

NASA Robotic Jumping Leg Project

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Abstract

To finish our curriculum as Mechanical Engineering Technology students at the University of Cincinnati, we are required to complete a senior design / capstone project. This project was completed by three students, each with their own responsibilities throughout the project. The purpose of this senior design project is to redesign certain problematic parts/areas of the lunar jumping leg apparatus, that was initially created in 2020 – 2021 for a capstone project. This is the third iteration of this project and will be passed to another group following the spring semester of 2022. This report will entail the entire senior design process of our group from research, design, testing, and results of our fixture redesigns.

Problem Statement

The purpose of this project was to redesign certain parts of the lunar jumping leg testing apparatus. These parts included the latching/releasing mechanism, the motor and gear drive system, the cable mechanism, the footpad, and if we were capable of finishing that with extra time, automating the compression and decompression sequences. The release mechanism on the previous iteration did not release the pressure from the springs evenly across the load plate, causing the weight to be unevenly distributed upon release and even as far as bending the guide bars. The cable, which connects the leg to the load plate, was just a single string of paracord on the previous fixture iteration. This paracord was elastic and absorbed some of the upward force that needed to be asserted into the leg. The old motor could not provide enough torque to fully compress the springs in the release mechanism and the foot of the testing leg needed to be redesigned to allow the cable and footpad to be replaceable.

Research

Background of the Problem

The Department of Aerospace Engineering and Engineering Mechanics at The University of Cincinnati chose to partake in a proposal for a grant from NASA to design a means of data acquisition on extra-terrestrial bodies. The goal is to solidify the groundwork for a remotely piloted robot with the ability to collect geological samples and atmospheric data.

The project had already been started by a previous senior design group, and a basic prototype had already been produced. The current design resembles that of a kangaroo leg, with the end goal being a two-legged device with a stabilizing tail/sample collector. Our focus was to do an overhaul of the current state of the leg and testing apparatus. There were several major flaws in the prototype design. These flaws included the release mechanism causing inconsistent releases, the gear drive system could not produce enough torque to compress the springs, the cable controlling the ligaments of the leg caused energy loss due to high elasticity, and the foot design was not ideal configurability.

Applicable Standards

We used the same standards used last year for this project. The previous group for this project used two engineering standards, International Space Power System Interoperability Standards (ISPSIS) Code 3.3.1 and International External Robotic Interface Interoperability Standards (IERIIS) Standard E.2.3.

The International Space Power System Interoperability Standards (ISPSIS) are “electrical power quality standards to ensure commonality, reliability, safety, interchangeability, and interoperability for electrical load applications” for spacecraft systems (1). The Code 3.3.1 is the specific code for electric power generating sources. This standard will be used when using electrical motors and other electrical components of the fixture.

The International External Robotic Interface Interoperability Standards (IERIIS) are standards for mounting interfaces for robotic compatible spacecraft (2). This is to prevent the use of incompatible units. The Standard E.2.3 is for the berthing operations of robotic compatible systems. This applies to the overall scope of this project but not directly to this iteration of the project. At the current time, this project is for the testing of a possible hopping lunar robot.

State of the Art



Figure 1: Previous fixture iteration from Summer 2021

Latching Mechanism

Previous Iteration – Latching Mechanism

The latching mechanism previously used on the testing apparatus consisted of a cylindrical tapered bar that moved in a linear motion. There were only 2 of these latches used to hold down the pressure plate which caused the pressure plate to release crooked. A crooked release resulted in the pressure plate binding on the guide rails leading to a loss in energy within the system, ultimately causing skewed data.

The previous latching system also featured a point of leverage for withdrawing the bars from the system that were manually pulled outwards. Because the mechanism was manually actuated, human error became another issue resulting in a crooked release of the pressure plate.

Other Latching Mechanisms

Most of the linear release mechanisms on the market today are mostly electrically and pneumatically actuated, like a latching solenoid from GeePlus (3). These actuators are designed to be bolted down to a surface and create the same motion as the latches that are currently on the fixture. However, these actuators are limited by the amount of force they can output versus the previous system which relied on the strength of the operator.

Gear / Drive System

Previous Iteration – Stepper Motor & Gears

The previous gear drive system consisted of a NEMA-17 stepper motor, a 20-tooth driver gear, and a 75-tooth driven gear. The gear ratio created was 3.75:1. The NEMA-17 motor had planetary gears inside it to provide higher torque output. This motor was attached to a 20-tooth gear and that gear drove another 75-tooth gear. The motor was controlled by a motor controller and Arduino so it could be operated remotely. The motor would be told to run and would fully compress the three springs so the plate can be latched and secured. However, the torque became too great for the motor and the motor could not provide enough power to fully compress the springs (4) (5). For previous testing, the operator would have to manually turn the 75-tooth gear that was connected to a threaded rod and then therefore, guiding the bottom plate of the latching mechanism, compressing the springs.

Gearmotor

A gearmotor is the combination of an electric motor along with a gearbox (6). They are useful when it comes to the need of a relatively low-cost and high-torque providing unit. They come in multiple sizes providing different power and torque specifications. They also come in different gear systems (i.e., planetary gears) that can provide different torque specifications as well. A gearmotor is compact and can provide efficient power transmission (7).

Planetary Gear System

Planetary gear systems, or epicyclic gears, are made up of three types of gears; a centric sun gear, “orbiting” planet gears, and a ring gear to hold them all together (8). These gear systems add more gears in a compact space, can provide high gear ratios, and have high torque capabilities. The load put on these gears is more distributed throughout the system, allowing for those higher torque capabilities (8). However, these systems can be relatively expensive, and they have to be in-line with the drive and driven components.

Harmonic Gear System

Harmonic gear systems, or strain wave gearing, consist of three components, like planetary gears do. They consist of an outside static circular spline, a rotary middle spline, and an inner oval (or wave generator) (9). These gear systems provide similar advantages to planetary gears with providing high torque and are compact. These systems also provide no backlash and offer high gear ratios. However, these systems have high elasticity and have nonlinear stiffness and damping (10). They are also relatively expensive and are not as readily available as a planetary gearbox.

Foot / Footpad

Lunar Rover

The Lunar Roving Vehicle (LRV) was first used during NASA's Apollo 15-17 missions. The rover was roughly the size of "a modern Volkswagen Beetle" and bore a resemblance to a dune buggy (11). This machine was manually operated and used as a transportation method during these Apollo missions, carrying the astronauts themselves, equipment, and moon rocks. The rover could support up to 1,080 pounds fully loaded (11). The LRV could drive at a max speed of 12 mph, but it would not be a smooth ride due to the moon's low gravity (12). Also, the astronauts could only take the rover a maximum of 6 miles from their lunar module (11). The latest NASA Mars rover, Perseverance, was launched in July 2020 and landed on Mars in February 2021. This Mars rover was larger than the lunar rover used during the Apollo missions, being larger than the average car today. This machine was used for data collection, unlike the lunar rover whose primary function was transportation. Perseverance was composed of instruments and components to take pictures/videos, microphones to take audio recordings, an arm to gather physical samples, and more (13). This rover might be controlled by a human, but the operator is not sitting in the driver's seat. The driver remotely operates the rover from Earth. Since it is being remotely operated, the driver cannot instantaneously see where they are driving, causing issues when it comes to steering. Also, the rover is solar-powered, and it can only operate for an average of 20 minutes a day during a 4-hour window (14).

Other Robotics

When it comes to robotics and the use of robotic legs, there is no bigger name out there than Boston Dynamics and their numerous cutting-edge robots. More specifically the robots "Spot" and "Atlas". Spot is a quadruped exploration robot that resembles a small dog. Standing at a max height of 7.5 inches and weighing 70 pounds, Spot is unmatched in its mobility on uneven surfaces showing its capabilities in climbing stairs and rocky surfaces (15). Spot is also able to explore areas not safe for human existence. This has been proven with Spot's exploration of Chernobyl's highly radioactive reactor (16).

Atlas, on the other hand, is a bipedal humanoid robot that has demonstrated that it is very capable of traversing complex obstacles like Boston Dynamic's parkour course performing human like maneuverability. However, this has only been tested on flat surfaces and may not

have the same off-roading capabilities as Spot but demonstrated that it is very capable of jumping various heights and hurdling over objects.

End User

The primary end user for the robotic jumping leg and its associated testing fixture would be NASA's Explorers program (17). This program accepts proposals from schools and universities across the world and issues grants once a year to a selected few projects to conduct further research. It is our hope that down the line, this project will be selected for this outreach program and see use in future planetary exploration and research.

Summary of Research

Although technology exists for getting around in lower gravity exists already, it can be argued that there is a more efficient way, for instance, jumping or leaping. The goal of this project was to solve some of the problems with the current testing apparatus so we can test the use of a jumping mechanism for a robot on the moon or on Mars. Our tasks were to redesign and re-evaluate the latching/releasing mechanism, the motor and gear drive system, the cable mechanism, and the footpad of the current leg and testing apparatus.

Quality Function Deployment

Customer Survey

A customer survey was conducted the week of September 20th, 2021. The survey was given to undergraduate and graduate students and faculty members that are involved in the creation and development of the NASA Robotic Jumping Leg project. You can see an example of our customer survey in Appendix A of this report.

Customer Features

Weight

Overall Size

Flexibility

Configurability

Maneuverability

Initial Investment Cost

Engineering Characteristics

Electrical Motor Selection (Torque Specifications, Motor Size, etc.)

