THE UNIVERSITY OF ILLINOIS AT CHICAGO

Senior Design Team P05
Spring 2020

Bipedal Robot

Submitted by:

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Abstract

This project encompasses the design and construction of a bipedal robot. A bipedal robot is defined as having two legs which rotate about the same axis. The current design of the robot is comprised of a body to house all the required components for inducing motion, but it appears to have three legs instead of two, as defined. However, by linking the legs on either side of the body, their motions become the same, and they act as one leg. Combined with the singular, stationary leg attached at the center of the body, the design meets the requirements described by the definition of a bipedal robot.

The bipedal robot specifications laid out by the sponsor for this project call for a budget of no more than $200, an overall size no larger than an average backpack, the use of easily replaceable, open-source materials, zero-body length, and small feet. Dr. Pranav Bhounsule is the sponsor for this project, and this group has been collaborating continuously with him throughout this semester to ensure that the robot design meets his expectations.

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Problem Statement

This project entails the design and construction of a planar bipedal robot capable of sustained walking motion for use in Dr. Pranav Bhounsule's robotics classes. The professor's intended use for the robot is to demonstrate basic mechanics, motions, and operations so that students in his future robotics classes may better understand the fundamental principles that govern robotic bipedalism. Dr. Bhounsule has provided requirements regarding the overall cost and design of the robot. First, the robot should be relatively cheap in price. Given its purpose as an exemplary tool for a class, the maximum budget has been set at $200. In terms of design, the robot must have zero body length. This means that all parts used to propel the robot in forward motion rotate about the same axis. Zero body length is what defines bipedalism in robots. Next, the motion of the robot must be described as "planar." This means that the primary motion of the robot acts in one direction. Simply stated, the robot must walk only forward. Additionally, the robot's size must not be too excessive. For Dr. Bhounsule to tote it between classrooms, he requests that it be able to fit comfortably within a standard backpack. Furthermore, the feet of the robot must not be overbearingly large. Bipedal robots are inherently unstable; thus, balance is a key issue to consider during the process. Dr. Bhounsule requires that the robot relies on its other physical features and the principles of balance to sustain itself, rather than remaining upright by maintaining a large contact area with the ground. Finally, and most importantly, the robot must be modular, meaning it should be simple to recreate and build. If a part of the robot were to malfunction or break, the parts could be easily replaced using items that are either purchased off-the-shelf or manufactured both quickly and effortlessly.

Sponsor Background

Dr. Pranav Bhounsule is an Assistant Professor in the Department of Mechanical and Industrial Engineering. Professor Bhounsule earned a B.E. In Mechanical Engineering from Goa Engineering College in Goa, India, in 2004. Following the completion of his Bachelor's degree, he earned a Master's in Applied Mechanics from the Indian Institute of Technology in Madras, Chennai, India, in 2006. He then earned a doctorate in Mechanical Engineering from Cornell University in 2012. Beginning in January 2012, Professor Bhounsule was a visiting researcher for two years at Carnegie Mellon University, as well as a postdoctoral researcher for Disney Research until July 2014, both of which took place in Pittsburgh, Pennsylvania. From August 2014 to July 2019, he was an Assistant Professor in Mechanical Engineering at the University of Texas San Antonio. Today, he teaches at the University of Illinois at Chicago, where he specializes in robotics courses.

Product Specifications

In order to meet the design criteria provided by Dr. Bhounsule, certain metrics and design restrictions are introduced and applied to the design. Metrics are used to quantify a process in question, allowing measurements to be taken to determine the functionality of said process. Engineers use metrics to identify weaknesses, make decisions, and improve the project. For the cost requirement, the robot should be designed to be as cheap as possible, with a maximum allowable budget set at $200. This spending limit enticed the team to seek out components that are ideal, both functionally and economically, for creating motion in the robot. As there is no requirement for the speed with which the robot walks, the team was able to find servo motors that are reliable and inexpensive, yet still meet the needs of the robot. The overall size of the robot should allow it to safely fit within the confines of a standard backpack. However, backpacks come in a variety of shapes and sizes. The team assumes average dimensions for a standard backpack to be approximately 18" x 12" x 8". Therefore, the design for the robot must not exceed these values for their respective dimensions. In addition, Dr. Bhounsule requires that the feet of the robot not be extremely large. To demonstrate the balancing capabilities of bipedalism, the robot must not rely on a large base (i.e. its feet) to sustain balance during motion. Rather, it should be able to balance itself by adjusting its posture and finding support on its limbs. Unfortunately, there is no simple quantified definition of "big feet." Dr. Bhounsule states that an acceptable size for a robotic foot should not exceed one quarter of the robot's leg dimensions. This means that the feet should be no longer than one quarter of the length of its leg.

The robot should also have zero body length, move in a planar fashion, and maintain a high degree of modularity. These features are difficult to quantify as they are either included in the design or not. Thus, they are design restrictions. A zero-length body is one where all features that drive motion rotate about the same axis. For the bipedal robot, both legs rotate about a single shaft, though they will have oscillating positions on opposite sides of the shaft. To achieve planar motion, the force that affects the dynamics of the robot and drives its motion must act in only one direction. In the case of the bipedal robot, that force drives the robot in the forward direction and nowhere else. Finally, modularity refers to the ease in individual parts' replaceability should they break or malfunction.

There are key assumptions and conditions regarding the operation of the robot that must be considered during the design process. First, it is assumed that the robot is untethered. This means that there are no external cords providing power or control to the robot. It is also assumed that, while the driving force acts in the forward direction, the robot moves along a straight path. There is no minimum time or distance that the robot must walk, therefore it is assumed that it continually walks without interruption. Finally, the robot walks across a flat surface, such as a table or countertop.

	Aspect	Objective	Criteria	Test Conditions
1	Cost	Acceptable cost for sponsor	$200 or less	Obtain estimates for components
2	Size	Small-medium	Must fit in a backpack	Determine size from CAD model
3	Materials	Appropriate to design	Modular/open source	Bench test
4	Repair	Easy to repair	Easy to replace and repair parts	Parts based on CAD
5	Design	Fulfill sponsor's specifications	Small feet and zero-body length	Measured on CAD

Figure 1. Product Design Specification chart for the bipedal robot

Technical Content

To begin the design process, thorough research is conducted to gain a better understanding of the problem at hand. Bipedal motion is among the most challenging to recreate in robotics due to the difficulties with balance. In classical physics, the inverted pendulum problem is often used to model bipedal motion at its most basic principles.

The inverted pendulum involves a mass attached to the top of a spring, the other end of which is attached to the ground. With the mass positioned above the pivot point, the system is then allowed to oscillate freely. However, the inverted pendulum does not oscillate in the typical fashion of most pendulums as it does not have a characteristic frequency. The nature of the mass-spring system, when inverted, is inherently unstable as it defies the known predictability commonly associated with pendulum oscillations. The mass atop the spring represents the center of mass of the body undergoing bipedal motion. Without carefully tuned control factors, a bipedal robot mimics the instability of the inverted pendulum.

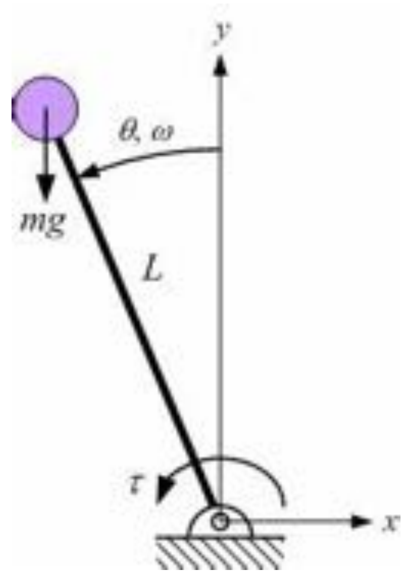


Figure 2. Inverted pendulum problem from classical physics

Once enough background information and significant understanding of the subject matter has been attained, early concepts and models of the bipedal robot begin to arise from the team's brainstorming sessions. When initiating the design process, the team must consider the most important characteristics of the robot. However, in any project, an engineer may encounter certain characteristics that counter each other. In other words, one cannot be attained without sacrificing the other. For this reason, engineers use a Quality Function Deployment. A QFD is a tool used to measure the importance of product characteristics against the customer's requirements for the product. Figure 3, shown below, features the QFD for this project.

