - \omega_{AB} \hat{k} \times L_1 (-\sin \theta_1 \hat{i} + \cos \theta_1 \hat{j})$$

$$V_B \hat{j} = (\omega_{OA} L_2 \cos \theta_2) \hat{j} - (\omega_{OA} L_2 \sin \theta_2) \hat{i} + (\omega_{AB} L_1 \sin \theta_1) \hat{j} + (\omega_{AB} L_1 \cos \theta_1) \hat{i}$$

$$\hat{j}: V_B = \omega_{OA} L_2 \cos \theta_2 + \omega_{AB} L_1 \sin \theta_1$$

$$\hat{i}: 0 = -\omega_{OA} L_2 \sin \theta_2 + \omega_{AB} L_1 \cos \theta_1$$

$$\frac{\omega_{OA}}{\omega_{AB}} = + \frac{L_1 \cos \theta_1}{L_2 \sin \theta_2}$$

$$r_1 \cos \theta_1 + r_2 \cos \theta_2 = 0$$

## APPENDIX G: LEG CONCEPT DESIGN SKETCHES

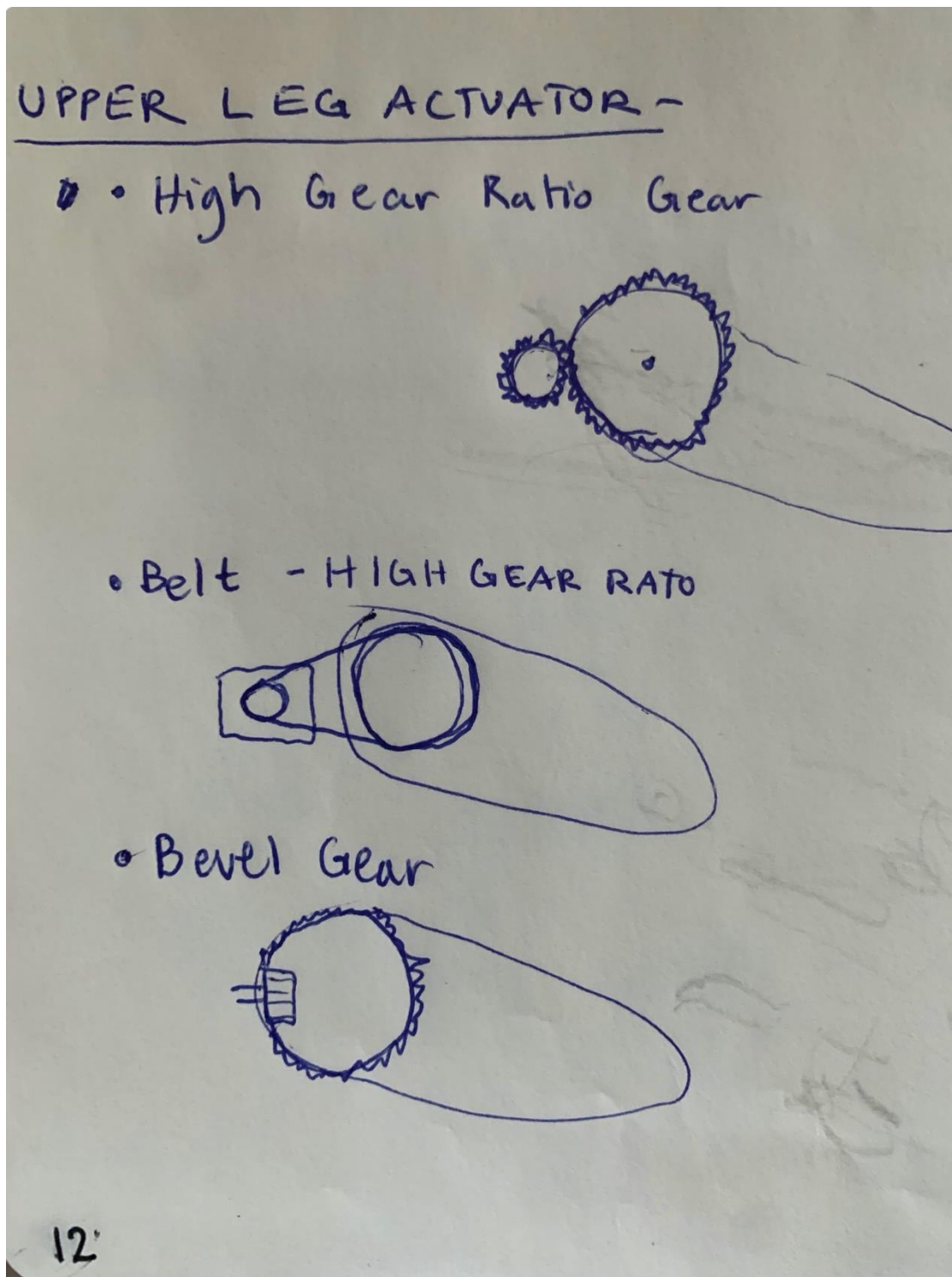


Figure G1. Suggested upper leg motion system.