Cable Selection/Properties

Motorized Gear Drive Selection/Properties

Test Apparatus Functionality

Footpad Design

Release/Latching Mechanism Selection

House of Quality

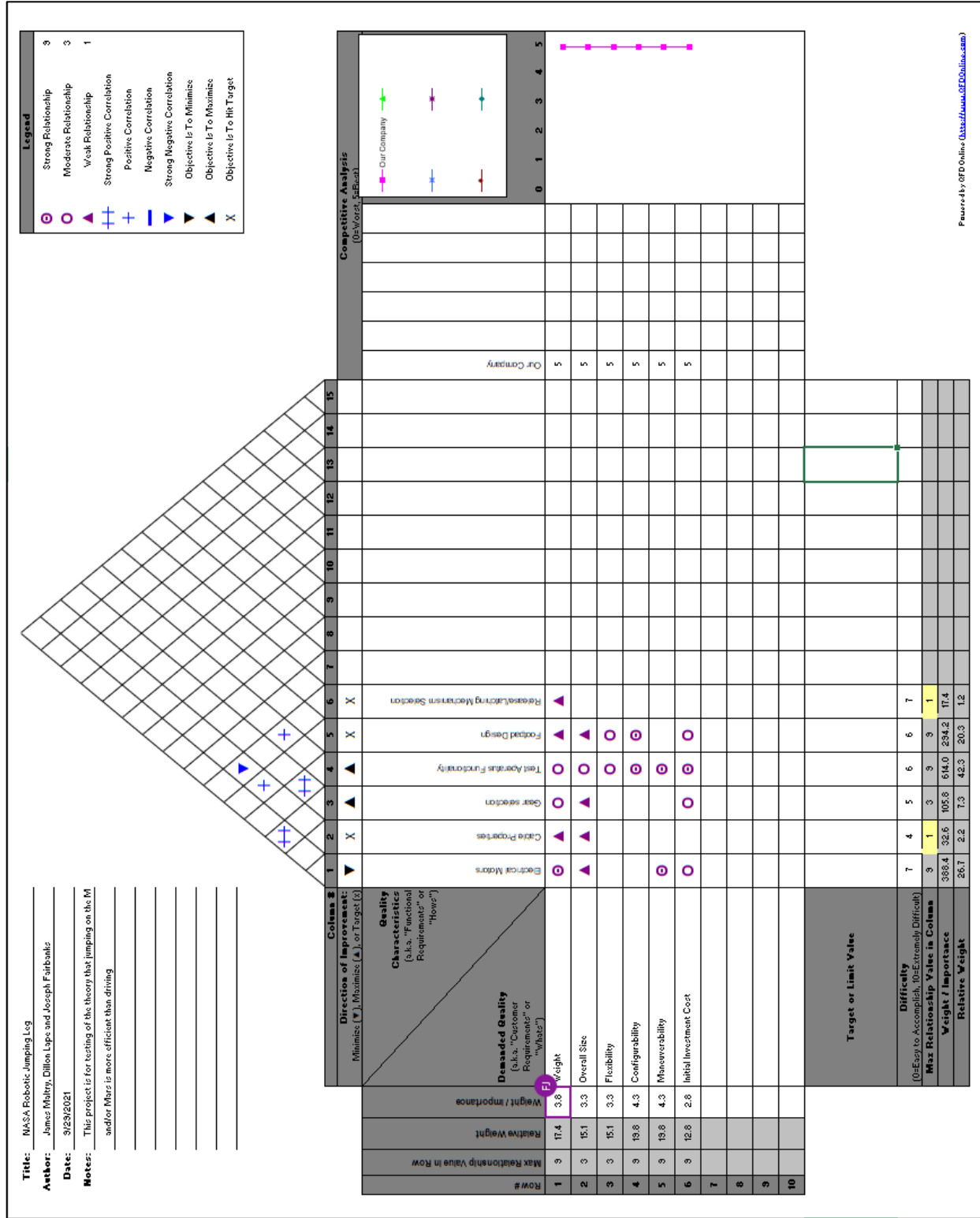


Figure 2: House of Quality

Product Objectives

Weight

17.4%

Since this testing apparatus is for something that would go to space, the material needs to be relatively lightweight. Our material selection of all systems and components are going to need to be considered when making a selection. Weight will also factor when selecting types of systems, for example a mechanical and electrical system operation will be more lightweight than using pneumatics and/or hydraulic systems.

Overall Size

15.1%

For the same reasons as the overall weight of the testing apparatus, the overall size needs to be minimized to take up as little space as possible in transit/storage.

Flexibility

15.1%

Flexibility will be used to help reduce the overall size of the system. This can be achieved by configuring the frame of the testing apparatus to be adjustable in conjunction with overall size.

Configurability

19.8%

The configurability will address the initial starting height of the leg and other potential configurations for the testing apparatus.

Maneuverability

19.8%

Maneuverability relates to the ability to maneuver the leg in the most efficient way possible to decrease the energy lost in the system. Friction, elasticity, and release timing within the system all needs to be accounted for.

Initial Investment Cost

12.8%

The initial investment cost encompasses the amount of funding allowed for the project.

Design

Concept Drawings

Latching Mechanism

To improve upon the latching mechanism on the system, a design was needed that can withstand the 1,181 N of force exerted by the springs on the load plate. In addition, the release mechanism needed to be able to release simultaneously to allow the plate an even release without binding on the guide rods. This system needed to be electrically actuated for ease of use and needed accurate testing to take place in conjunction with the gear drive system.

Pictured below was the concept drawing of the new latching mechanism. This mechanism utilized three car door latches, which are held to a legal standard to hold a minimum of 4,500 N of force, mounted at each spring. On the pressure plate, there are three circular bars attached parallel to the pressure plate that will act as the other latching point with the car latches. Located next to each car door latch is a length of aluminum angle bar that holds a 1-inch stroke linear actuator that would be used to actuate each latch electrically. To support the front end of this latching mechanism, there are two round aluminum bars left over from the previous design and are fixed to the bracket for extra support.

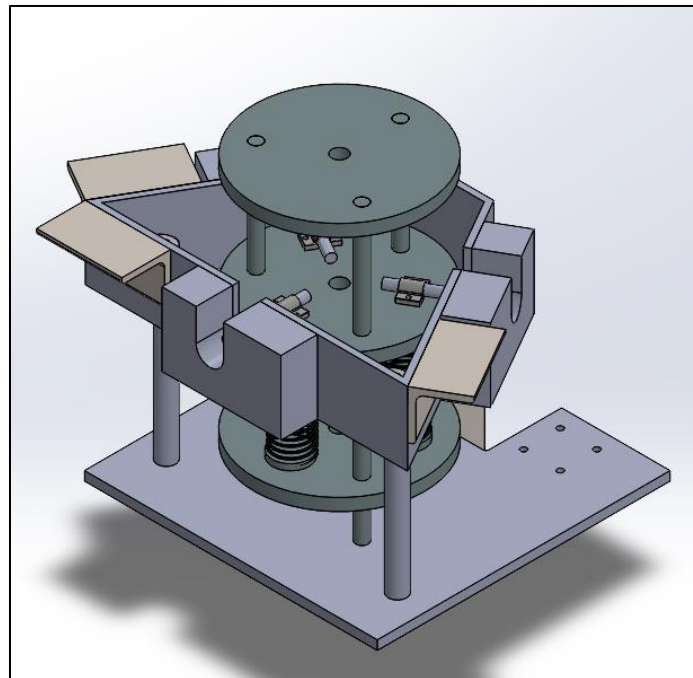


Figure 3: Latching Mechanism concept model

Spring Plate Load Analysis

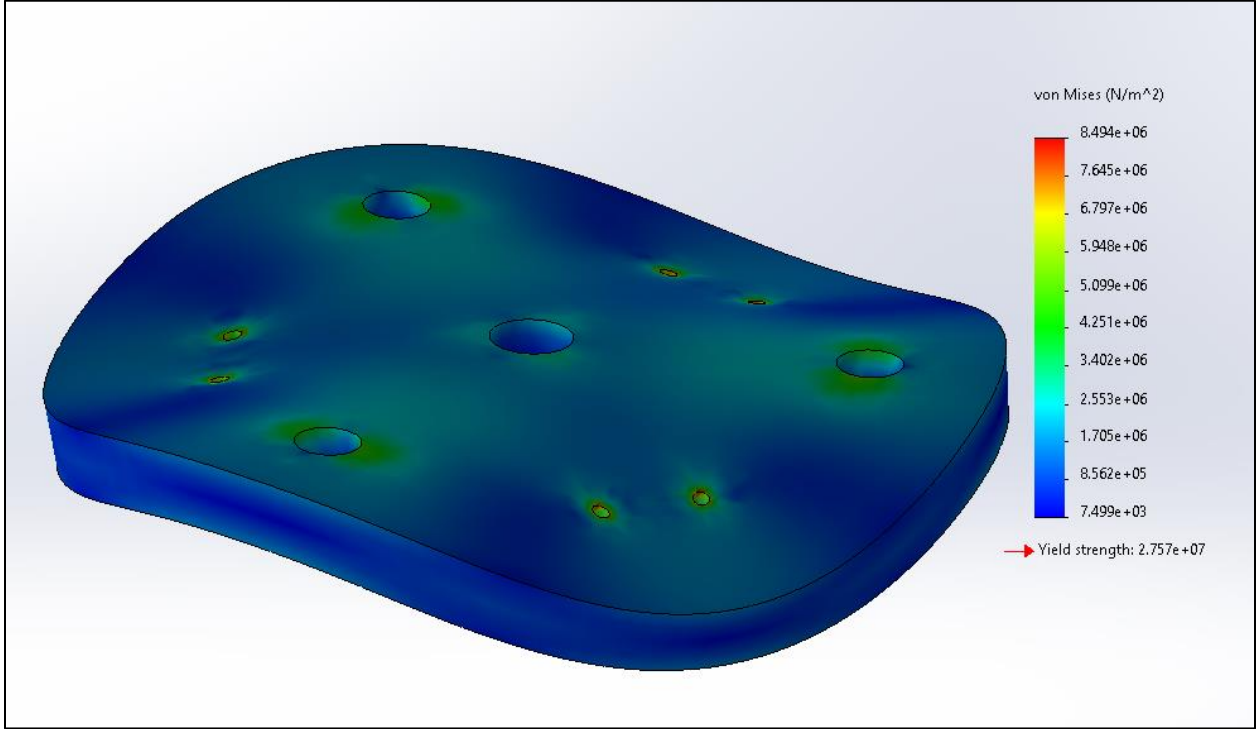


Figure 4: von Mises CAD analysis of spring plate

Gear / Motor Drive System

These concept drawings were added to the CAD assembly for the previous fixture and modified for the purpose of 3D concept drawings.

Gearmotor / Larger Motor

This concept used a larger gearmotor. This is the simplest solution to the motor not having enough torque and is also the cheapest route. This would replace the previous motor with a gearmotor, a combination of a motor and a gearbox, allowing for higher gear ratios and higher torque output. The gears themselves that compress the springs would not be changed. A new mounted bracket would have to be designed and machined for the new gearmotor of our choice. However, there have been problems with the gears meshing so new gears may need to be selected. Also, just a small motor may not provide enough force to compress three springs (of 4,000 N/m spring constant) that need 26.02 Nm to fully compress (5).

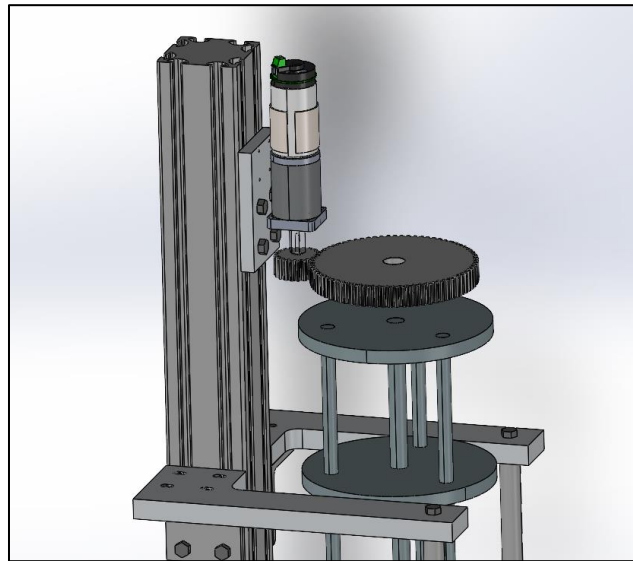


Figure 5: Gearmotor concept model

Planetary Gear System

This concept involved replacing the previous gear system with a more linear transfer of energy with a planetary gear system. This concept also used the previous NEMA-17 motor that was used last year. Instead of getting a new motor, the new planetary gear system would provide enough torque to fully compress the springs. This also would make the design more compact and could make the mechanism lighter, pending on material selection and dimensional requirements. However, these gear systems are more expensive and can be difficult to calculate the required gear ratios for the needed force and torque.