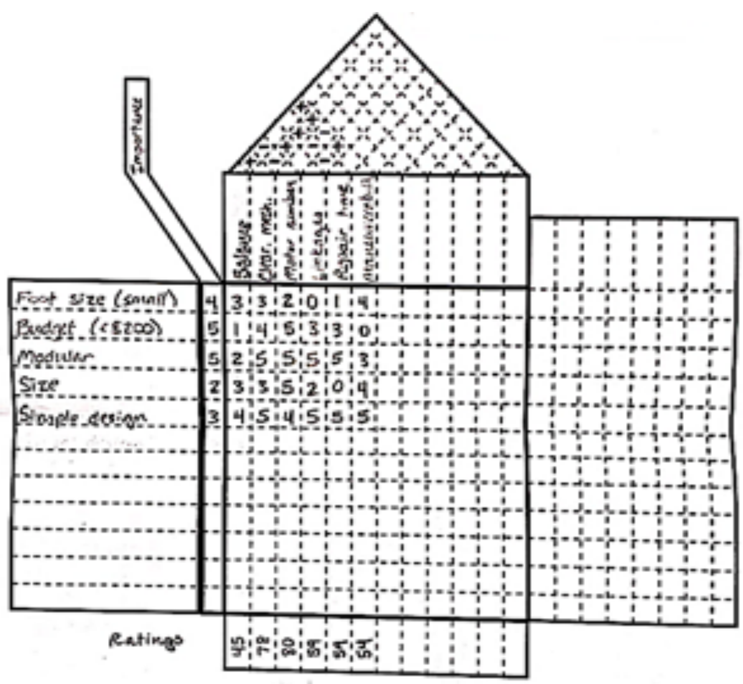


Figure 3. QFD diagram for the bipedal robot

The leftmost column of a QFD lists the customer's requirements for the design. They are as follows: Foot size (small), budget (<$200), modular, size, and simple design. Each of these attributes is given a coefficient of importance, which is used to denote the difficulty in achieving the requirement or the significance that the requirement has on the project. Obtaining modularity and staying within the allotted budget warrant significant importance to the project, so they are given the highest coefficients of importance (5). The size of the robot, however, has the lowest coefficient (2) because there is a large size range in which the robot must fit, and creating a model that fits within that range is not overly difficult. The top row houses a list of product characteristics. In the chart shown, these are as follows: Balance, clearance mechanism, number of motors, linkages, repair time, and maneuverability. The triangular region above the product characteristics is used to describe the relationship between each pair of these characteristics. If they are positively correlated, a "+' is placed in the box. Similarly, if they are negatively correlated, a "-" is placed in the box. The center of the QFD houses the relationship matrix between the product characteristics and the customer requirements. Each characteristic is given a score on its relativity to each of the customer requirements. For example, the number of motors is directly related to the modularity of the robot, so it is given a score of 5, but the robot's ability to balance has no effect on the budget, so it is given a score of 1. To determine the importance score of each product characteristic, the score is multiplied by the coefficient of importance for each requirement and summed at the end. Based on the results of the QFD, the number of motors used in the design has the highest ranking, with a score of 80. Meanwhile, balance has the lowest ranking, with a score of 49. The remaining characteristics fall within this range. This reveals that the customer's requirements lean more heavily towards the mechanics and components of the design rather than the governing principles.

When the QFD is completed and the most important characteristics are known, brainstorming begins on designs. Each member of the team has developed conceptual designs for the robot, so the team must choose one to pursue. A decision matrix is a tool used to help engineers decide by quantifying attributes about their options and producing a numerical score. Figure 4 below shows the decision matrix used to determine the best course of action.

		Cost	Modular	Reliability	Simplicity	Balance	
Weighing	Factor	0.3	0.2	0.2	0.15	0.15	
Alex	Crutch	8	8	8	8	10	8.3
Felipe	Sidestep	6	8	8	7	8	7.25
John	Walker	4	7	6	7	7	5.9
John	Wobble	10	9	4	10	2	7.4
Felipe	Linkage	9	5	9	5	10	7.75

Figure 4. Decision Matrix to choose the design of the bipedal robot

The top row contains the project requirements. Like the QFD, each one is given a weighing factor relative to their importance. Each weighing factor is a fraction, with the total weighing factor being equal to 1. The left column shows the list of options for the design of the robot. They are the Crutch, Sidestep, Walker, Wobble, and Linkage. Renderings of these design options are shown in Figures 26-29, found in the Appendix. Each option is given a ranking on a scale of 1-10 on how achievable each requirement is for the given option. At the end, the score is acquired by taking the summing the products of each option's ranking by each requirement's weighing factor. The Crutch method is shown to have the highest score; thus, it is the method the team uses in its designs moving forward.

After a few weeks of concept sketching, discussion, and CAD drawing, the team narrowed down on a final design. For the time being, the team decided to maintain two CAD models. The first involves two sets of paired legs being driven, with one servo controlling the outer paired legs and another controlling the inner pair. Drawings and renderings of this model and all of its subsequent versions are found in Figures 7-23 in the Appendix. The second model contains one set of paired legs on the outside of the robot with a stationary central leg attached to the body to provide stability. The drawing and rendering for this model is shown in Figures 24 and 25 in the Appendix. The second model is simpler than the first, but it requires more testing to be done prior to completion; therefore, the team has opted to keep both models until more testing can be performed to prove whether or not the stationary leg concept is feasible. Solidworks drawing of both models can be found in the Appendix below. A preliminary bill of materials, shown below in Figure 5, has been completed for the first model to show the projected material cost of the product.

Part	Unit Cost	Quantity	Total
DS3218MG servo	17.98	2	35.96
MG90S servo (4-pack)	13.99	1	13.99
UNO R3 Microcontroller	15.98	1	15.98
Lithium Ion Battery	20.93	1	20.93
3/8" Acrylic Sheet	17.00	1	17.00
Screws and Pins	15.00	1	15.00
		Total Cost	118.86

Figure 5. Preliminary cost analysis of the bipedal robot

What Remains

- ANSYS structural analysis
- Completion of prototype testing
- Build the final product
- Expo board due 4/17
- Engineering Expo, 4/24
- Cost Analysis

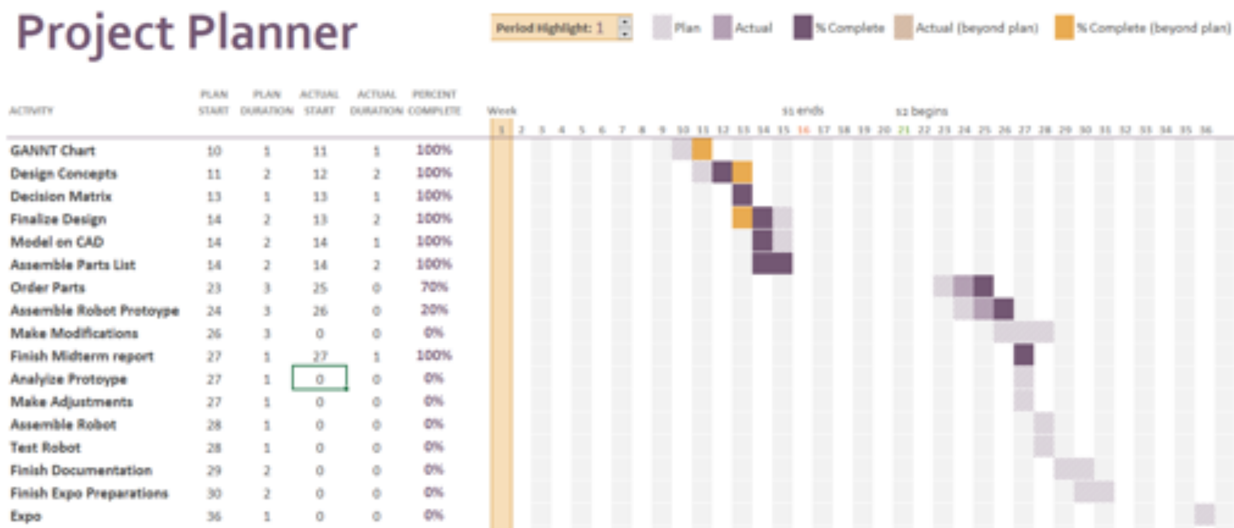
Conclusion

The project at hand calls for the design and assembly of a bipedal robot which fulfills all the criteria specified by the sponsor. In order to commence the designing process, extensive research is conducted on the concepts applied in the scope of this project. These include the basics of the walking theory, which revolves around the inverted pendulum theory. The group then examined several design ideas for the robot. Models are employed to obtain the desired design, after several important product characteristics are taken into account.