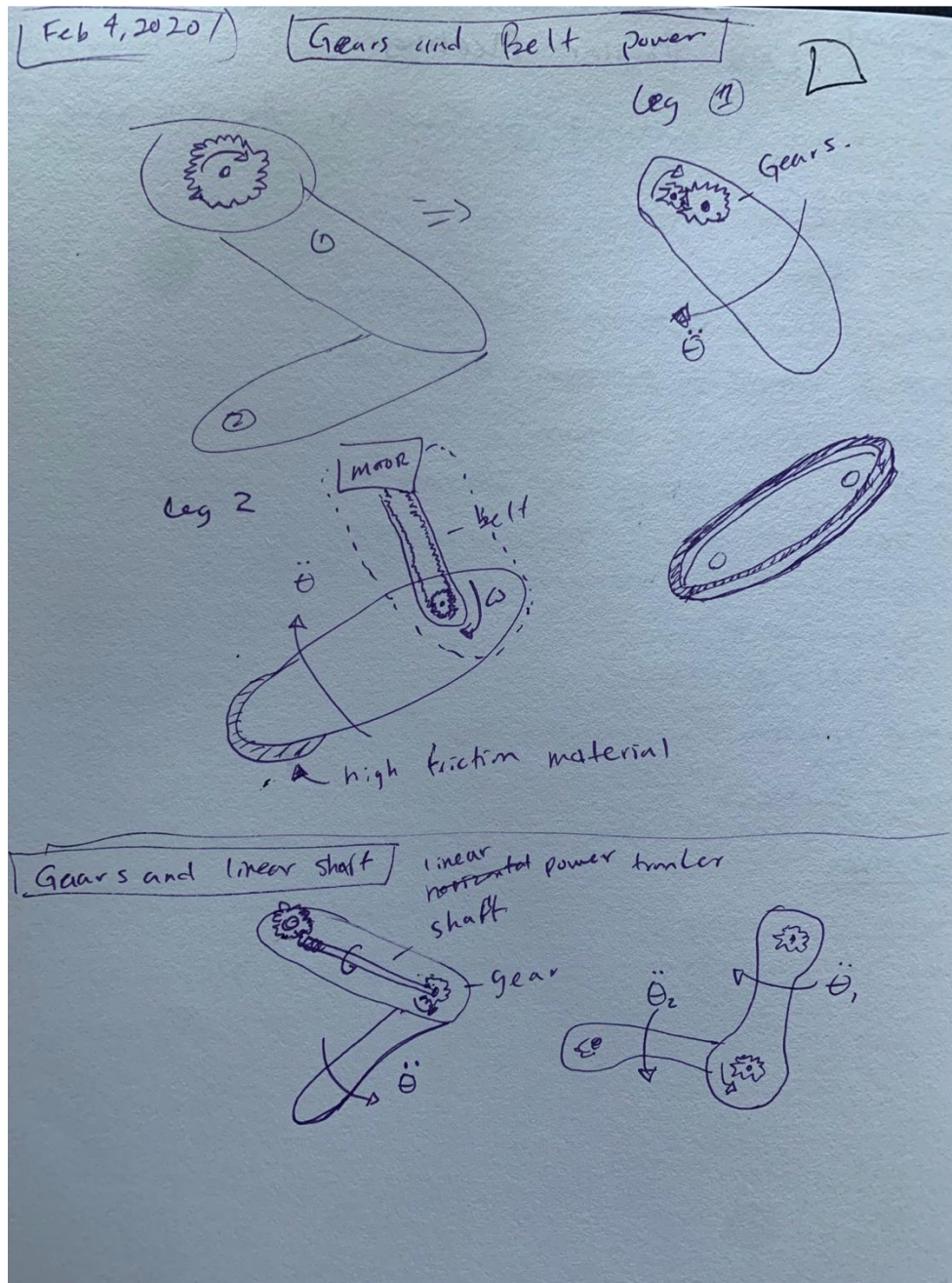


Figure G2. Suggested leg motion design idea.