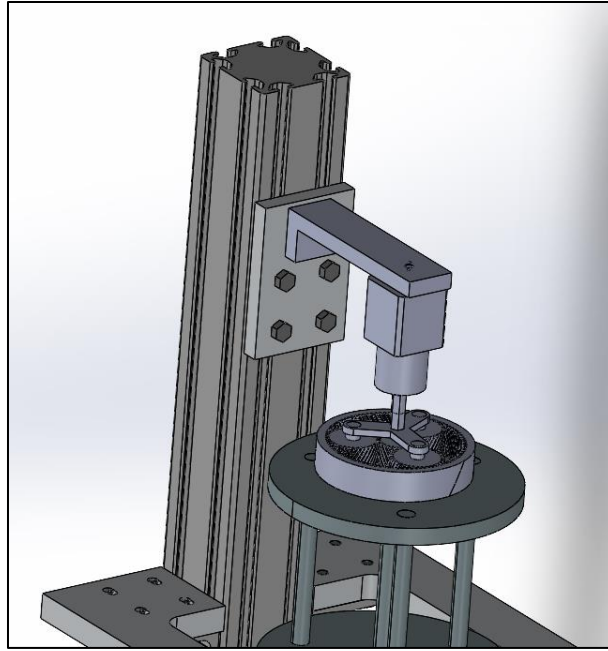


Figure 6: Planetary gearbox w/ NEMA-17 motor concept model

Harmonic Drive Gear System

This concept was very similar to the planetary gear system. This system replaced the previous gearing with a new harmonic drive system that is directly driven by the previous NEMA-17 motor. The high gear ratios of the gear system would allow for higher torque and high torsional stiffness. This also makes the design more compact, which is necessary if this is for a robot. A new mounting bracket would need to be manufactured for this new drive system as well. However, this system has drawbacks. This gear system is the most expensive of these three concepts, can be difficult to calculate necessary gear ratios, and this system can be susceptible to fatigue.

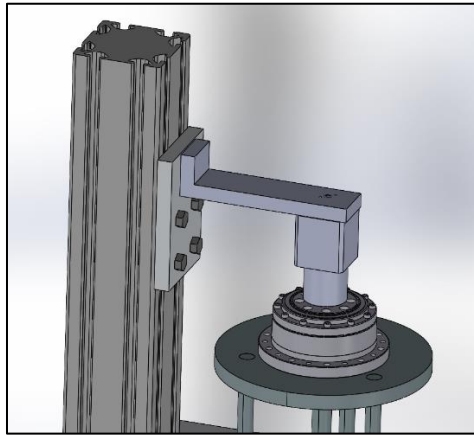


Figure 7: Harmonic drive gearbox with NEMA-17 motor concept model

Foot / Footpad

The design of the foot was created around two needs: a detachable cable pin and a replaceable footpad. The purpose of the detachable cable pin is to allow for the quick swapping between different length of cable. The different lengths of cable would be for testing purposes, due to the cable dictating how low the leg would sit for its initial test. The purpose of the detachable footpad would be to allow for future testing of various footpad tread patterns.

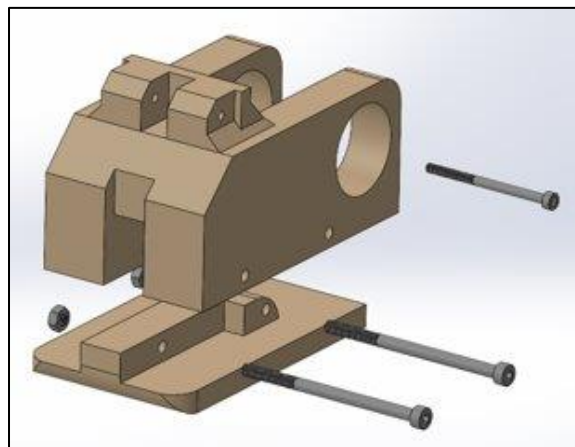


Figure 8: Exploded view of foot assembly

Cable Selection / Additions

Cable Selection

The issue with the previous cable stems from its large elongation percentage. The previous cable was made from paracord, which had an elongation of around 30%. A new cable could be made from a material such as Novabraid Vectec-12 liquid crystal polymer rope. This rope offers a very high maximum load of 11,743 N (needed load strength is 2,362 N), whilst also keeping to an impressive 3% elongation. This would allow us to drastically reduce the amount of force lost due to elongation.

Cable Adjuster

The cable adjuster was designed to allow for small tweaks to the length of rope so precision could be achieved during testing. It works by using a ratcheting system to reduce the cable size while maintaining the tension in the rope. The outer casing of the adjuster would be made of 3D printed ABS plastic, and the rod going through the middle will be an aluminum alloy stock rod machined to the needed specifications.

The following images are of the cable adjuster assembly and where it would sit in the testing setup.

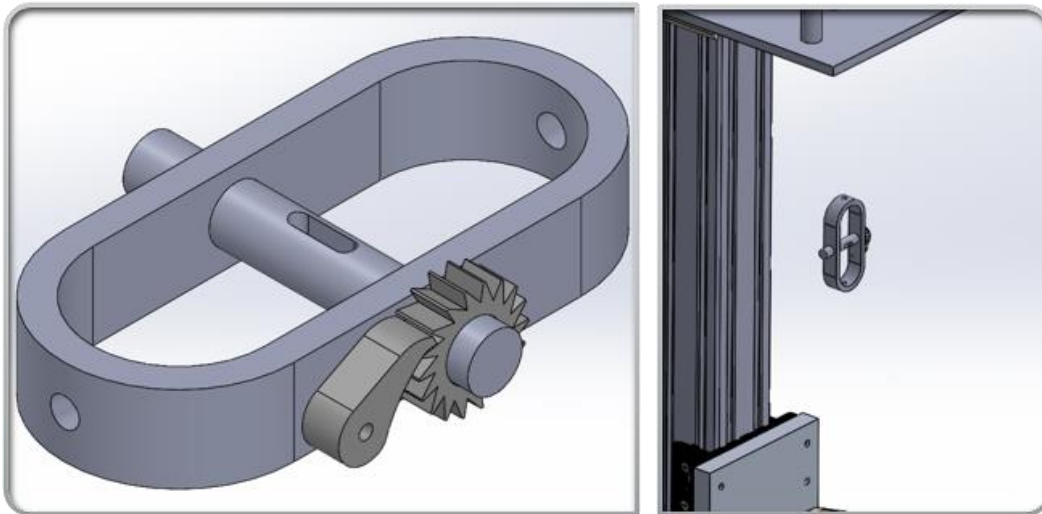


Figure 9: Cable ratchet and pawl for adjustable cable length

Final Component Selection

Latching Mechanism

The components used for this design are predominantly made from aluminum for its lightweight traits with some parts being made from carbon steel for strength. Car door latches were selected for their ability to hold at minimum 4,500 N of force and ease of release. Linear actuators will be utilized due to the nature of the car door latches and the nature of their actuation.

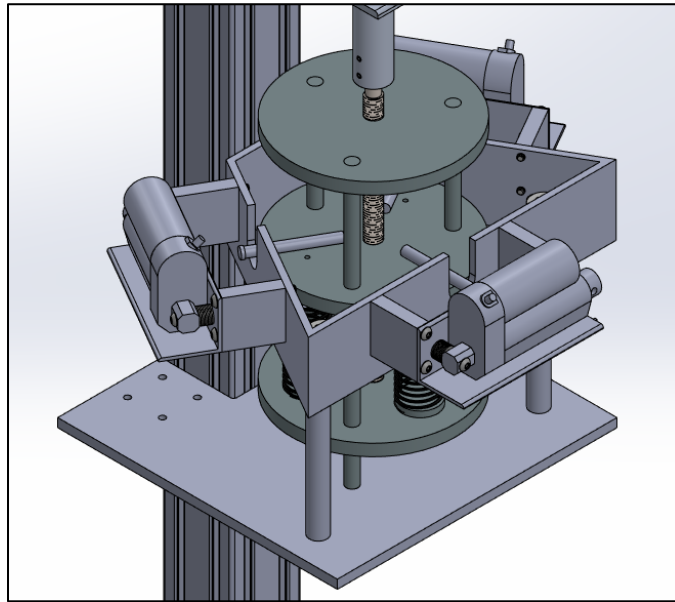


Figure 10: Final model of the latching mechanism

Gear / Motor Drive System

We selected a gear and motor combination for our drive system. This new assembly (pictured below) consists of a NEMA-34 Stepper Motor (with an encoder) capable of 4.8 Nm of holding torque. We combined this motor with a NEMA-34 Planetary Gearbox with a maximum permissible torque of 100 Nm and a gear ratio of 50:1. We chose this combination because we needed at minimum 26.02 Nm of torque (52.04 Nm with a safety factor of 2) and this motor and gearbox combination allows for torque well beyond that. The reason for the high torque capabilities is for future additions to the fixture, for example, adding a fourth spring to the system, therefore requiring more torque for spring compression. The motor and gearbox will be held up by a NEMA-34 bracket connected to a custom manufactured mounting plate that will be adjustable [by various mounting points] on the 8020 center post. The gearbox will connect to the center screw via a custom made coupler, using an aluminum rod and held in by set screws.

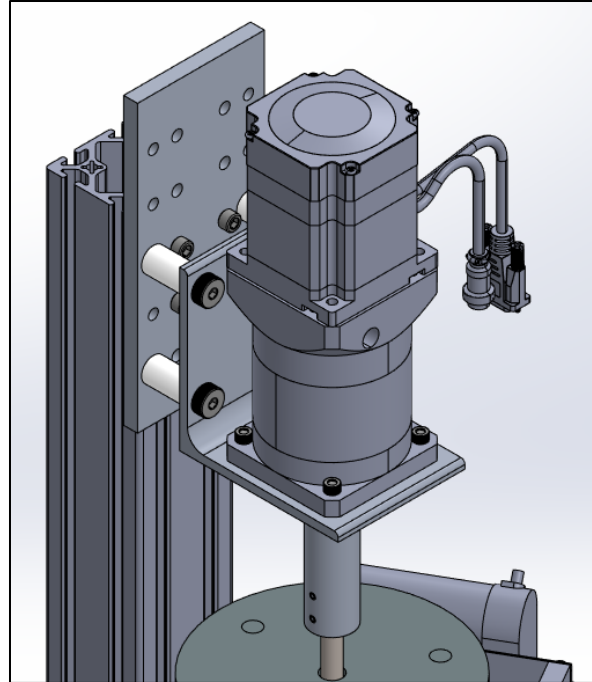


Figure 11: Final component CAD model for new gear drive assembly

Foot / Footpad

The new foot design is based off the need for several new features. The new foot needed to have a replaceable footpad to test various tread patterns under the foot. The new design splits up the foot into two components: the foot and the foot pad. The foot itself is to remain fixed to the leg at all times, whereas the footpad is meant to be easily created using additive manufacturing methods and can be swapped out very easily by removing two bolts.