Several models have been developed, with each subsequent version correcting the shortcomings of the earlier work, enhancing the design in such a way that it optimizes both cost as well as functionality. Key steps to building the robot still remain. These include completing structural analysis, prototype testing, and building the final product to be presented at the Engineering Expo later this semester.

Appendix

GANTT Chart



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
GANNT Chart	10	1	11	1	100%
Design Concepts	11	2	12	2	100%
Decision Matrix	13	1	13	1	100%
Finalize Design	14	2	13	2	100%
Model on CAD	14	2	14	1	100%
Assemble Parts List	14	2	14	2	100%
Order Parts	23	3	25	0	70%
Assemble Robot Protoype	24	3	26	0	20%
Make Modifications	26	3	0	0	0%
Finish Midterm report	27	1	27	1	100%
Analyze Protoype	27	1	0	0	0%
Make Adjustments	27	1	0	0	0%
Assemble Robot	28	1	0	0	0%
Test Robot	28	1	0	0	0%
Finish Documentation	29	2	0	0	0%
Finish Expo Preparations	30	2	0	0	0%
Expo	36	1	0	0	0%

Figure 6. GANTT chart showing projected schedule for the duration of the project

Beginning in Week 1 of the second semester, we worked with the design of the robot. A torque analysis is being conducted, as well as a structural analysis using ANSYS software. Parts began being ordered in Week 3. As more and more parts arrive, we are beginning to assemble the robot to begin initial testing. When significant testing has been completed, and we are satisfied with any corrections made in the process, we will begin assembling the final product. Testing will be finished by Spring Break. Over the course of Spring Break and the remaining weeks afterwards, we will be completing the final report and any presentation materials for Expo. Finally, the Engineering Expo takes place on Friday of Week 14. The final report for our project is due the following Friday.

Literature Search

- Bipedal robot Center of Mass article:

All parts of the human body can be broken up into components (arms, head, torso, etc.), and modeled. Thus, all the masses with their respective position in space can be accounted for.

https://www.hindawi.com/journals/jr/2010/278597/

- About the inverted pendulum, and how it pertains to human walking:

The inverted pendulum theory is a common approach to modeling human walking. The mass attached to the pendulum represents the center of mass (COM) of the human body, oscillating above the pivot point at an angle.

https://www.sciencedirect.com/science/article/pii/S0167945707000309?via%3Dihub

- Bipedal robot balancing:

Explores how bipedal robots can balance themselves on their feet when various forces are being applied on them. They have force sensors that pick up these disturbances and report the information to a feedback loop that adjusts the robot's position.

https://spectrum.ieee.org/automaton/robotics/humanoids/a-new-way-for-robots-to-balance-on-two-feet

- Here's an article on motors and how to choose the right one:

Description of the common motor types, including their uses and characteristics.
Namely, this article describes the difference between DC motors, Stepper motors, and Servo Motors.

https://www.seeedstudio.com/blog/2019/04/01/choosing-the-right-motor-for-your-project-dc-vs-stepper-vs-servo-motors/