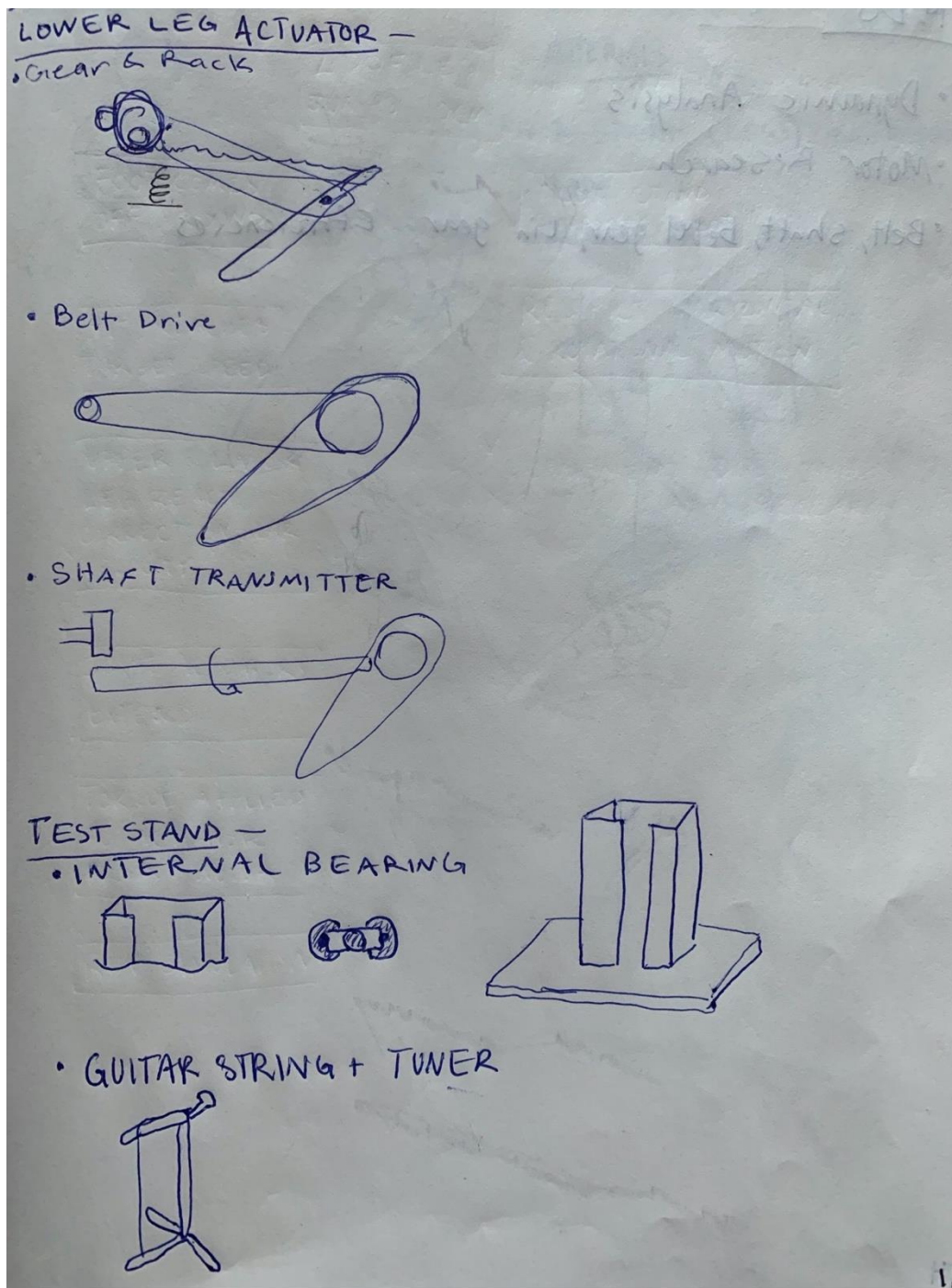
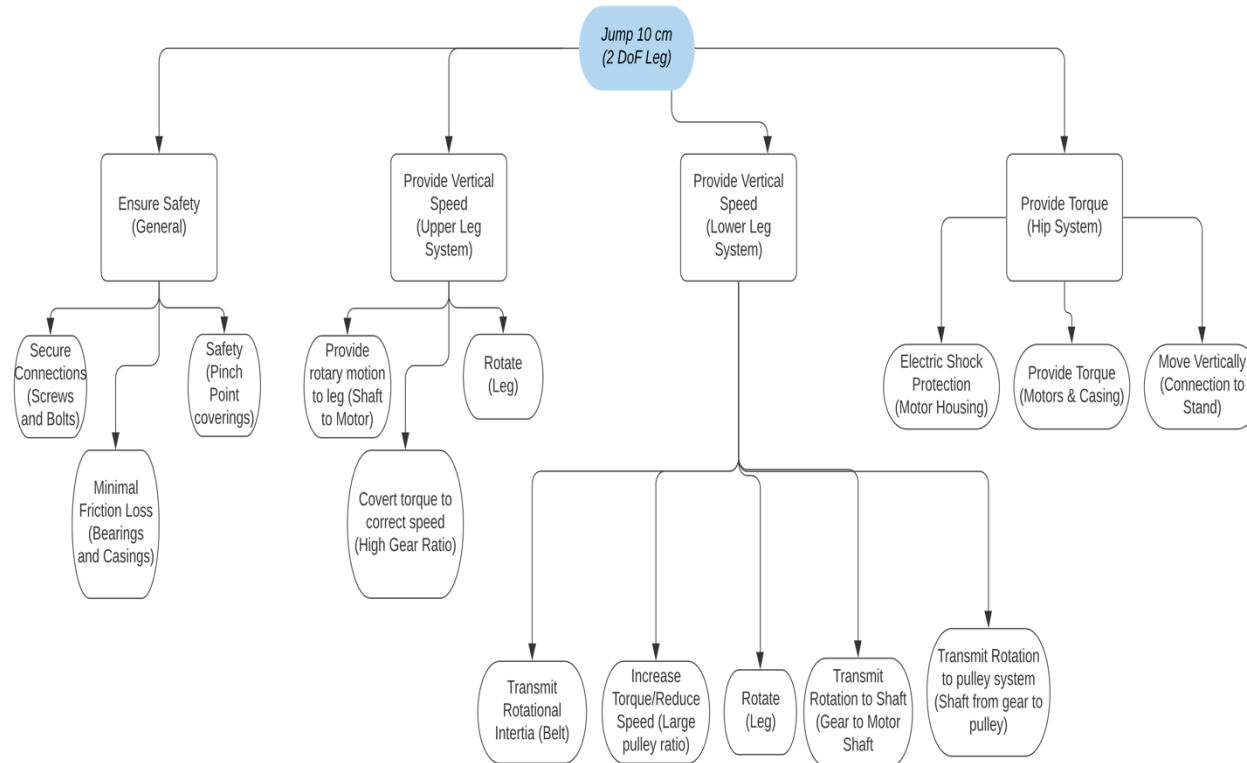


Figure G3. Lower leg concept idea.