Another design consideration was the addition of an easy to remove bolt where the cable running through the leg would connect to the foot. This will allow for the cable to be removed or replaced without needing to untie a knot, leaving the cable completely intact.

These parts, other than the bolts, will be made from 3D printed ABS plastic.

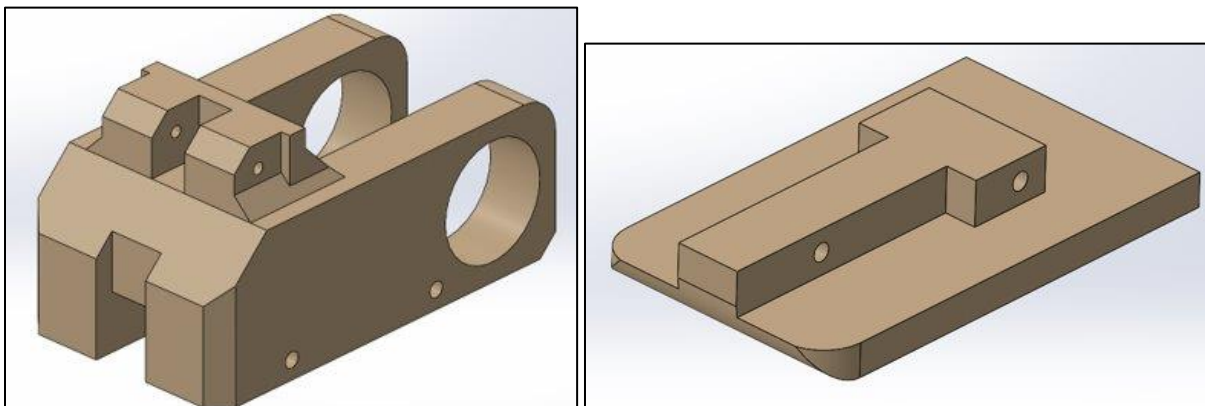


Figure 12: Retractable footpad CAD model

The following images are the final assembly of the foot, along with an image of it mounted on the foot.

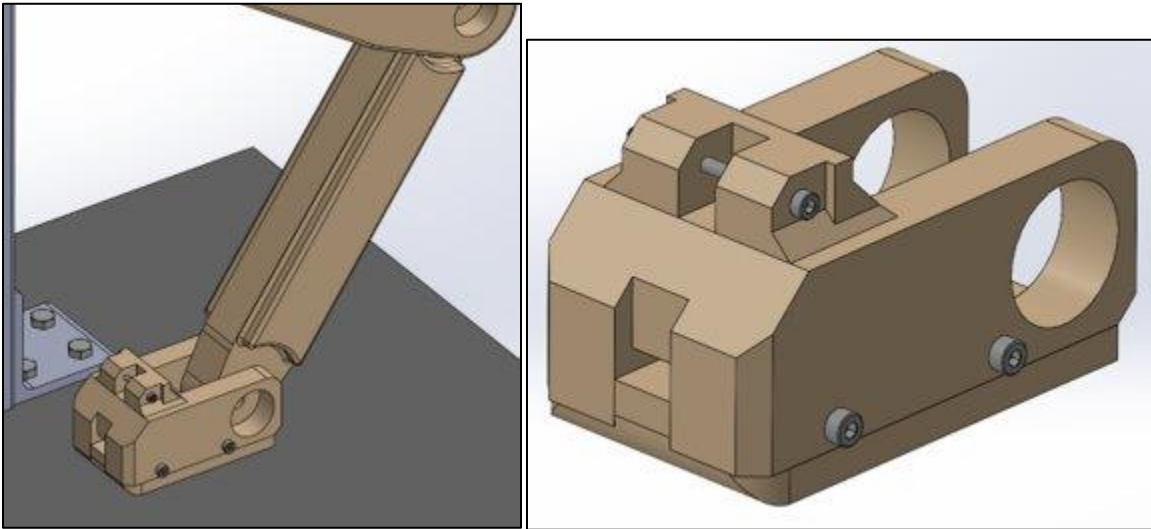


Figure 13: Complete foot CAD model along w/ shin and thigh

Cable

1/8" stainless steel aircraft cable was selected due to its low elongation percentage, high strength, and relatively thin diameter.

Final CAD Model & Diagram

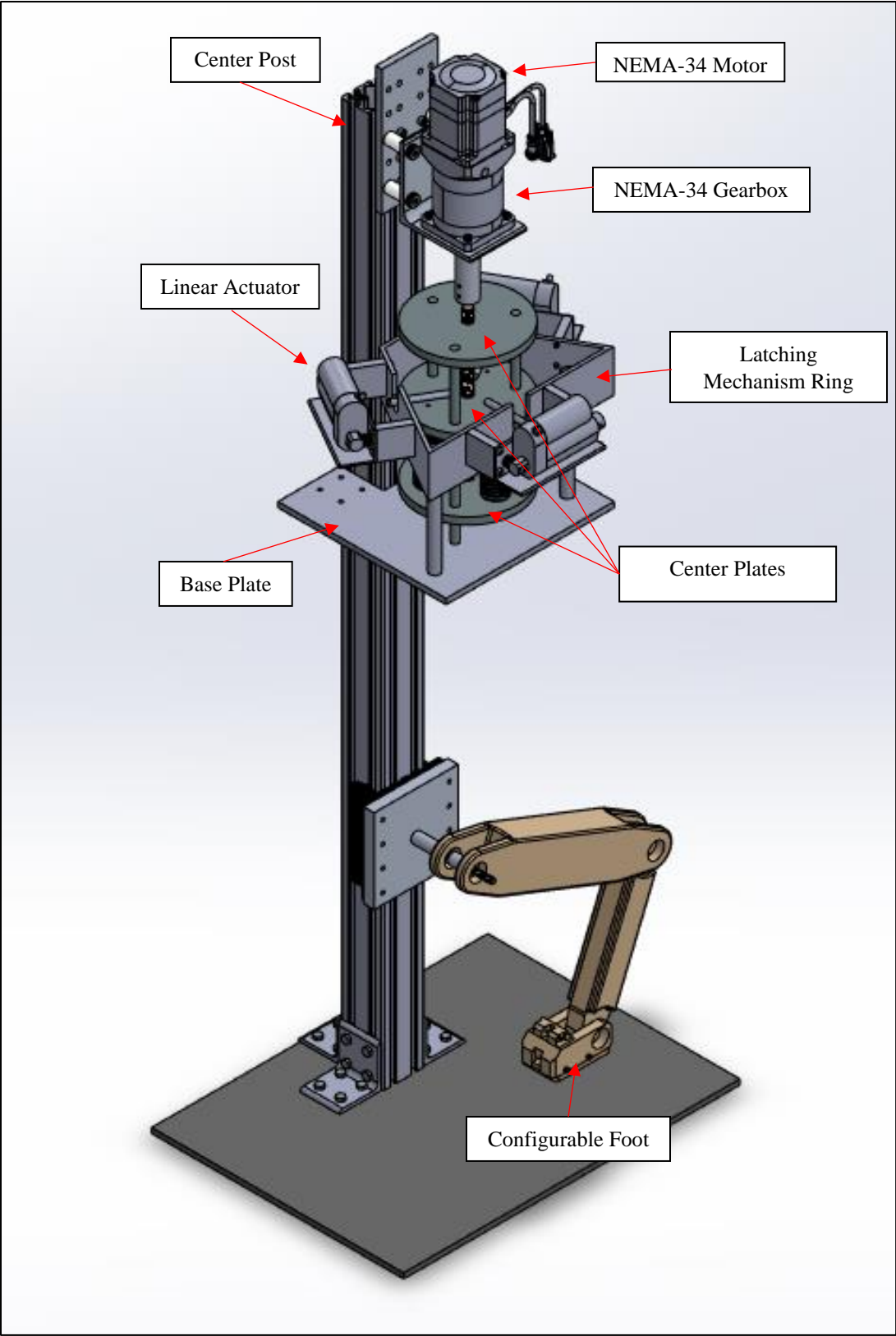


Figure 14: Final CAD model for this new iteration of the fixture

Build, Fabrication, & Assembly

Traditional Manufacturing / Machining

Any parts that needed traditional, subtractive machining or manufacturing methods were done at the University of Cincinnati's CEAS Rhodes Hall Machine Shop. These parts include a coupler for the gearbox and center screw, the base plate for the table, the shell of the latching mechanism, the center plate, and any other miscellaneous pieces or parts.

Welding

The welding for this project was done entirely by a professional welder, Andrew Reis. Most of the parts involved in the latching mechanism were assembled via a combination of MIG and TIG welding. The shell of the latching mechanism was fitted up, tacked and finally TIG welded together at the welder's personal residence while parts like the rail collars, latch rods, and corner support brackets needed to be welded at Upside Innovations where the welder had access to more effective MIG welding equipment.

3D Printing / Additive Manufacturing

Any parts that needed to be 3D printed, were either done via personal, consumer 3D printers or by the University of Cincinnati's Digital Fabrication Lab. For example, the bolt spacers used for the bolts used in the drive assembly, were printed with PLA using a personal 3D printer. The new foot and footpad however, needed to be stronger than PLA, so we used ABS plastic and printed the new foot at the Digital Fabrication Lab.

Automation & Control

The goal of the first fixture iteration was for the tests to be remotely operated. Since the motor and gears used were not strong enough to compress the springs, automation was no longer an option. Now that there is a motor and gearbox capable of compressing the three springs, the original goal of remote control can be fulfilled. The motor and linear actuators were able to be controlled electrically and could be programmed. An Arduino Due was used as the microcontroller for this assembly. The Arduino would control how fast the motor spins, how much to compress the springs (entered via user input), when to actuate the linear actuators, and when to reset back to "zero" position. The code used for testing can be found in Appendix C of this report.

Assembly Steps & Processes

We started the assembly process by disassembling the previous fixture. Many of the parts were going to be replaced, but a handful of the components would be utilized in the new design. The

interior spring plate assembly was kept relatively intact with a few minor additions. Next, we put together the sub-assemblies, such as the motor and its mounting brackets, the actuator mounts, and the latching mechanism ring. The assemblies were then combined, and everything was attached to the post and the bottom support plate. All of the subassemblies then went through alignment and were made sure to be fitted up properly.

Project Management

Project Budget Limit

There was no set limit given to us by the Aerospace Engineering Department at the University of Cincinnati. The purchases we made just needed to be a reasonable price. The amount we spent for the project was compensated for by the University of Cincinnati.

Proposed vs Actual Bill of Materials

Proposed Bill of Materials

The items listed below were used in our Bill of Materials that we proposed at the end of the Fall 2021 semester. The total cost was calculated using the parts' base prices.