CAD Drawings

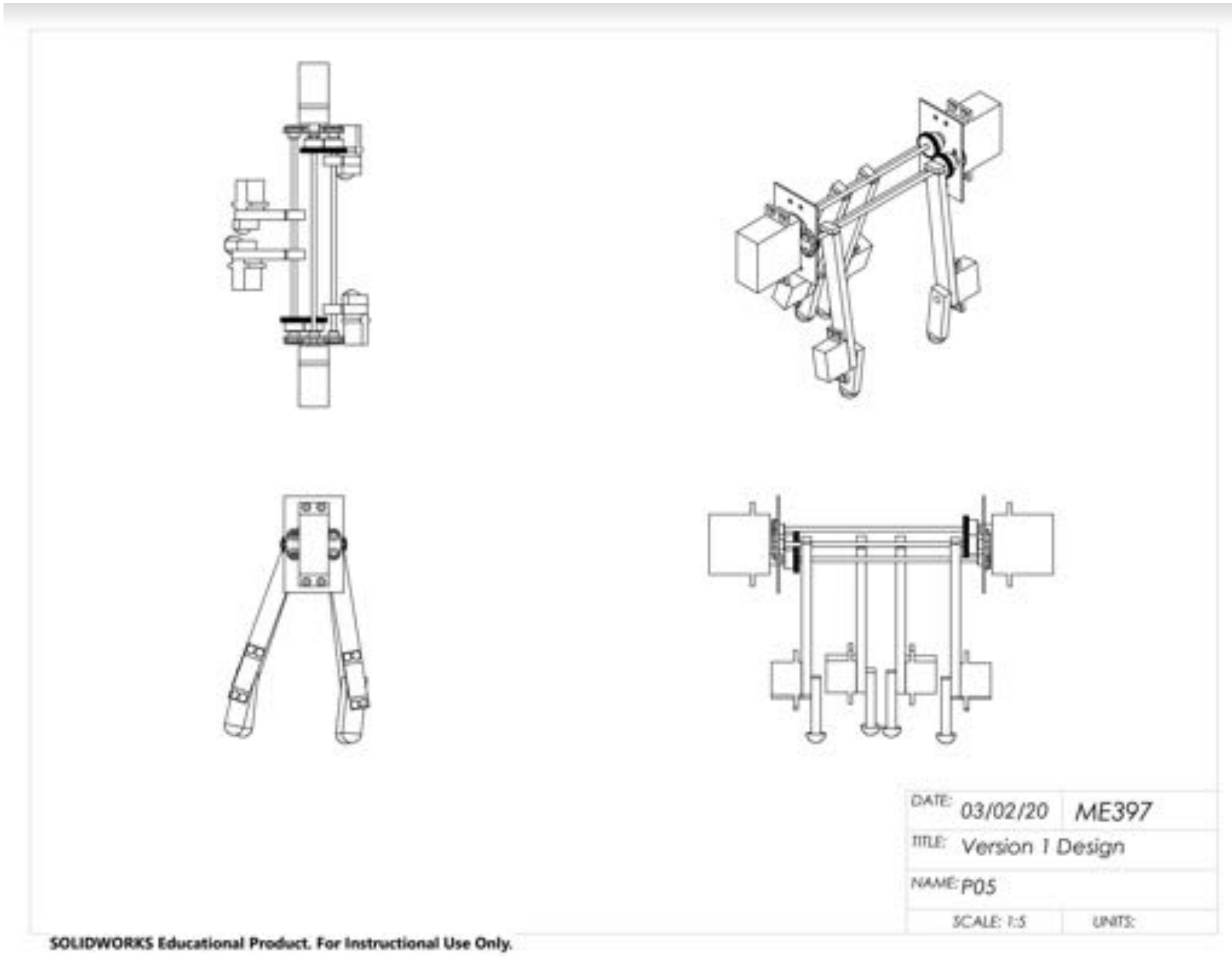


Figure 7. Model 1, Version 1 drawing

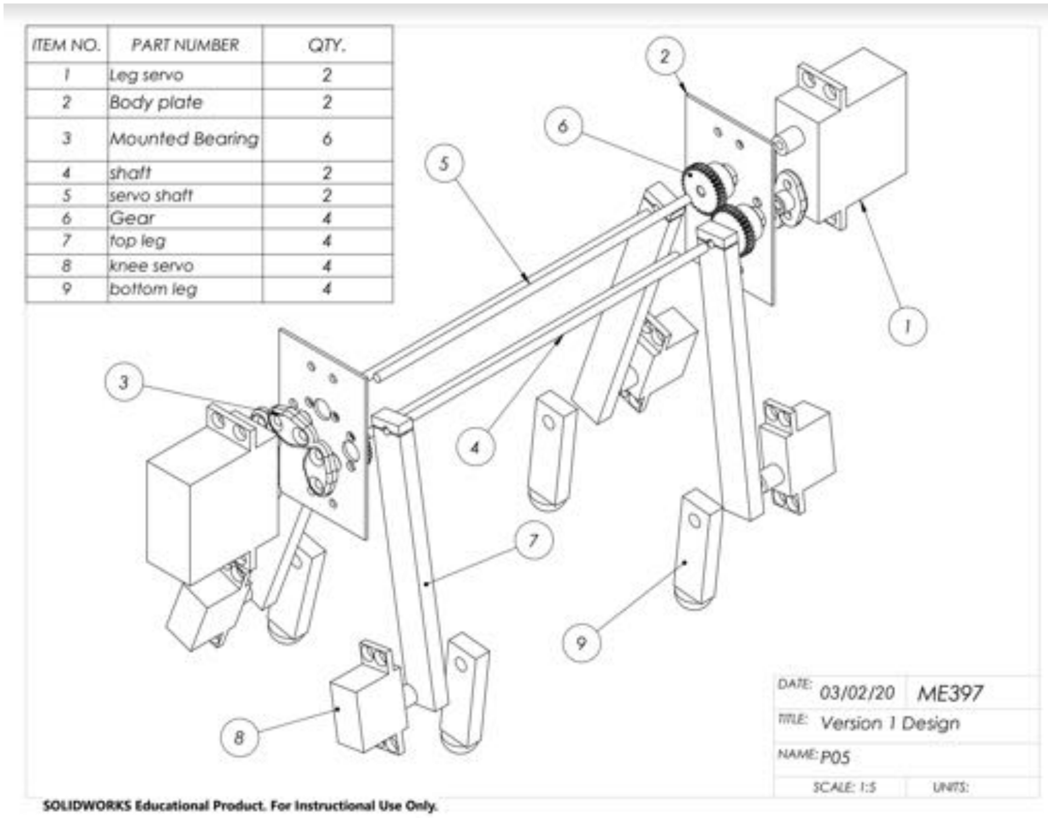


Figure 8. Model 1, Version 1 exploded view drawing

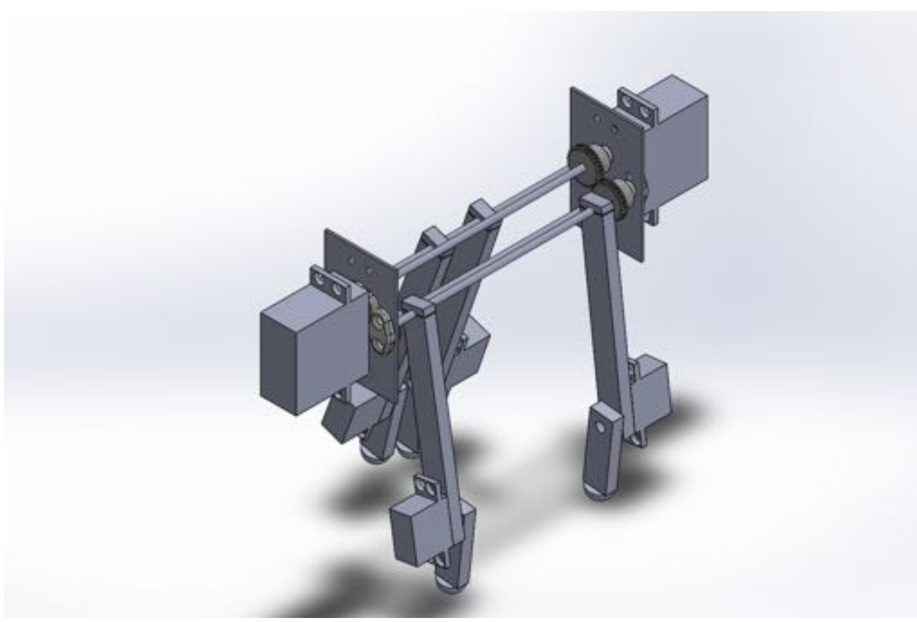


Figure 9. Isometric view of Model 1, Version 1 solid model rendering