## APPENDIX I: BILL OF MATERIALS

0	100000	Final Assembly										
1			Hip Assembly									
2				Motor Casing				240	0.229	54.96	Online Metals	0.19in thick Aluminun sheet, sold 24in by 24in for \$132
3					Motors			2	N/A	N/A	Provided	Servo motor only. DC and without encoder.
3					Motor Shaft			1	102.63	102.63	MSC / Machine	50mm diamter steel rod, cold rolled. Total length is 12in. We might need more than anticipated
3					Bearing Holder			1				Alminum or steel
3					Bevel Gear: Gear			1	64.02	64.02	KHK-USA	Made of steel. Attach to the motor for the upper leg.
3					Bevel Gear: Pinion			1	46.9	46.9	KHK-USA	Made of steel and is attach to the hollow shaft.
4					Bearing			---	---	---	---	---
4						Bearing		1	5.35	5.35	McMaster Carr	Holds inner shaft relative to the bearing holder
1			Upper Leg Assembly					---	---	---	---	---
3				Upper Leg				1	43	43	Online Metals	The upper leg will have to be machine to shape. The material is Aluminum, cold finished.
3				Bolts				4	\$7.92/100bolts	7.92	McMaster Carr	Joints Hollow shaft to upper leg. 4 fully threaded bolted joints with no nut and washer.
3				Bearings				---	---	---	---	---
3					Inner Bearings			4	5.35	21.4	McMaster Carr	Two bearing are place at each end of the upper leg. Two connect to the inner shaft.
2				Upper Pulley				1	22.44	22.44		
1			Lower Leg Assembly					1	43	43	MSC / Machine	20mm(thick) by 50mm(width) by 225mm(long) flat aluminum bar
2				Lower leg				1	43	43	Online Metals	The upper leg will have to be machine to shape. The material is Aluminum, cold finished.
2				Shaft				1	1.7	1.7	Online Metals	Fixed to lower leg and bulley. Connect upper and lower leg through a bearing in the upper leg. 62mm x 8mm steel rod.
2				Lower Leg Pulley				1	12.94	12.94	McMaster Carr	The pulley is press fitted to the shaft.
2			Timing Belt					1	6.05	6.05	McMaster Carr	
1			Power Supply					1	86	86		24V 20A 480W Power supply Transformer
				wires				10	0.34	3.4	Amazon	18AWG electrical for power supply and electronics connection sold per feet.
Total Parts							33 Total Leg Assembly			509.75		
Assembly Level	Part Number	Lvl0	Description				Lvl4	Qty	Cost/unit	Total Cost	Source	More Info
0	100000	Final Assembly						---	---	---	---	---
1			Test Stand Assembly					---	---	---	---	---
2				Frame				---	---	---	---	---
3					Steel Square Tubing			2	46.1	92.2	McMaster-Carr	1.5"x1.5"x4'
3					Steel Square Tubing			2	34.95	69.9	McMaster-Carr	1.5"x1.5"x3'
3					Traingular Plate Support			2	42	84	McMaster-Carr	8"x8"x1-1/4" - 6 holes
3					Support Bars			2	42.81	85.62	McMaster-Carr	Requires cutting and drilling
3					Screws			22	0.37	8.14	McMaster-Carr	Bolted joints for beams
3					Screws			30	0.37	11.1	McMaster-Carr	For Support Bar
3					Washers			1	11.33	11.33	McMaster-Carr	
3					Hex Locknuts			34	0.0646	2.1964	McMaster-Carr	\$6.46/100count
3					Flange Hex Locknuts			14	0.326	4.564	McMaster-Carr	Dfor course M10 bolts. \$8.15/25count
					Flange Button Head Screws			14	3.09	43.26	McMaster-Carr	Each sold separately
					Landing Plate			1	200	200	Metal Store	A 10mm thick by 200mm by 200mm sheet metal
								---	---	---	---	---
2				Hip Connection						0		
3					Guide Rails			2	400	800	McMaster-Carr	1000 mm (\$.40 per mm)
3					Carriages			2	140	280	McMaster-Carr	20-lb capable for longer track
3					Hole Plugs			30	1.09	32.7	McMaster-Carr	To plug the hole?
3					Screws			14		0	McMaster-Carr	Connecting the rail to steel frame
3					Washers			14		0	McMaster-Carr	
3					Nuts			14		0	McMaster-Carr	
								---	---	---	---	---
2				Additional						0		
3					Pressure Pad			1	500	500		Track Landing Position & Magnitude
3					Encoder			1	250	250		Track Vertical Position
										0		
										0		
										0		
										0		
										0		
Total Parts							202			2475.0104		



## APPENDIX J: SIGNED EXPECTATIONS & DELIVERABLES

### Expectations & Deliverables Document

Written by Team 41 on 10/6/2020 - Oded Tzori, Henry Terrell, Adan Martinez-Cruz

Listed below are expectations and deliverables agreed upon between Senior Project Team 41 and Professors Siyuan (Simon) Xing and Charlie Refvem on October 1<sup>st</sup>, 2020. Team advisor Professor Lee McFarland was present as well. All deliverables are expected to be ready and delivered to Charlie and Simon by November 20<sup>th</sup>, 2020.