Qty.	Part Name	Part No.	Price ea(\$)	Link to Site	Total Price
1	Ratchet Gear	6283K12	\$35.18	https://www.mcmaster.com/6283K12/	\$35.18
1	Ratchet Paw	6283K15	\$47.76	https://www.mcmaster.com/6283K15/	\$47.76
100ft.	VecTec-12 Rope				N/A
2	Right Hand Door Latch	940-102	\$84.59	https://www.amazon.com/Dorman-940-103-Door-Latch-Assembly/dp/B00TEFL8NU	\$169.18
1	Aluminum Bar, 1/4 thk x 3", 2' Lg	89215K109	\$74.49	https://www.mcmaster.com/89215K109-89215K648/	\$74.49
1	Aluminum Bar, 1/4 thk x 3", 1' Lg	89215K109	\$40.48	https://www.mcmaster.com/89215K109-89215K476/	\$40.48
1	Steel Rnd Bar, 3/8" DIA x 3' Lg	8924K94	\$4.09	https://www.mcmaster.com/8924K94-8924K943/	\$4.09
1	Aluminum Angle, 1/4 x 2 x 2 x 1' Lg	8982K36	\$17.93	https://www.mcmaster.com/8982K36-8982K361/	\$17.93
1	Aluminum Plt 3/8" thk x 1" sqr	8975K154	\$47.62	https://www.mcmaster.com/8975K154-9246K23/	\$47.62
3	Mounting Base	8685A17	\$23.64	https://www.mcmaster.com/8685A17/	\$70.92
1	E Series Nema 34 Stepper Motor 4.8 Nm	34HE31-60045	\$36.14	https://www.omc-stepperonline.com/nema-34-stepper-motor/e-series-nema-34-stepper-motor-bipolar-1-8deg-4-8-nm-679-87oz-in-6-0a-86x86x80mm-4-wires.html	\$36.14
1	PLE Series Nema 34 Planetary Gearbox Gear Ratio 150:1 Gear Ratio	PLE34-G50	\$152.97	https://www.omc-stepperonline.com/ple-series-planetary-gearbox-gear-ratio-50-1-backlash-20-arc-min-for-nema-34-stepper-motor.html?search=ple34-g50	\$152.97
1	Nema 34 Bracket	ST-M7	\$6.65	https://www.omc-stepperonline.com/nema-34-bracket-for-stepper-motor-alloy-steel-bracket-st-m7.html?search=nema%2034%20bracket	\$6.65
4	Shoulder Screw - M5x0.8	91273A389	\$5.97	https://www.mcmaster.com/catalog/91273a389	\$23.88
1	Socket Screw - M6x1, 65mm Long	91290A346	\$15.81	https://www.mcmaster.com/catalog/91290a346	\$15.81
1	Rounded Key - 6mm Dia., 30mm Length	96717A220	\$11.31	https://www.mcmaster.com/catalog/96717a220	\$11.31
1	AI 6061 Rod - 1.25" Dia x 1ft Length	2655N24	\$22.74	https://www.mcmaster.com/catalog/2655n24	\$22.74
1	AI 6061 Sheet - 6" x 12" x 7/8"	9246K574	\$63.27	https://www.mcmaster.com/catalog/9246k574	\$63.27
TOTAL:					\$840.42

Figure 15: Proposed Bill of Materials

Actual Bill of Materials

The items listed below were used in our final Bill of Materials. The total cost was calculated using the parts' base prices.

Qty.	Part Name	Part No.	Price ea(\$)	Link to Site	Total Price	Notes
1	Ratchet Gear	6283K12	\$35.18	https://www.mcmaster.com/6283K12/	\$35.18	
1	Ratchet Paw	6283K15	\$47.76	https://www.mcmaster.com/6283K15/	\$47.76	
2	Right Hand Door Latch	940-103	\$84.59	https://www.amazon.com/Dorman-940-103-Door-Latch-Assembly/dp/B00TEFL8NU	\$169.18	
1	Aluminum Bar, 1/4 thk x 3", 2' Lg	89215K648	\$74.49	https://www.mcmaster.com/89215K109-89215K648/	\$74.49	
1	Aluminum Bar, 1/4 thk x 3", 1' Lg	89215K476	\$40.48	https://www.mcmaster.com/89215K109-89215K476/	\$40.48	
1	Steel Rnd Bar, 3/8" DIA x 3' Lg	8924K943	\$4.09	https://www.mcmaster.com/8924K94-8924K943/	\$4.09	
1	Aluminum Angle, 1/4 x 2 x 2 x 1' Lg	8982K361	\$17.93	https://www.mcmaster.com/8982K36-8982K361/	\$17.93	
1	Aluminum Plt 3/8" thk x 1" sgr	9246K23	\$47.62	https://www.mcmaster.com/8975K154-9246K23/	\$47.62	
3	Mounting Base	8685A17	\$23.64	https://www.mcmaster.com/8685A17/	\$70.92	
3	1" Stroke linear actuator	FA-35-S-12-1	\$109.00	https://www.e-motioninc.com/1_stroke_Hi_Speed_35_lbs_force_std_actuator_p/fa-35-s-12-1.htm	\$327.00	
1	TS Series 4.8 Nm/679.87oz.in 1 Axis Closed Loop Stepper CNC Kit Nema 34 Motor & Driver w/ 2m Cable	1-CL86T-S48	\$113.80	https://www.omc-stepperonline.com/closed-loop-stepper-kit/ts-series-4-8-nm-679-87oz-in-1-axis-closed-loop-stepper-cnc-kit-nema-34-motor-and-driver-w-2m-cable.html?mfp=160-ship-from%5B59%5D%2C184-frame-size-m%5B8Nema%2034%20%2886%20x%2086%29%5D	\$113.80	Motor Kit
-	S Series Nema 34 Closed Loop Stepper Motor 4.8 Nm(679.87oz.in) Encoder 1000PPR(4000CPR)	34HS31-6004D-E1000	-	-	-	Part of motor kit
-	Closed Loop Stepper Driver 0-8.2A 24-80VDC for Nema 34 Stepper Motor	CL86T	-	-	-	Part of motor kit
-	1.7m(67") AWG18 Motor and Encoder Extension Cable Kit for Nema 34 Closed Loop Stepper Motors	CE2-M2-18	-	-	-	Part of motor kit
1	350W 60V 5.9A 115/230V Switching Power Supply Stepper Motor CNC Router Kits	S-350-60	\$29.77	https://www.omc-stepperonline.com/350w-60v-59a-115230v-switching-power-supply-stepper-motor-cnc-router-kits-s-350-60.html	\$29.77	
1	PLE Series Nema 34 Planetary Gearbox Gear Ratio 50:1 Gear Ratio	PLE34-G50	\$152.97	https://www.omc-stepperonline.com/ple-series-planetary-gearbox-gear-ratio-50-1-backlash-20-arc-min-for-nema-34-stepper-motor.html?search=ple34-g50	\$152.97	
3	Forward and Reverse Relay Module for Motor/Linear Actuator, Reversing Relay Module (DC 12V)	F-1020	\$17.40	https://www.amazon.com/Forward-Reverse-Module-Actuator-Reversing/dp/B0879GGVPZ/ref=sr_1_9?crid=2U5K0SYJV0U8&keywords=reverse+polarity+relay&qid=1643174627&srefix=reverse+polarity+relay%2Ccaps%2C88&sr=8-9	\$52.20	
1	Black-Oxide Alloy Steel Hex Drive Flat Head Screw, 90 Degree Countersink, M6 x 1.00 mm Thread, 20 mm Long	91294A240	\$7.14	https://www.mcmaster.com/91294A240/	\$7.14	
10 ft.	Ultra-Flexible Wire Rope - for Lifting Galvanized Steel, 6 x 31 Construction, 3/16" Diameter	1999N1	\$33.20	https://www.mcmaster.com/1999N1/	\$33.20	
10 ft.	Ultra-Flexible Wire Rope - for Lifting Galvanized Steel, 6 x 37, 1/4" Diameter	3323T21	\$28.50	https://www.mcmaster.com/3323T21/	\$28.50	
1	Multipurpose 6061 Aluminum 90 Degree Angle with Round Edge, 1/4" Thickness, 5" High x 5" Wide Outside	8982K441	\$36.69	https://www.mcmaster.com/8982K44-8982K441/	\$36.69	
1 pkg	Steel Hex Nut Medium-Strength, Class 8, M6 x 1 mm Thread	90592A016	\$3.12	https://www.mcmaster.com/90592A016/	\$3.12	