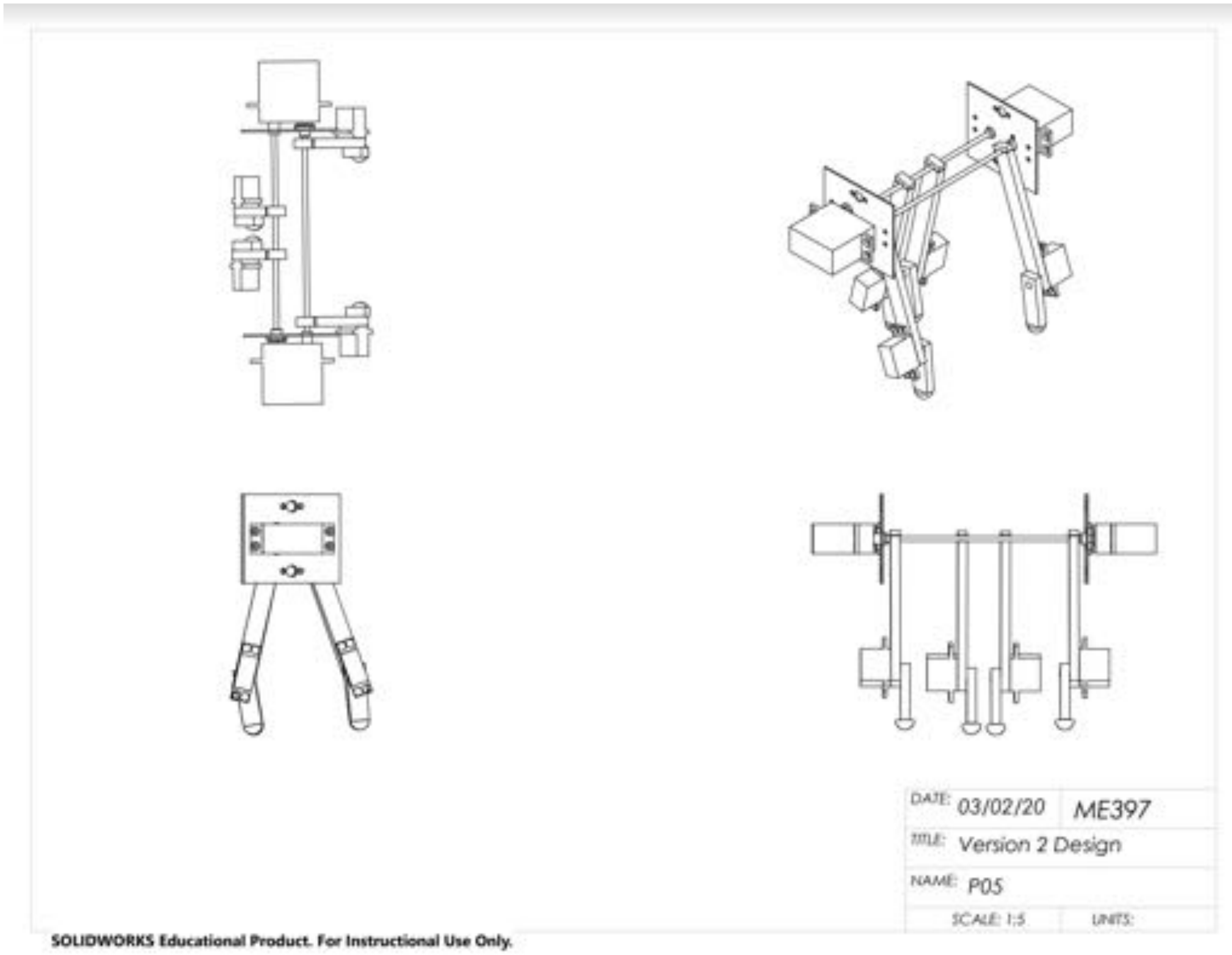


Figure 10. Model 1, Version 2 drawing

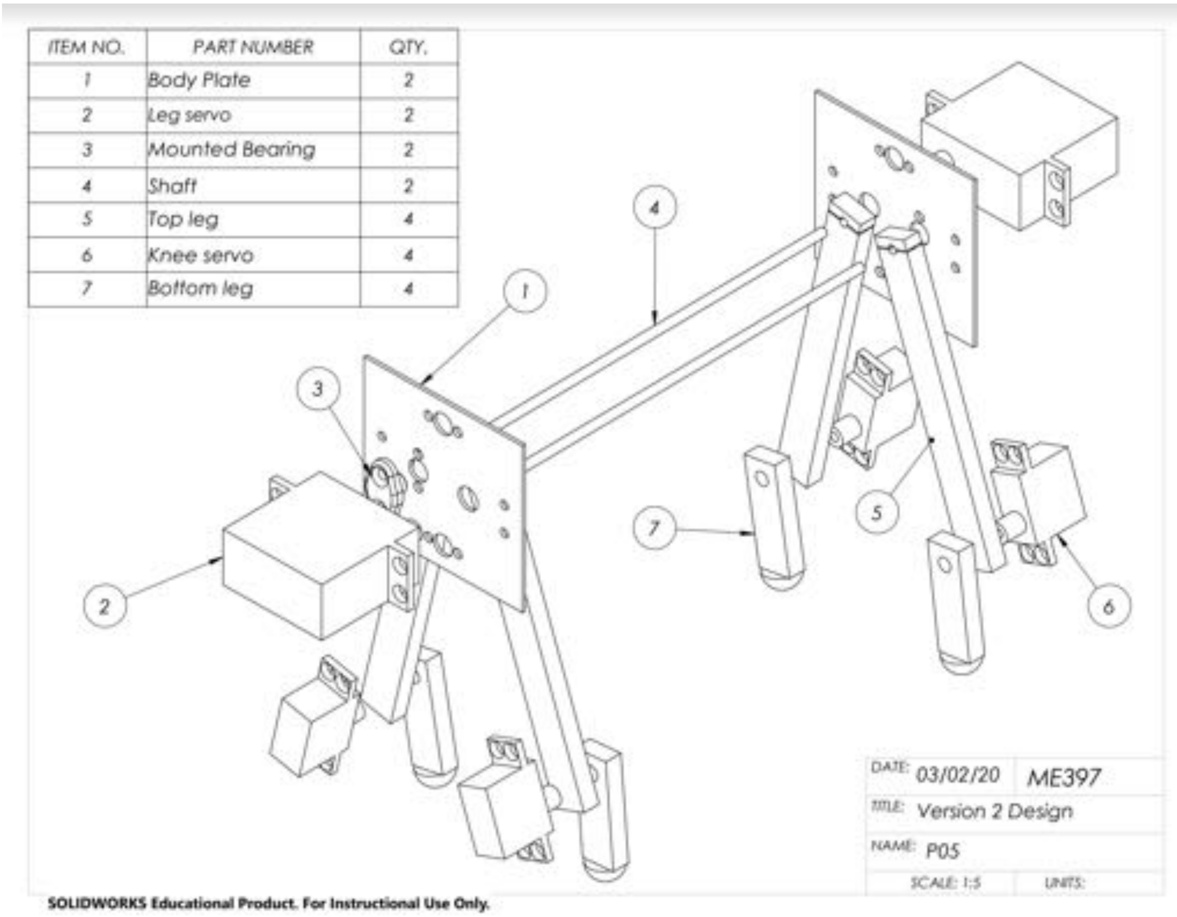


Figure 11. Model 1, Version 2 exploded view drawing

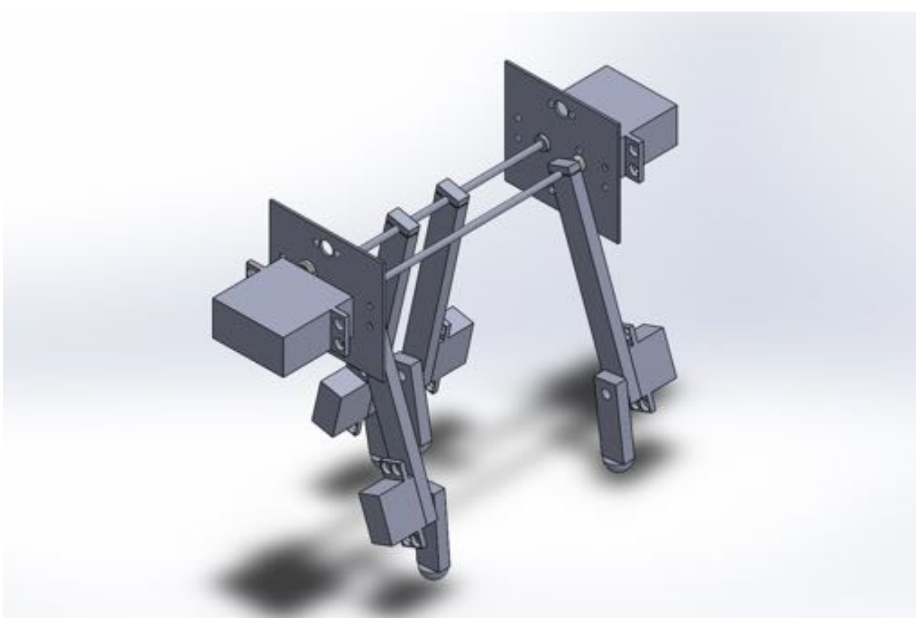


Figure 12. Isometric view of Model 1, Version 1 solid model rendering