### Meeting Minutes Highlights (10/01/20)

- Team 41 was told to not plan for connecting electronics this quarter
  - Team 41 should no longer plan for purchasing encoder(s) this quarter
  - Testing plans no longer include jumping/kicking repeatability
    - Shift to capturing angles & vectors using high speed camera
    - Measure and define mechanical limitations
      - Quantitatively
  - No software of computation simulations provided by Team 41
    - No electronics excluding motors
- Charlie and Simon are interested in purchasing 1 new motor for the leg
  - <https://store-en.tmotor.com/goods.php?id=981>
  - AK80-6
- Team 41 should plan for passing project resources over to a new team
  - Assembly Manual
  - Organize project files and folders
  - Provide accurate information
    - CAD Models
    - Weight & Scale of parts

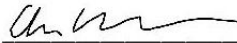
### Expectations and Deliverables (To be delivered by 11/20/20 if not otherwise stated)

1. Create an updated budget and bill of materials by 10/13/20
  - a. B.O.M. should include one motor
  - b. Order form submitted to Merideth by same date
2. Leg and Test Stand
  - a. All parts necessary for assembly
    - i. not including electronics or computational simulation
  - b. Team 41 should share a video ahead of 11/20/20 showing assembled parts with motion
3. Assembly Manual
  - a. Includes assembly procedures
  - b. Include instructions to easily navigate resources
    - i. A "ReadMe" for the Drive and Fusion directories



- c. Include drawings from the CAD models
  - i. Purchased or fabricated
- d. Bill of Materials of all ordered parts (raw materials included)
  - i. Includes part description, count, price/unit, total price, etc.
    - 1. Mimic purchase request from
- e. Fabrication process described for individual parts (raw materials)
- f. Compare part measurements (weight & scale) to simulated measurements
- g. Testing section
  - i. Discusses (quantifies) range of motion testing done by Team 41
  - ii. High-speed (high fps) camera & background set up analysis (recommendation)
  - iii. Add section on use of encoders (recommendation)
    - 1. Non-contact encoders
- h. Operational Cautions and Safety Procedures
  - i. Pinch points, electric shocks
  - ii. Limits (rotational, translational)
- i. Acrylic Casing (recommendation)
  - i. Surrounding entire test stand and leg
  - ii. Must be in place for leg to be operational
    - 1. Safeties