1 pkg	Black-Oxide Alloy Steel Socket Head Screw M6 x 1 mm Thread, 25 mm Long	91290A330	\$9.44	https://www.mcmaster.com/91290A330/	\$9.44	
5	Alloy Steel Shoulder Screw 1/2" Shoulder Diameter, 1-3/8" Shoulder Length, 3/8"-16 Thread	91259A489	\$6.98	https://www.mcmaster.com/91259A489/	\$34.90	
1 pkg	Alloy Steel Flat-Tip Set Screws Black Oxide, 10-32 Thread, 3/8" Long	94105A826	\$10.11	https://www.mcmaster.com/94105A826/	\$10.11	
1 pkg	Black-Oxide Alloy Steel Socket Head Screw 5/16"-18 Thread Size, 7/8" Long	91251A582	\$12.95	https://www.mcmaster.com/91251A582/	\$12.95	
1	Multipurpose 6061 Aluminum 7/16" Thick, 6" x 12"	9246K484	\$31.17	https://www.mcmaster.com/9246K484/	\$31.17	
1	Grade B7 Medium-Strength Steel Threaded Rod 5/8"-11 Thread Size, 1-1/2 Feet Long	98957A164	\$10.61	https://www.mcmaster.com/98957A164/	\$10.61	
1	Ace 16/3 SJT 125 V 6 ft. L Appliance Cord	31470	\$9.99	https://www.acehardware.com/departments/lighting-and-electrical/extension-cords-and-power-strips/power-cords/31470	\$9.99	Bought Independently - Dillon
4	Ball Bearing, Open, Trade Number 6200, for 10 mm Shaft Diameter	5972K101	\$5.06	https://www.mcmaster.com/bearings/id=10mm/od=30mm/	\$20.24	
1	Multipurpose 6061 Aluminum, 3/8" Diameter, 3ft Long	8974K24	\$2.74	https://www.mcmaster.com/8974K24-8974K243/	\$2.74	
1	USB to RS-232 Serial Adapter, 1ft	NS-PU99501	\$19.99	https://www.bestbuy.com/site/insignia-1-3-usb-to-rs-232-db9-pda-serial-adapter-cable-black/5883029.p?skuId=5883029	\$19.99	Bought Independently - Dillon
1	14mm ID Shaft Sleeve for PLE34 Series Planetary Gearbox	SS-14	\$10.18	https://www.omc-stepperonline.com/14mm-id-shaft-sleeve-for-ple34-series-planetary-gearbox-gear-ss-14	\$10.18	Bought Independently - Dillon
1	Arduino Due with Headers	A000062	\$43.77	https://www.amazon.com/gp/product/B00A6C3JN2/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1	\$43.77	Bought Independently - Dillon
1	QVS LogoQVS USB 2.0 (Type-A) Male to Micro-USB (Type-B) Male 9.8 ft. - Black	CC2218C-3M	\$16.99	https://www.microcenter.com/product/316202/qvs-usb-20-type-a-male-to-micro-usb-type-b-male-98-ft-black	\$16.99	Bought Independently - Dillon
1	The Best Connection Expandable Sleeving Clean Cut PET 1/4" x 16 ft Black	25759	\$19.99	https://www.microcenter.com/product/348552/the-best-connection-expandable-sleeving-clean-cut-pet-1-4-x-16-ft-black	\$19.99	Bought Independently - Dillon
1	Velcro ONE - WRAP Roll 12' x 3/4" - White	217554	\$11.99	https://www.microcenter.com/product/632358/velcro-one-wrap-roll-12-x-3-4-white	\$11.99	Bought Independently - Dillon
1	1/8 in. Zinc-Plated Wire Rope Clamp (2-Pack)	42594	\$1.60	https://www.homedepot.com/p/Everbilt-1-8-in-Zinc-Plated-Wire-Rope-Clamp-2-Pack-42594/205883055	\$1.60	Bought Independently - Dillon
1	3/16 in. Zinc-Plated Clamp Set (4-Pack)	43104	\$3.65	https://www.homedepot.com/p/Everbilt-3-16-in-Zinc-Plated-Clamp-Set-4-Pack-43104/205887568	\$3.65	Bought Independently - Dillon
1	18-8 Stainless Steel Button Head Hex Drive Screw, 1/4"-20 Thread Size, 1-3/8" Long	92949A836	\$7.15	https://www.mcmaster.com/92949A836/	\$7.15	
1	316 Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD	90107A029	\$10.01	https://www.mcmaster.com/90107A029/	\$10.01	
2	18-8 Stainless Steel Button Head Hex Drive Screw 1/4"-20 Thread Size, 2-1/2" Long	92949A552	\$6.09	https://www.mcmaster.com/92949A552/	\$12.18	
2 ft	Multipurpose 6061 Aluminum 1/2" Thick x 2" Wide	8975K74	\$28.15	https://www.mcmaster.com/8975K74-8975K904/	\$28.15	
1	18-8 Stainless Steel Button Head Hex Drive Screw, 10-32 Thread Size, 3/16" Long	92949A259	\$6.67	https://www.mcmaster.com/92949A259/	\$6.67	
1	High-Strength 2024 Aluminum Bar, 1/4" thk x 3" W, 1/2" lg	89215K109	\$40.41	https://www.mcmaster.com/89215K109/	\$40.41	Bought Independently - Joe
2	Multipurpose 6061 Aluminum, 1/4" Thick x 3" Wide, 2 Feet Long	8975K87	\$27.45	https://www.mcmaster.com/8975K87/	\$54.90	Bought Independently - Joe
1	Multipurpose 6061 Aluminum 90 Degree Angle with Round Edge, 1/4" Thickness, 2" High x 2" Wide Outside, 1" Long	8982K361	\$31.20	https://www.mcmaster.com/8982K361/	\$31.21	Bought Independently - Joe
1	JB Weld	-	\$7.98	In Store	\$7.98	Bought Independently - Joe
1	Supreme Silicone K&B 2.8 OZ White	-	\$7.28	In Store	\$7.28	Bought Independently - Joe
1	315Pcs Metric 304 Stainless Steel Hex Nuts Assortment Kit	-	\$15.99	https://www.amazon.com/dp/B087R22HM2?psc=1&ref=ppx_yo2ov_dt_b_product_details	\$15.99	Bought Independently - James
1	M4x65mm Machine Screws	-	\$11.99	https://www.amazon.com/dp/B07MBHNBP?psc=1&ref=ppx_yo2ov_dt_b_product_details	\$11.99	Bought Independently - James
1	100 Pcs M3 x 30/35/40/45/50 mm Stainless Steel 304 Hex Socket Head Cap Screws	-	\$11.99	https://www.amazon.com/dp/B07C9F2347?psc=1&ref=ppx_yo2ov_dt_b_product_details	\$11.99	Bought Independently - James
1	1/16 Inch x 33 Feet 304 Stainless Steel Wire Rope Cable	-	\$9.69	https://www.amazon.com/dp/B07TQSHY1X?psc=1&ref=ppx_yo2ov_dt_b_product_details	\$9.69	Bought Independently - James
1	165 Feet 1/8inch Stainless Steel Wire Rope	-	\$39.99	https://www.amazon.com/dp/B01N0N4IME?psc=1&ref=ppx_yo2ov_dt_b_product_details	\$39.99	Bought Independently - James
1	Aluminum Crimping Loop Sleeve for Wire Rope and Cable 1/16" 5/64" 3/32" 1/8" 3/16" 1/4"	-	\$11.99	https://www.amazon.com/dp/B08D67G5S7?psc=1&ref=ppx_yo2ov_dt_b_product_details	\$11.99	Bought Independently - James
1	Wire Rope Crimping Tool for Aluminum Oval Sleeves	-	\$37.39	https://www.amazon.com/IWISS-Crimping-Aluminum-Sleeves-Ferrules/dp/B0195XJ16Y/ref=dp_prsubs_2?pd_rd_i=B0195XJ16Y&th=1	\$37.39	Bought Independently - James
TOTAL (Before Tax):					\$1,907.32	

Figure 16: Actual Bill of Materials

Bill of Materials Discussion

As shown in the above figures, our proposed bill of materials was considerably less than the actual amount of material we bought for this project. In fact, we spent a whopping \$1,066.90 over our proposed BOM. The reasoning for spending some much more than initially proposed was due to redesigns and buying various hardware we did not know we would need down the line. As a reminder, we weren't given a set budget for this project, so we did not have a limit, we just needed to make reasonable and realistic purchases.

Project Schedule/Timeline

Proposed Project Schedule

Proposed Schedule - Fall Semester													
2021													
Task Name	Duration	August			September			October			November		December
SD I Proposal	8 Weeks												
Research	13 Weeks												
Concept Designs	6 Weeks												
Material/Component Selection	4 Weeks												
Final Design/Analysis	3 Weeks												
Order Parts	2 Weeks												
SD II Presentation/Report	2 Weeks												

Proposed Schedule - Spring Semester													
2022													
Task Name	Duration	January			February			March			April		May
Simulations	3 Weeks												
Assembly	4 Weeks												
Testing	5 Weeks												
Modifications	6 Weeks												
Documentation	5 Weeks												
Presentation/UC Tech Expo	2 Weeks												

Figure 17: Proposed schedule for 2021-2022

Actual Project Schedule

Actual Schedule - Fall Semester													
2021													
Task Name	Duration	August			September			October			November		December
SD I Proposal	5 Weeks												
Research	11 Weeks												
Concept Designs	7 Weeks												
Material/Component Selection	6 Weeks												
Final Design/Analysis	6 Weeks												
Order Parts	1 Week												
SD II Presentation/Report	2 Weeks												

Actual Schedule - Spring Semester													
2022													
Task Name	Duration	January			February			March			April		May
Order Parts	6 Weeks												
Machining	7 Weeks												
Assembly	4 Weeks												
Testing	3 Weeks												
Modifications	5 Weeks												
Documentation	3 Weeks												
Presentation/UC Tech Expo	1 Week												

Figure 18: Actual schedule for 2021-2022

Project Schedule Discussion

Comparing the proposed schedule made at the beginning of the project and the actual schedule, we can clearly see how our team underestimated the time it would take to complete the project. We had several setbacks from several design changes, waiting on ordered parts, and other unforeseen circumstances.

Group Meetings

Lunar Robotic Leg - 2021-2022 Meetings					
Date	Meeting Description	Student Participants	Advisors	Time (hrs.)	Notes
8/11/2021	First Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Andy Barth	1.75	Project selected and team formed
9/3/2021	Assignment	James Maltry, Joe Fairbanks, Dillon Lape		0.25	SD I - Student Advisor Agreement
9/8/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong	0.50	Discuss research & concepts
9/15/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong	0.50	Discuss research & concepts
9/17/2021	Assignment	James Maltry, Joe Fairbanks, Dillon Lape		5.00	SD I - Research Portion
9/21/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		3.00	Develop 2D/3D concepts
9/22/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	1.25	Review of Latch, Drive System, Cable, Footpad, & Fixture concepts
9/24/2021	Assignment	James Maltry, Joe Fairbanks, Dillon Lape		2.50	SD I - Customer Survey
10/1/2021	Assignment	James Maltry, Joe Fairbanks, Dillon Lape		4.50	SD I - QFD
10/5/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		2.00	Continue developing 3D concept models
10/6/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	1.00	Continuation of concept design discussion
10/8/2021	Assignment	James Maltry, Joe Fairbanks, Dillon Lape		5.00	SD I - Final Proposal
10/18/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		2.50	Concept designs and further research
10/20/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	1.25	Continuation of concept design discussion
10/25/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		2.25	Contact component companies; further develop concept models
10/27/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	1.00	Continuation of concept design discussion; Review of gear torque calculations
10/31/2021	Assignment	James Maltry, Joe Fairbanks, Dillon Lape		1.50	SD II - Bi-Weekly Report for 10/18-10/31
11/2/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		2.50	Work on 3D models; Discuss component selection
11/3/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	1.00	Discussion of component selection; concept design discussion
11/9/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		2.75	Begin intergrating models in current 3D model
11/10/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	0.75	Continuation of concept design discussion
11/14/2021	Assignment	James Maltry, Joe Fairbanks, Dillon Lape		1.25	SD II - Bi-Weekly Report for 11/1-11/14
11/17/2021	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	0.75	Concept designs; actuation force testing review
11/29/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		3.00	Work on SD II Presentation
11/30/2021	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		8.00	Work on & Review SD II Presentation
12/22/2021	Student Meeting	Joe Fairbanks, Dillon Lape		3.00	Disassemble last years fixture; reached out to StepperOnline about power needed for our motor and if the motor has any feedback
1/19/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Andy Barth	0.75	Discussion of motor and rope; introduced engineering drawings
1/24/2022	Consulatation	James Maltry, Joe Fairbanks, Dillon Lape		0.25	Meeting w/ Ron Hudepohl
1/26/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Andy Barth	1.00	Finalized motor and gear selection; finalized rope selection; discussed fabrication

1/26/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Andy Barth	1.00	Finalized motor and gear selection; finalized rope selection; discussed fabrication
2/8/2022	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		0.75	Registered for Tech Expo; worked on design changes
2/9/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	1.00	Went over projected schedule for semester and design and fabrication updates
2/10/2022	Work Session	Dillon Lape	Andy Barth	0.75	Went over how to use Arduino and last years code for it
2/23/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Andy Barth	0.75	Went over design updates and updates on drive assembly
3/2/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Andy Barth	0.75	Went over design updates and updates on drive assembly
3/3/2022	Work Session	Dillon Lape	Andy Barth	1.25	Worked on motor code
3/9/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	0.75	Went over design updates and updates on drive assembly
3/16/2022	Student Meeting	James Maltry, Joe Fairbanks, Dillon Lape		0.50	Went over code updates; Received new printed foot; Went over release mechanism updates
3/21/2022	Work Session	Joe Fairbanks, Dillon Lape		1.50	Worked on assembling/updating drive and release assemblies
3/22/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		2.00	Worked on code; worked on assembling/updating drive and release assemblies
3/23/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Dr. Ma, Andy Barth	1.00	Went over release assembly updates and drive assembly
3/23/2022	Work Session	Joe Fairbanks, Dillon Lape		2.00	Worked on actuator code
3/24/2022	Work Session	James Maltry, Joe Fairbanks		3.00	Worked on linear actuator mount
3/28/2022	Progress Meeting	James Maltry, Joe Fairbanks, Dillon Lape	Dr. Dong, Andy Barth	0.75	Went over code updates; went over release mechanism updates
4/4/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		4.00	Updated code; machined actuator mounts
4/5/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		3.00	Updated code; machined actuator mounts
4/6/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		5.00	
4/7/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		8.00	Mounted all assemblies; made adjustments as needed
4/8/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		8.00	Made adjustments; added foot and cable of Team3; ran testing; updated code
4/9/2022	Work Session	Joe Fairbanks, Dillon Lape		4.50	Tested old leg w/ new foot; recorded slo-mo videos
4/10/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		6.00	Ran more tests; made tech expo video
4/20/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		3.50	Ran more tests using various compressions and ground materials
4/22/2022	Work Session	James Maltry, Joe Fairbanks, Dillon Lape		5.50	Evaluated results; worked on final report
				Total Hrs:	125.00

Figure 19: Group meetings throughout the project and approx.. time spent (Note: does not include individual work sessions)

Testing & Results

Criteria for Success

We measured success by achieving a higher average jump height than the previous testing fixture, as well as streamlining the testing process through automation.