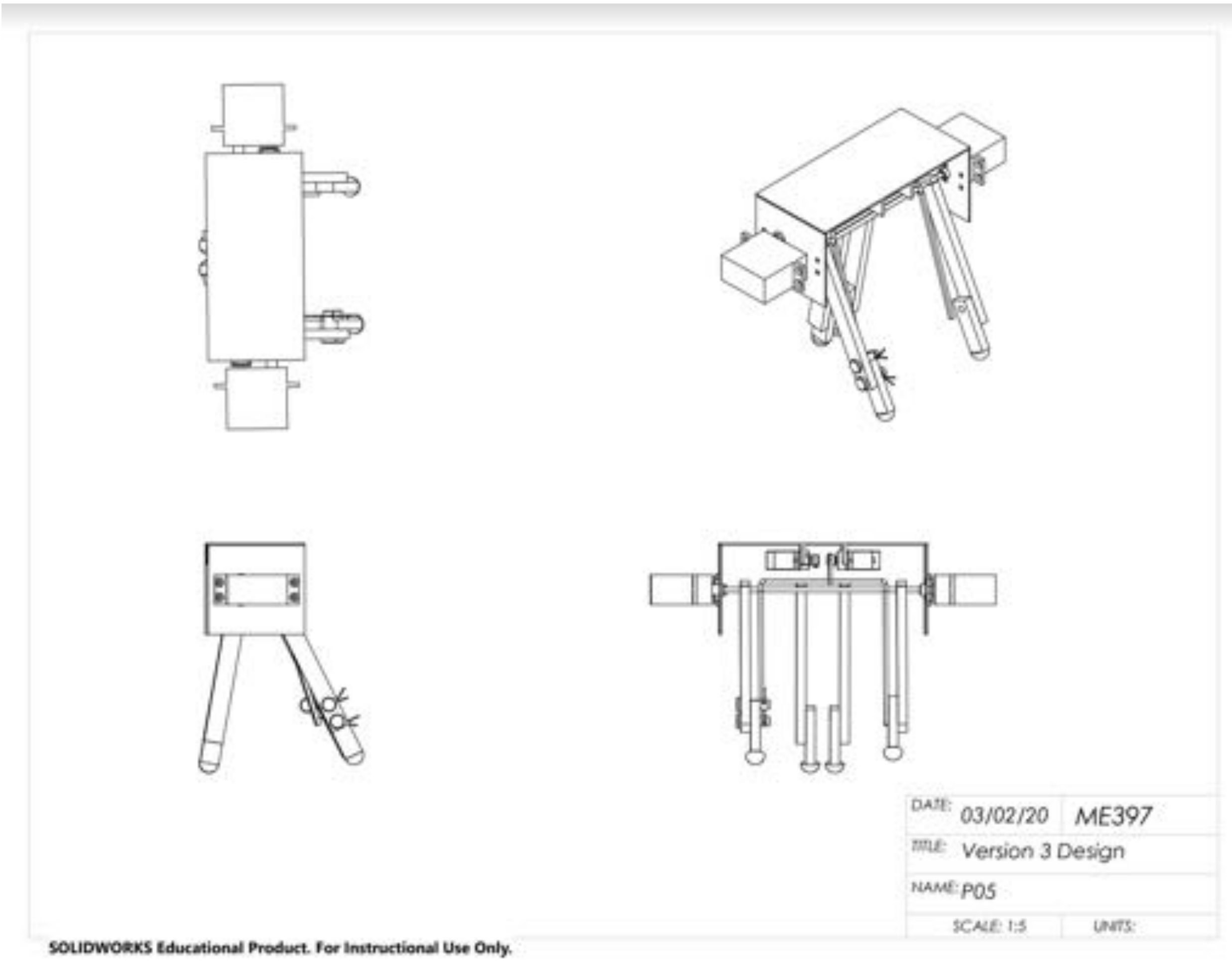


Figure 13. Model 1, Version 3 drawing

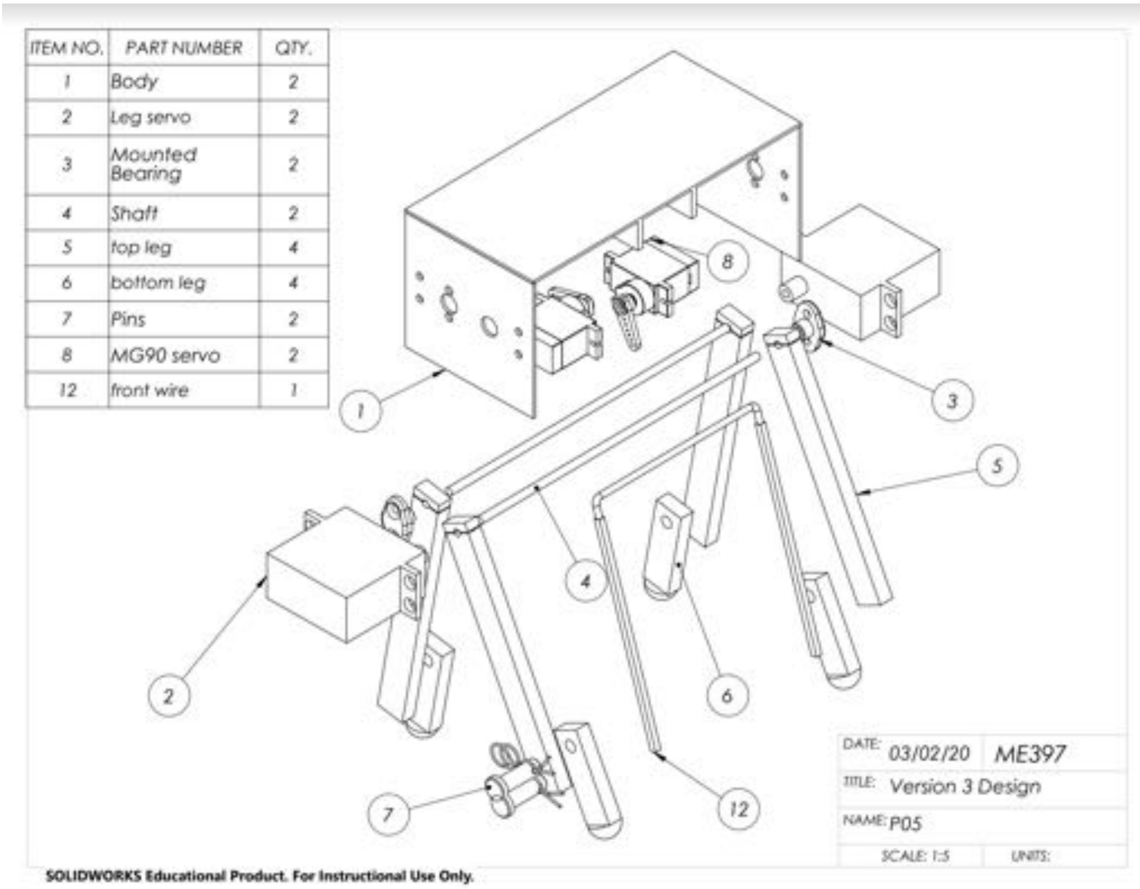


Figure 14. Model 1, Version 3 exploded view drawing

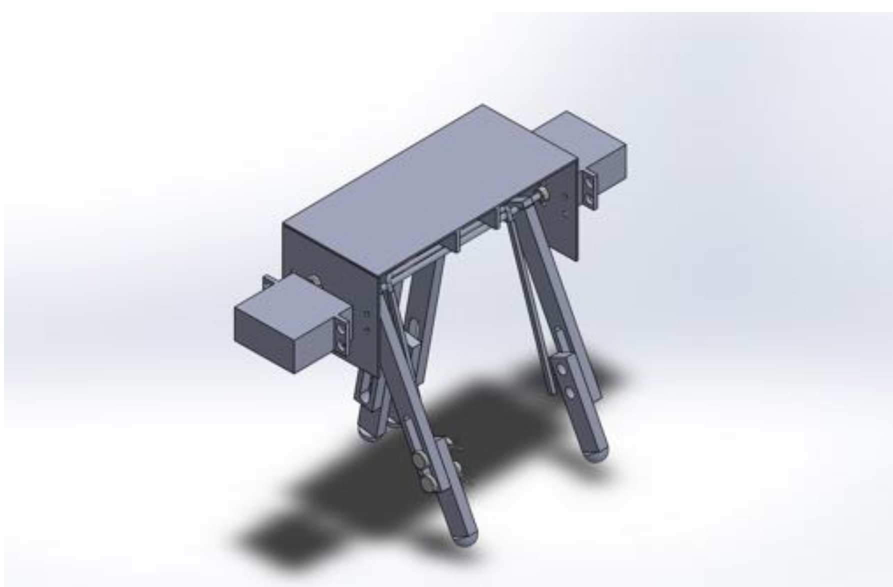


Figure 15. Isometric view of Model 1, Version 3 solid model rendering