Sponsor Signatures



Charles Refvem

10/14/2020

Date

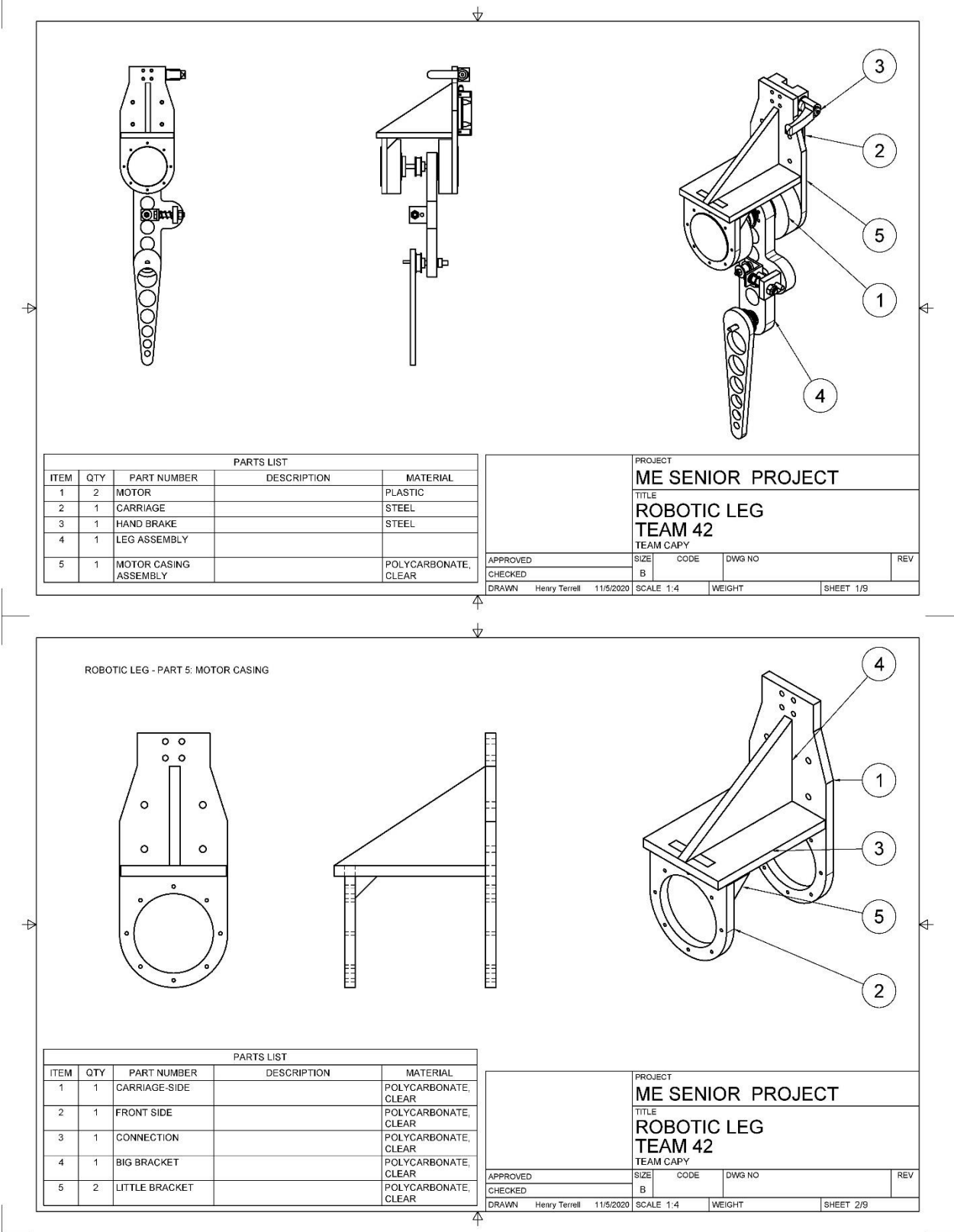


Siyuan Xing

10/14/2020

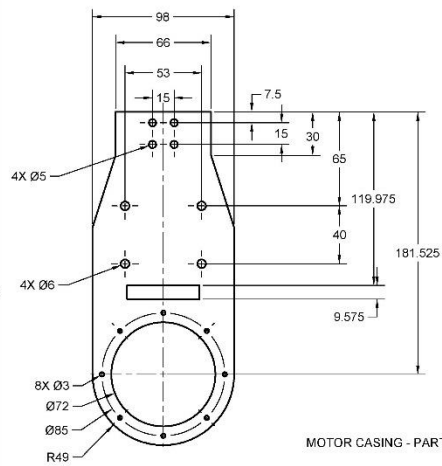
Date

APPENDIX K: ROBOTIC LEG DRAWING PACKAGE

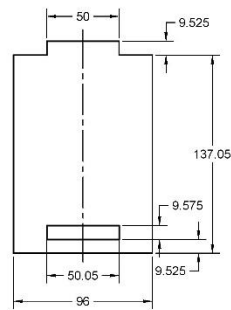


NOTE: ALL COMPONENTS CUT FROM  $\frac{1}{8}$ " POLYCARBONATE SHEET

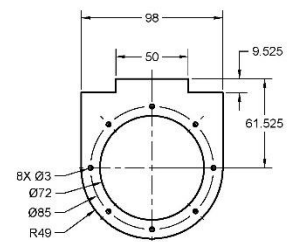
MOTOR CASING - PART 1: CARRIAGE-SIDE



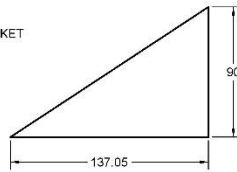
MOTOR CASING - PART 3: CONNECTION



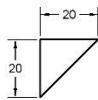
MOTOR CASING - PART 2: FRONT SIDE



MOTOR CASING - PART 4: BIG BRACKET