Test Settings

Some of the settings we used for testing our results were varying compression distances of the springs, between 7 and 9 cm. The use of two different ground materials in which the leg would jump from were also utilized. The materials used were steel plate and coarse sand.

Testing Processes

The process starts by ensuring that the top spring plate is fully pushed into the latches, and that the leg is in the correct starting position. The number of centimeters in which you wish to compress the springs is then entered into the code. The motor will then compress the springs to desired amount, and then after a further two seconds, the latches will release the plate. After the data is recorded via slow motion video, the command to return the plates to their starting position is entered into the code. The motor will then rotate in the opposite direction for the previously specified amount of compression. After the plates return to their “zero” or “home” position, the actuators retract and therefore, closing the latches, and the process will be ready to repeat.

Test Results

Jump Height

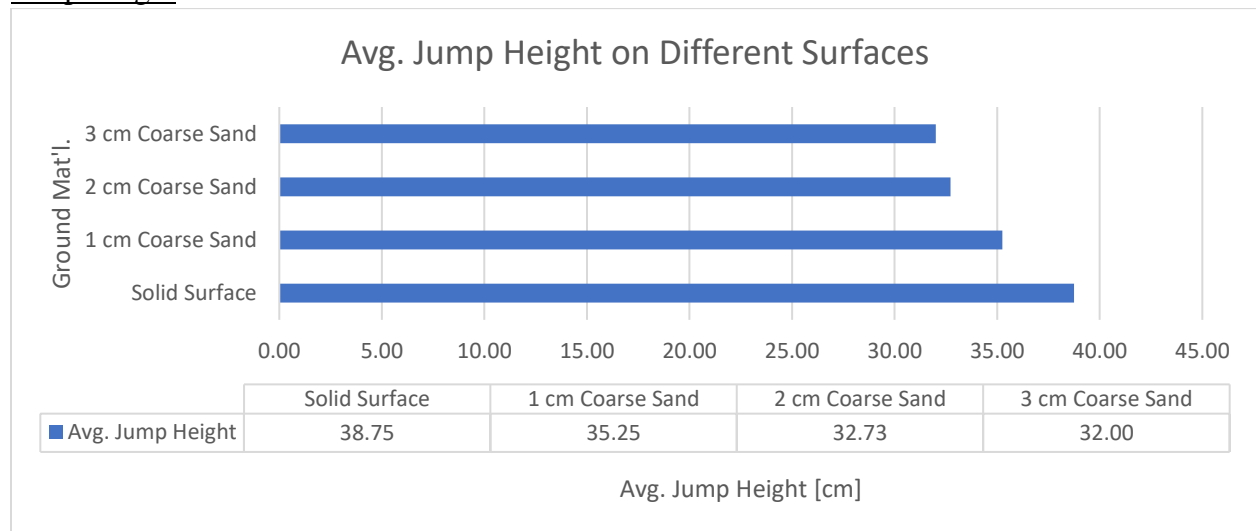


Figure 20: The average jump height, in centimeters, compared between all surfaces used during testing



Figure 21: Average jump height, in centimeters, compared between the last iteration of the fixture and the current

Analysis

The primary goal of this project was not to increase the jump height of the leg, but to complete an overhaul of the issues with the previous iteration of the fixture. These previous problems included the release mechanism causing inconsistent releases, the gear drive system could not produce enough torque to compress the springs, the cable controlling the ligaments of the leg caused energy loss due to high elasticity, and the foot design was not ideal configurability. Through fixing those flaws within the fixture, we were able to increase the jump height of the leg.

Looking at the graphs above, we can see the increase in leg jump height compared to testing during Summer of 2021. Comparing the total average between the two fixture iterations, the new, current fixture had a 34.55% increase in jump height. Since this new fixture is offering a higher jump height, we can conclude that less energy is being lost during the transfer of energy between the springs and the leg.

We can also see a difference in average jump heights when using different ground materials. As expected, the solid surface of the base plate resulted in having the highest average jump height. Also as expected, when more sand was added (1 cm, 2 cm, or 3cm), the average jump height decreased.

Conclusions

Lessons Learned

What Didn't Work?

There are a few things that did not work the way we thought it would. The first thing being that the latches do not stay fully open after release. So, the latches would fall and impede the reset of the latching mechanism. To counter this, we would manually have to hold two of three latches open during the resetting of the middle plates. One of our goals was to automate the testing process and not have to reset anything besides the leg itself. Manually holding the latches open during reset is not automation and will need to be improved during the next iteration of the project.

Another part of the project that did not work as expected was the latches fully closing. The car door latches have two catch points, “fully latched” and “half-latched”. After running some initial tests, we discovered that two of the three latches would not “fully latch” once the middle plates were reset to zero position. We found ourselves having to manually pushing down on the top plate to fully latch those two troublesome latches. Again, this takes away from our goal of automation and will need to be touched upon again during the next iteration.

We also ran into the problem of compressing the springs to the maximum compression, but not due to power and torque capabilities. The ferrules that tied the steel cable were taking up too much space in between the middle and bottom plates, therefore our maximum compression of the springs was shortened. We ended up to only going up to around 8 cm of compression instead of testing up to the 9.84 cm maximum possible compression of the springs.

The ratchet and pawl device meant to adjust the length of the rope ended up not working due to the switch to stainless steel cable. The new steel cable is not flexible enough to be wound up, so the device had to be removed entirely.

What Would We Do Differently?

One of the things that we would have done differently would be to do more prototyping. We found that there were a lot of small issues that could have been addressed if we would have allotted for more time to test alignment and do small redesigns.

Another thing that we would have done differently is research material properties more thoroughly. When material was first ordered, 2024 aluminum was selected to be machined and welded together. This was a poor decision as it was later found that 2024 aluminum is considered un-weldable as it easily forms internal cracks within welds. 6061 was then ordered in its place. Knowing this earlier would have saved a lot of time.

What Did We Learn?

This senior design process gave us an opportunity to learn more about the engineering process and how projects are done, from Day 1 to the final presentation. We learned about several aspects of engineering throughout this project from motor control, coding (with Arduino IDE), material selection, CAD design, manufacturing, and testing.

Future Work & Suggestions

The first thing to address would be testing multiple leg configurations. The new fixture was designed to allow for the testing of multiple tread patterns for the foot, as well as different lengths of cable that would affect the starting position of the leg. These changes and options should be utilized for further testing.

The addition of sensors is a logical next step in the transformation of the test fixture. The current automation for the motor is done by calculating distance using steps in the stepper motor. This works well but has the potential for skipping steps and therefore move inexact distances. The introduction of sensors would positively impact the accuracy of testing.

Conclusion

Our overall goal was to improve the functionality of the testing fixture which would in turn increase the overall jump height of the leg. With these improvements in place, we were able to achieve an average of 34.55% increase in jump height along with a multiple of ease-of-use improvements. Additionally, we achieved a safer testing apparatus through automated systems and an overall minimum safety factor of 2. Looking back at our statement of what we consider success for this project, it can be concluded that we have achieved all our goals with excellent results.

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Appendix A

Survey Sample

Below is an example of a completed survey submitted on 09/22/2021:

NASA Robotic Jumping Leg Survey

Project Description

The goal of this project is to upgrade key parts of the robotic jumping leg. These parts include the latching/releasing mechanism, the gear drive system, cable mechanism and the configurable foot pad with hopes of redesigning the fixture itself. By taking this survey, your answers can help us with these improvements.

Thanks,

Joe Fairbanks, Dillon Lape, James Maltry

Part I:

Are you student or faculty at UC?

Faculty

How do you want this system to be operated?

Pneumatic

Hydraulic

Electric

Other

Why?

Electricity is clean and renewable energy in space. Pneumatic and hydraulic have leaking problem and the leaked air/liquid is not replaceable. They both are not favorable for space applications.

Part II:

How important is each feature to you? (1 = Low Importance; 5 = High Importance)

Weight (5)

Overall Size (4)

Flexibility (3)

Configurable (4)

Maneuverability (5)

Initial Investment Cost (3)

How satisfied are you with the current prototype? (1 = Low Importance; 5 = High Importance)

Weight (2)

Overall Size (4)

Flexibility (3)

Configurable (2)

Maneuverability (3)

Initial Investment Cost (4)

Appendix B

Gear Drive System – Torque Calculations

Known Values (from last year's group):

- $F_{springs} = F = 1181 \text{ N}$
- $Spring \text{ Const.} = k = 4000 \text{ N/m}$
- $Compression \text{ Distance} = x = \sim 0.0984 \text{ m}$
- $Spring \text{ Dia.} = D = \sim 0.044 \text{ m}$

Energy:

- $PE = \frac{1}{2} * k * x^2 = \frac{1}{2} * \left(4000 \frac{\text{N}}{\text{m}}\right) * (0.0984 \text{ m})^2 = 19.37 \frac{\text{Nm}}{\text{spring}}$
 - For 3 Springs = $3 * 19.37 \text{ Nm} = 58.11 \text{ Nm} = \mathbf{58.11 \text{ J}}$

Power:

- Assume $t = 5 \text{ s}$
- $P = \frac{58.11 \text{ J}}{5 \text{ s}} = 11.62 \frac{\text{J}}{\text{s}} = \mathbf{11.62 \text{ W}}$

Velocity:

- $v = \frac{P}{F} = \frac{11.62 \text{ W}}{1574.7 \text{ N}} = \mathbf{0.00738 \text{ m/s}}$
- Angular Velocity:
 - $\omega = \frac{v}{r} = \frac{0.00738 \text{ m/s}}{\frac{0.044 \text{ m}}{2}} = \mathbf{0.335 \text{ rad/s}}$

Torque:

- $T = \frac{v * F}{\omega} = \frac{0.00738 \frac{\text{m}}{\text{s}} * 1181 \text{ N}}{0.335 \text{ rad/s}} = \mathbf{26.02 \text{ Nm}}$
 - With Safety Factor = 2: $T = 26.02 \text{ Nm} * 2 = \mathbf{52.04 \text{ Nm}}$