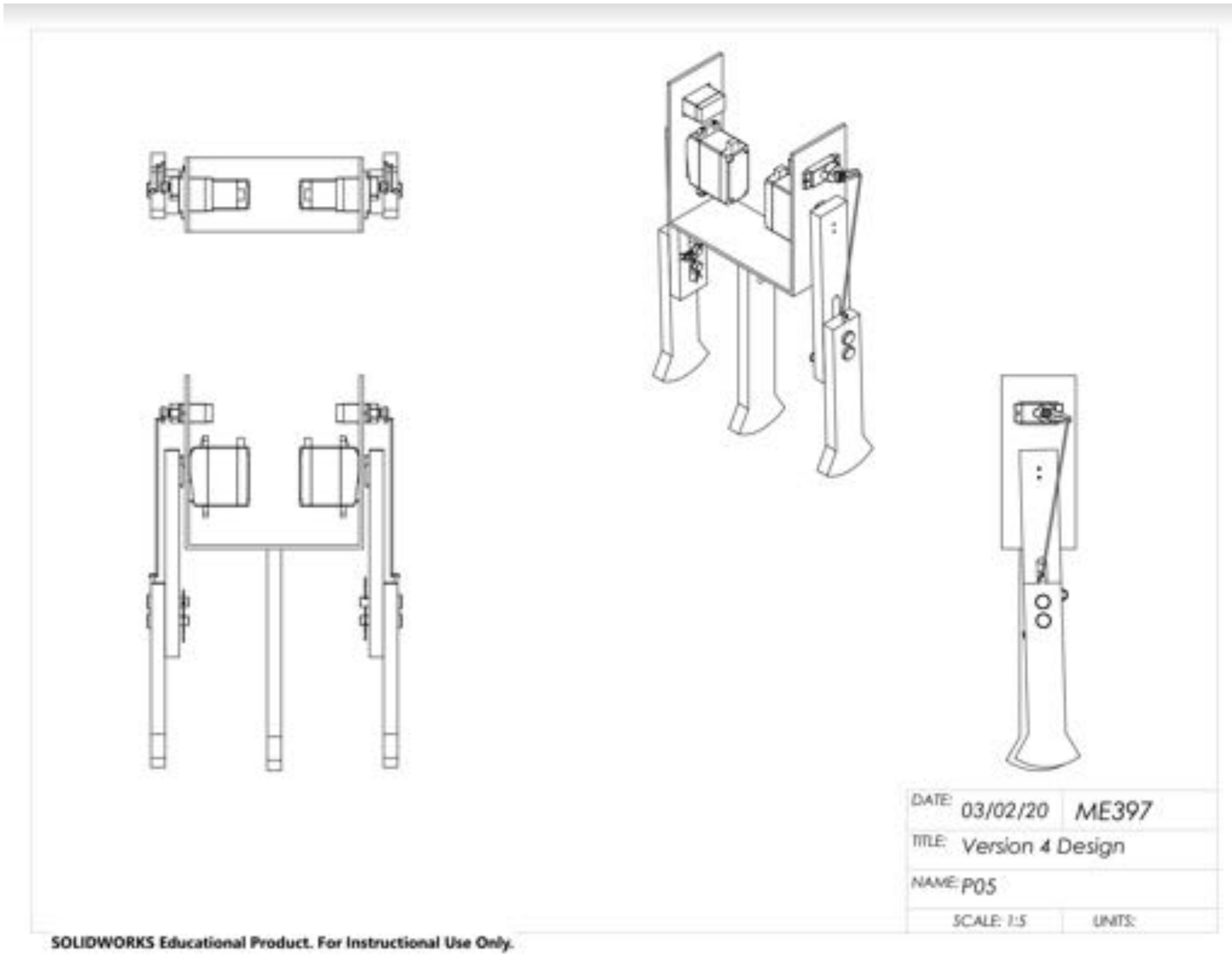


Figure 16. Model 1, Version 4 drawing

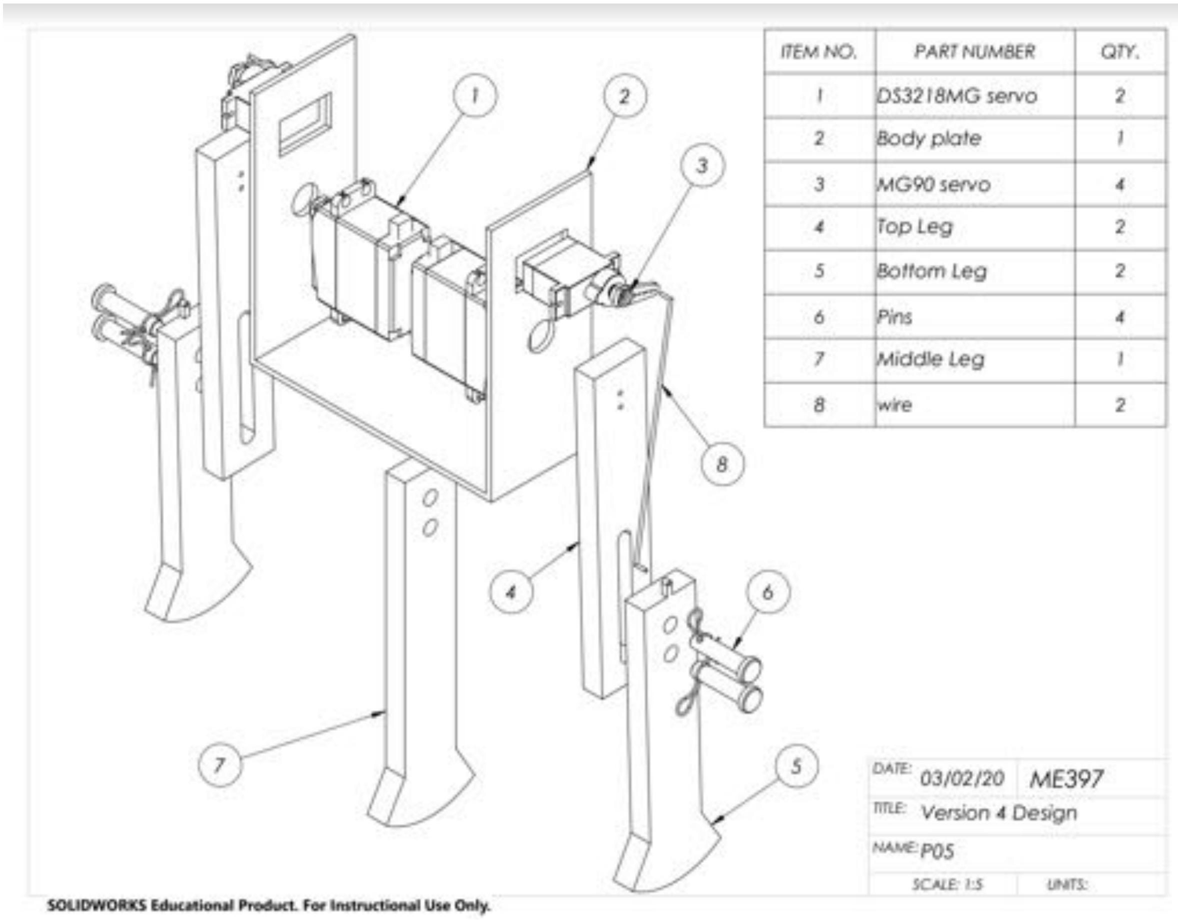


Figure 17. Model 1, Version 4 exploded view drawing

Figure 18. Isometric view of Model 1, Version 4 solid model rendering