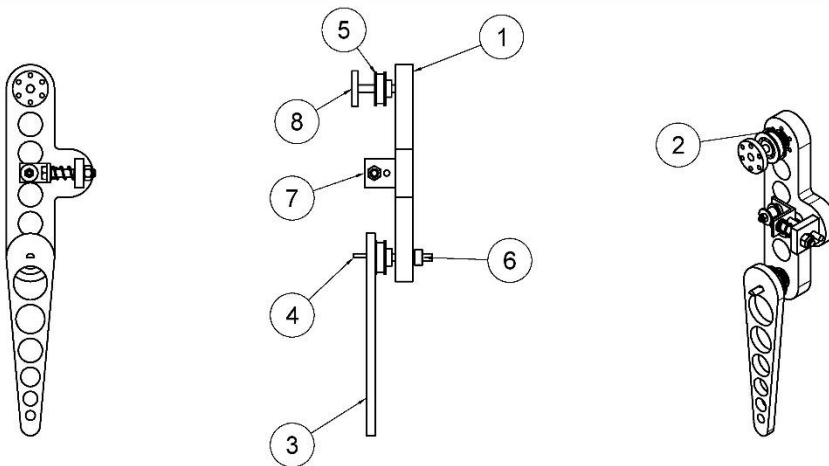
MOTOR CASING - PART 5: LITTLE BRACKET



PROJECT  
**ME SENIOR PROJECT**  
TITLE  
**ROBOTIC LEG**  
**TEAM 42**  
TEAM CAPY

APPROVED	SIZE	CODE	DWG NO	REV
CHECKED	B			
DRAWN	Henry Terrell	11/5/2020	SCALE 1:2	WEIGHT

SHEET 3/9



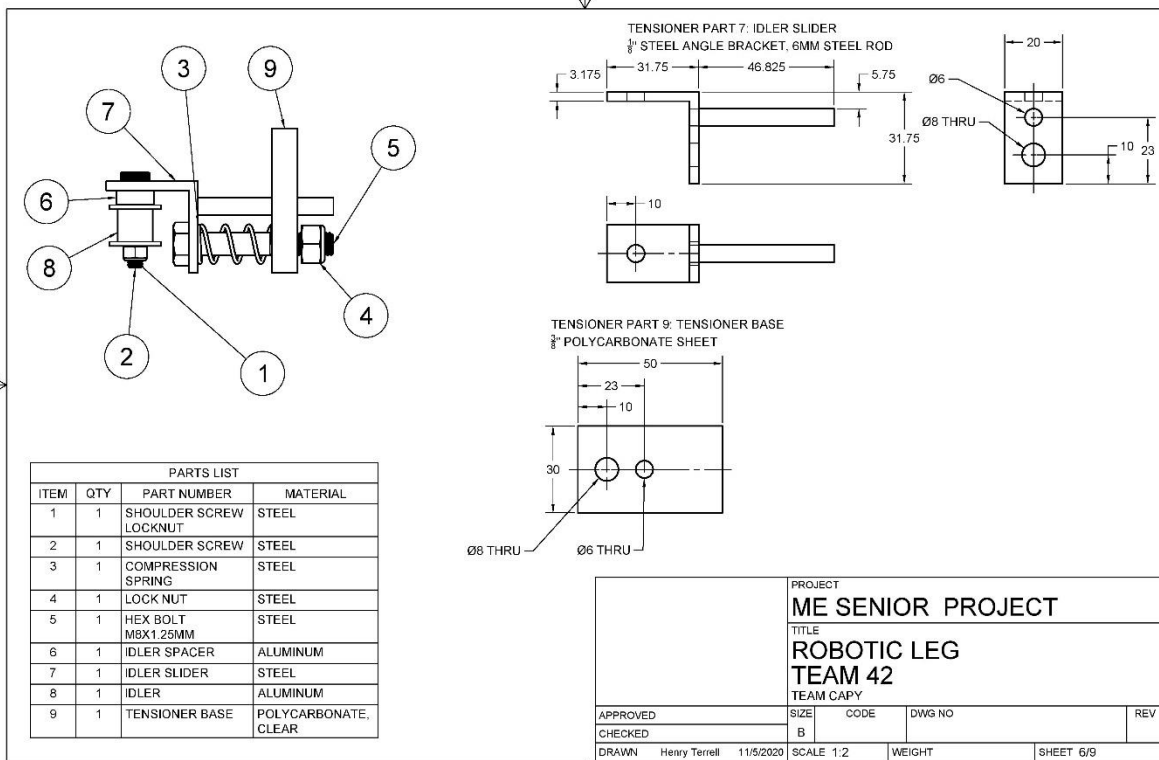
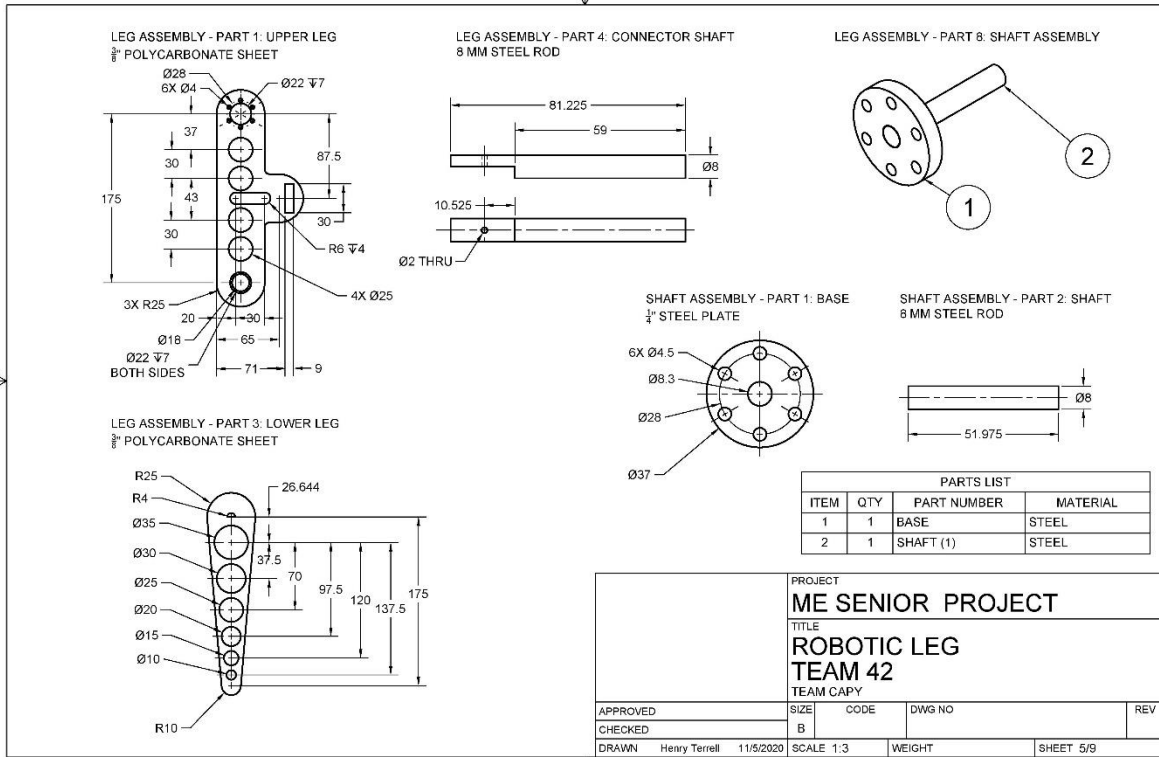
PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION	MATERIAL
1	1	UPPER LEG		POLYCARBONATE, CLEAR
2	3	BEARING		STEEL
3	1	LOWER LEG		POLYCARBONATE, CLEAR
4	1	CONNECTOR SHAFT		ALUMINUM
5	2	PULLEY1		STEEL
6	1	STOP COLLAR		STEEL
7	1	TENSIONER		
8	1	SHAFT V11		STEEL