Appendix C

Arduino Code – Controls Motor & Actuators

```
// Include AccelStepper Library:
#include <AccelStepper.h>

// Define Actuator Pins:
#define actuator1 4
#define actuator2 5
#define actuator3 6

// Define Motor Pins:
#define dirPin 2
#define stepPin 3
#define motorInterfaceType 1
AccelStepper stepper = AccelStepper(motorInterfaceType, stepPin,
dirPin); // stepper: stepper motor

// Define Motor Speed and Numb. of Steps/Rev:
#define stepsPerRev 800 // defined via driver
#define motorSpeed 32000 // steps/sec (32,000 steps/sec = 2,400 rpm)

// Variables:
#define gearboxRatio 50 // 50:1 gearbox ratio
#define TPI 11 // threads/inch
#define maxComp 9.8400 // max compression of springs [cm]
float rotations;
float distance;
float target;
String motorReturn;

void setup() {

// Start serial communication:
Serial.begin(9600); // Baudrate = 9600

// Declare pins as output:
pinMode(dirPin, OUTPUT);
pinMode(stepPin, OUTPUT);
pinMode(actuator1, OUTPUT);
pinMode(actuator2, OUTPUT);
pinMode(actuator3, OUTPUT);

// Set max speed and acceleration/deceleration:
stepper.setMaxSpeed(motorSpeed); // steps/sec
stepper.setAcceleration(motorSpeed); // steps/sec^2
stepper.setCurrentPosition(0); // set current position to 0

}

void loop() {
```

```

// Set motor direction:
digitalWrite(dirPin,HIGH);

startCode:
Serial.println("CAUTION: MAKE SURE ALL ACTUATOR CABLES ARE IN CORRECT
POSITION & CONFIRM PLATE IS LATCHED");
Serial.println();
Serial.println("Confirm bottom plate is in starting position and the leg is
set.");
Serial.println();
// Select compression distance:
Serial.println("How much would you like to compress the springs?");
Serial.print("Enter your value in cm. There is a max value of ");
Serial.print(maxComp,4); // displays 4 decimal places
Serial.println(" cm.");
while (Serial.available()==0) {
  // exits loop once input is made
}

// Read distance message:
distance=Serial.parseFloat();
// Display compression input:
if (distance > 0 && distance <= maxComp) {
  Serial.print("The motor will turn: ");
  Serial.print(distance,4);
  Serial.println(" cm");
}
// Display Error Message:
else {
  Serial.print("Error: Enter a number greater than 0 and less than ");
  Serial.println(maxComp);
  Serial.print("You entered: ");
  Serial.println(distance,4);
  return;
}

delay(1000); // wait 1 sec before starting motor

// Move to desired target:
target = stepsPerRev * gearboxRatio * TPI * distance / 2.54; // 2.54
conversion for in to cm
stepper.moveTo(target);
stepper.runToPosition();

// Serial.print(target,4);
// Serial.println(" steps");
Serial.println();
// rotations = target / stepsPerRev;
// Serial.print(rotations,4);
// Serial.println(" rotations");

// Activate actuators:
delay(2000);
// Note: add delays if the actuators dont move at same time
digitalWrite(actuator2,HIGH);
delay(100);

```

```

digitalWrite(actuator3,HIGH);
delay(100);
digitalWrite(actuator1,HIGH);

// Wait to return:
Serial.println("WARNING: CONFIRM ALL LATCHES ARE OPEN BEFORE RETURNING");
Serial.println("Enter YES to return.");
MotorReady:
while (Serial.available()==0) {
    // exits loop once input is made
}
// Read input:
motorReturn=Serial.readString();
motorReturn.trim();
if (motorReturn=="YES" || motorReturn=="yes" || motorReturn=="Yes") {
    Serial.print("You entered: ");
    Serial.println(motorReturn);
    goto ActuatorReturn;
}
else {
    //Serial.print("Enter valid response, YES or yes. You entered ");
    //Serial.println(motorReturn);
    goto MotorReady;
}

// Return motor:
ActuatorReturn:
delay(2000);
stepper.runToNewPosition(0);

// Return actuators:
delay(2000);
digitalWrite(actuator1,LOW);
digitalWrite(actuator2,LOW);
digitalWrite(actuator3,LOW);

//Serial.print("Exit and return to the Serial Monitor to restart.");

// Exit loop:
//exit(0);
Serial.println();
Serial.println("--");
Serial.println();
delay(1000);
goto startCode;

} // end of void loop

```

Wiring Directions

Actuator Wiring Diagram

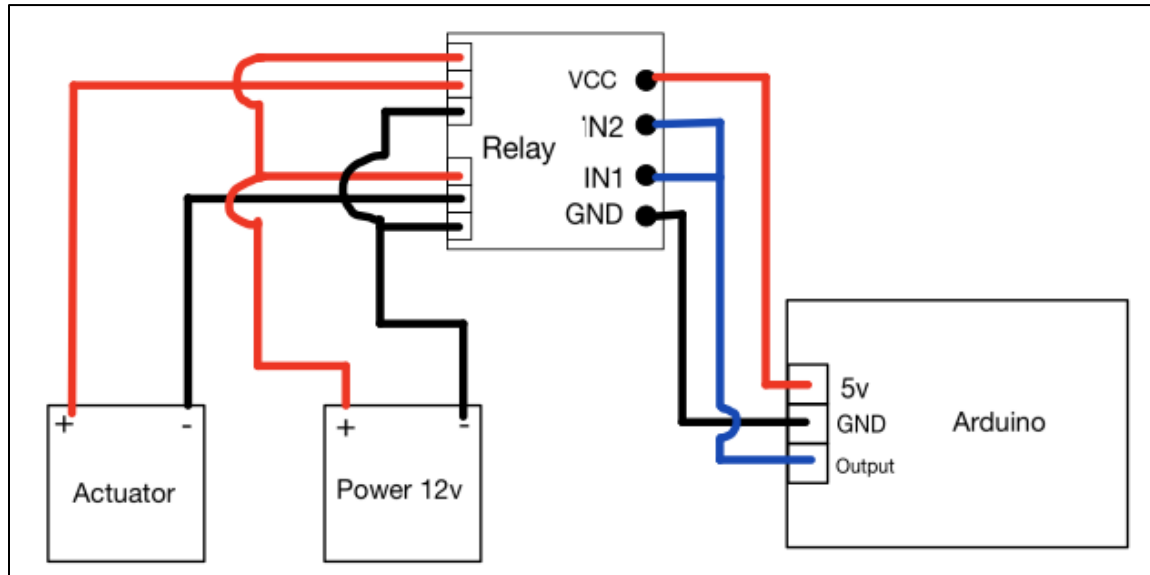


Figure 22: Wiring diagram for linear actuators

Motor Wiring Diagram

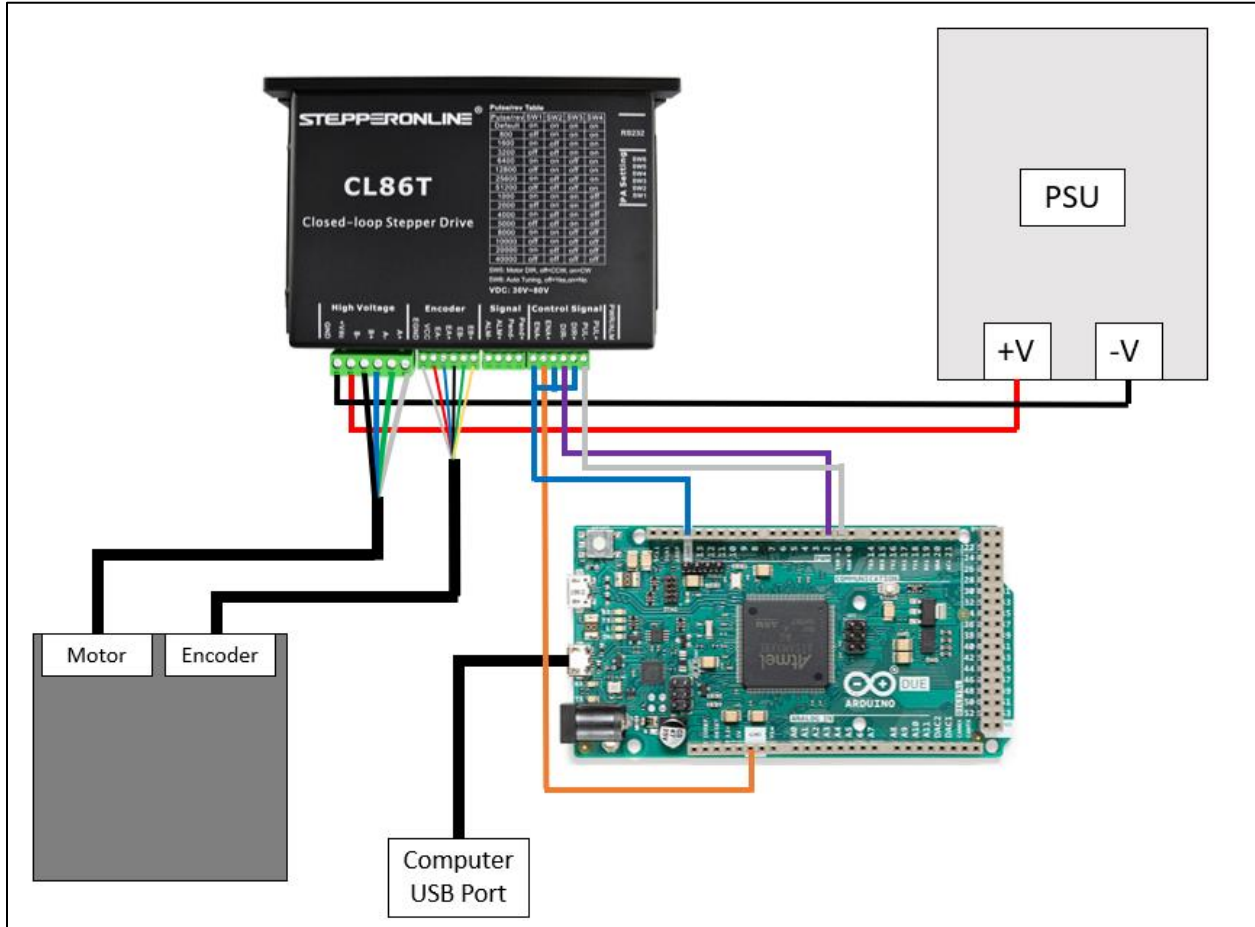


Figure 23: Wiring diagram for motor & encoder

Motor (With Extension Cables) Wire Chart

Table 1: Motor to driver wire table

PIN	1	2	3	4
BIPOLAR	A+	A-	B+	B-
COLOR	White	Green	Blue	Black

Encoder (With Extension Cables) Wire Chart

Table 2: Encoder to driver wire table

PIN	1	2	3	11	12	13
DESCRIPTION	EA+	VCC	GND	EB+	EB-	EA-
COLOR	Black	Red	White	Yellow	Green	Blue