PROJECT  
**ME SENIOR PROJECT**  
TITLE  
**ROBOTIC LEG**  
**TEAM 42**  
TEAM CAPY

APPROVED	SIZE	CODE	DWG NO	REV
CHECKED	B			
DRAWN	Henry Terrell	11/5/2020	SCALE 1:4	WEIGHT

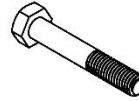
SHEET 4/9



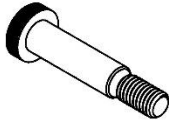
# TENSIONER ASSEMBLY STANDARD PARTS



TENSIONER ASSEMBLY - PART 1  
SHOULDER SCREW LOCKNUT  
VENDOR: MCMaster CARR  
PART #: 94645A102  
QUANTITY: 1



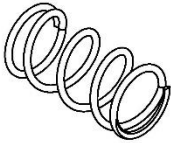
TENSIONER ASSEMBLY - PART 5  
HEX BOLT M8 X 1.25  
VENDOR: MCMaster CARR  
PART #: 91310A546  
QUANTITY: 1



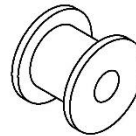
TENSIONER ASSEMBLY - PART 2  
SHOULDER SCREW  
VENDOR: MCMaster CARR  
PART #: 90833A115  
QUANTITY: 1



TENSIONER ASSEMBLY - PART 6  
IDLER SPACER  
VENDOR: MCMaster CARR  
PART #: 94669A165  
QUANTITY: 1



TENSIONER ASSEMBLY - PART 3  
COMPRESSION SPRING  
VENDOR: MCMaster CARR  
PART #: 94125K221  
QUANTITY: 1



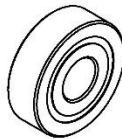
TENSIONER ASSEMBLY - PART 8  
IDLER  
VENDOR: AMAZON  
PART #: 10MHL20B6N  
QUANTITY: 1



TENSIONER ASSEMBLY - PART 4  
LOCK NUT  
VENDOR: MCMaster CARR  
PART #: 90576A117  
QUANTITY: 1

		PROJECT	
		ME SENIOR PROJECT	
		TITLE	
		ROBOTIC LEG TEAM 42	
		TEAM CAPY	
APPROVED	SIZE	CODE	DWG NO
CHECKED	B		
DRAWN	Henry Terrell	11/5/2020	SCALE 2:1
		WEIGHT	SHEET 7/9

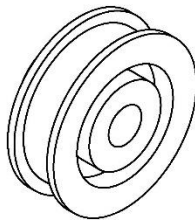
# LEG ASSEMBLY STANDARD PARTS



LEG ASSEMBLY - PART 2  
BEARING  
VENDOR: MCMaster CARR  
PART #: 5972K222  
QUANTITY: 3



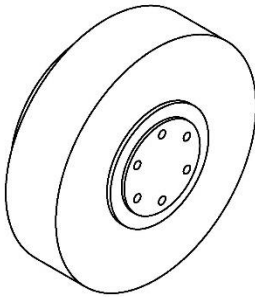
LEG ASSEMBLY - PART 6  
STOP COLLAR  
VENDOR: MCMaster CARR  
PART #: 6058N16  
QUANTITY: 1



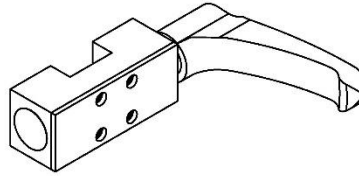
LEG ASSEMBLY - PART 5  
PULLEY  
VENDOR: SDP/SI  
PART #: A 6M16M048DF6008  
QUANTITY: 2

		PROJECT	
		ME SENIOR PROJECT	
		TITLE	
		ROBOTIC LEG TEAM 42	
		TEAM CAPY	
APPROVED	SIZE	CODE	DWG NO
CHECKED	B		
DRAWN	Henry Terrell	11/5/2020	SCALE 2:1
		WEIGHT	SHEET 8/9

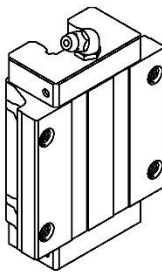
ROBOTIC LEG STANDARD PARTS



ROBOTIC LEG - PART 1  
MOTOR  
VENDOR: T-MOTOR  
PART #: AK80-6  
QUANTITY: 2  
FASTENER: 6X M4, 8X M3



ROBOTIC LEG - PART 3  
HAND-BRAKE  
VENDOR: MCMASTER CARR  
PART #: 1685N11  
QUANTITY: 1  
FASTENER: 4X M5



ROBOTIC LEG - PART 2  
CARRIAGE  
VENDOR: MCMASTER CARR  
PART #: 6688K22  
QUANTITY: 1  
FASTENER: 4X M5

PROJECT			
ME SENIOR PROJECT			
TITLE			
ROBOTIC LEG			
TEAM 42			
TEAM CAPY			
APPROVED	SIZE	CODE	DWG NO
CHECKED	B		REV
DRAWN	Henry Terrell	11/5/2020	SHEET 9/9

APPENDIX L: TEST STAND DRAWING PACKAGE