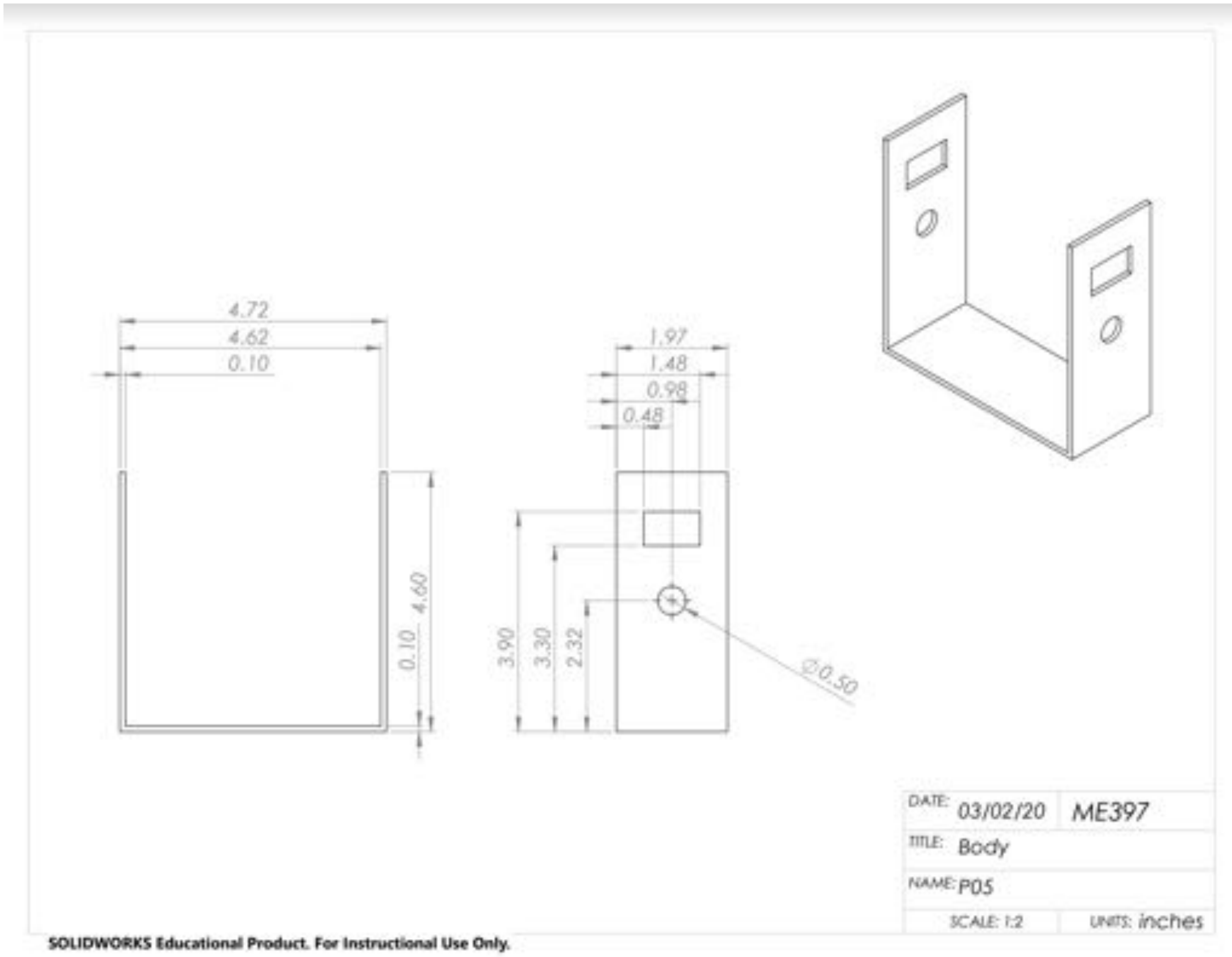


Figure 19. Drawing of the body for Model 1, Version 4

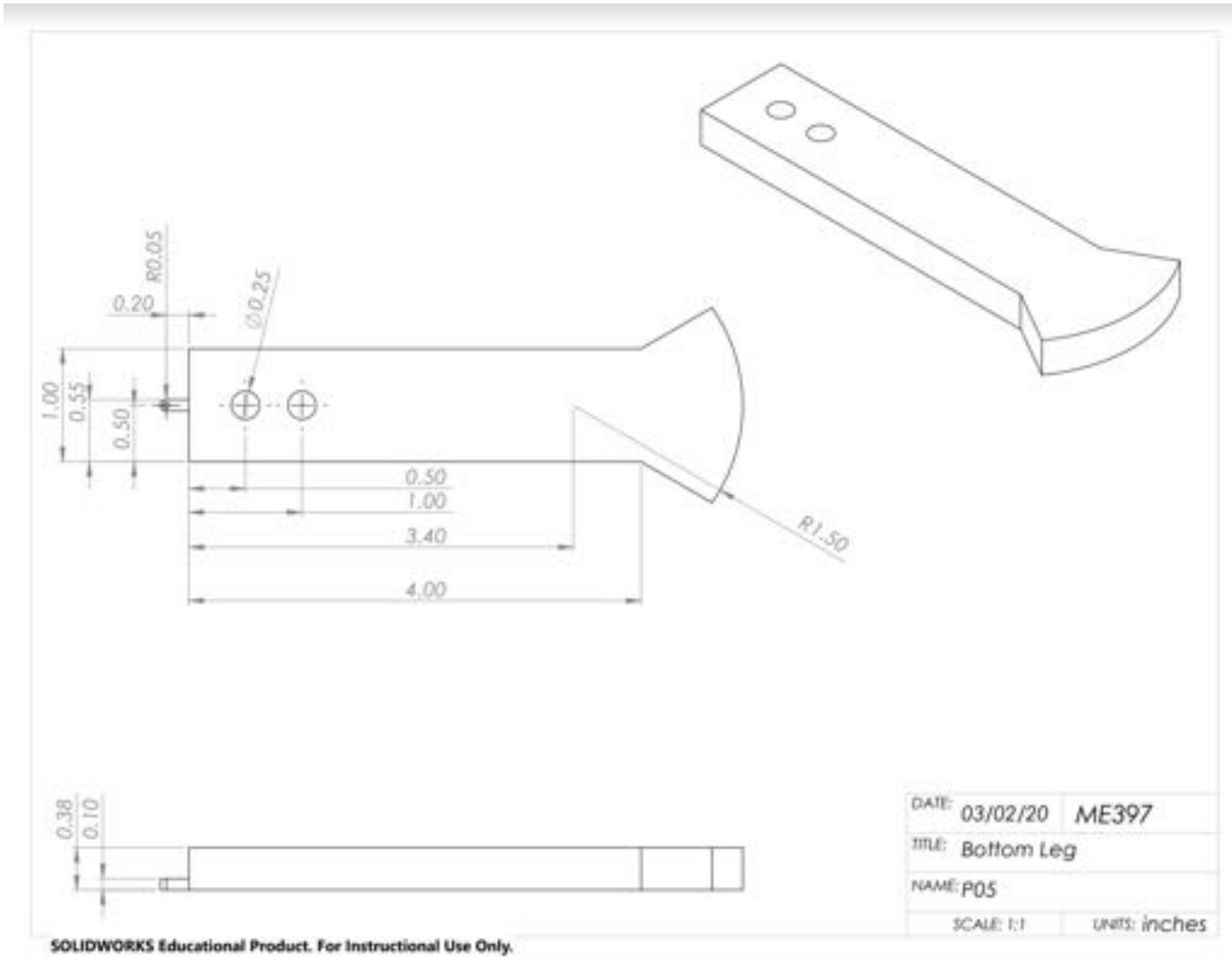


Figure 20. Drawing of the bottom leg for Model 1, Version 4

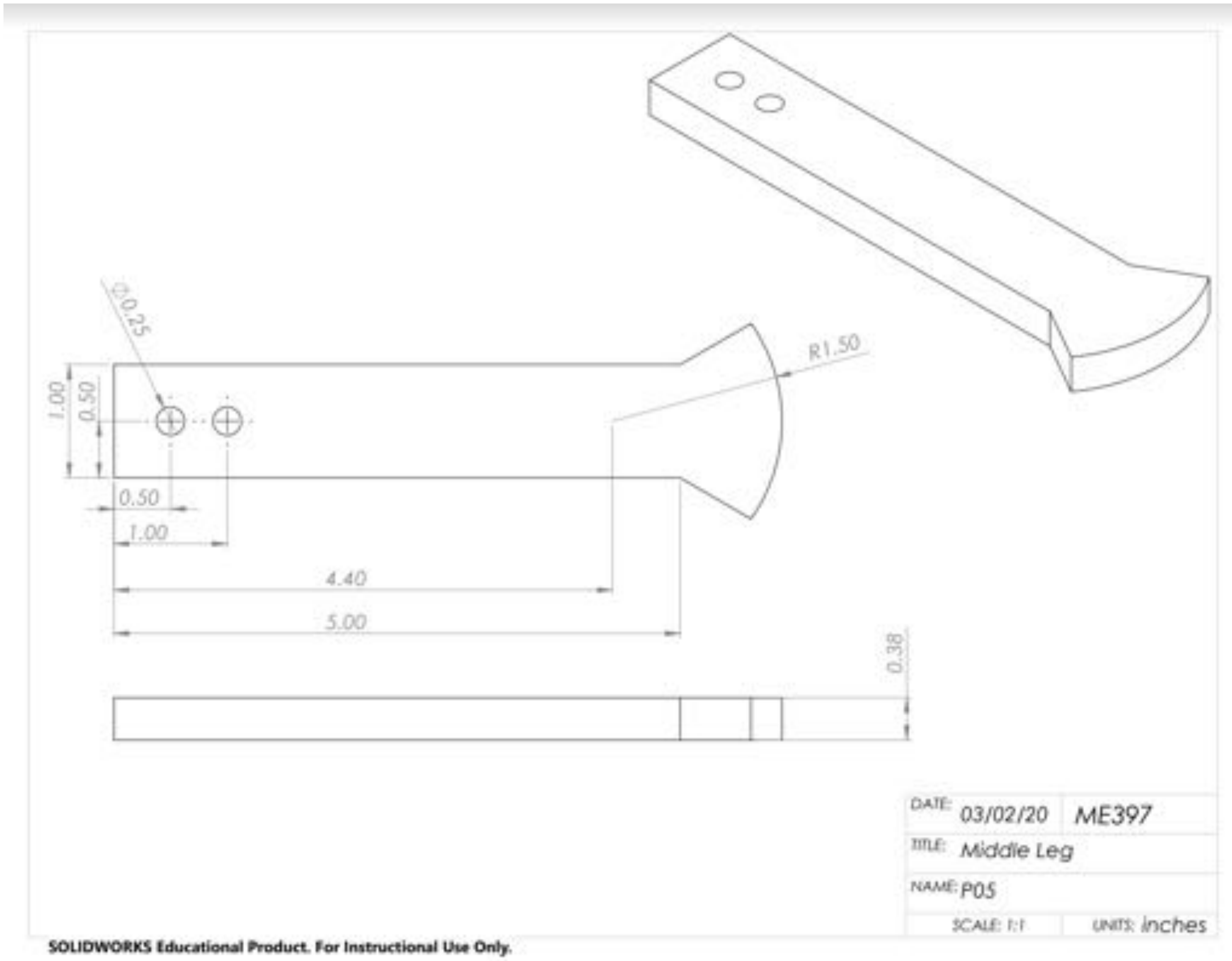


Figure 21. Drawing of the middle leg for Model 1, Version 4

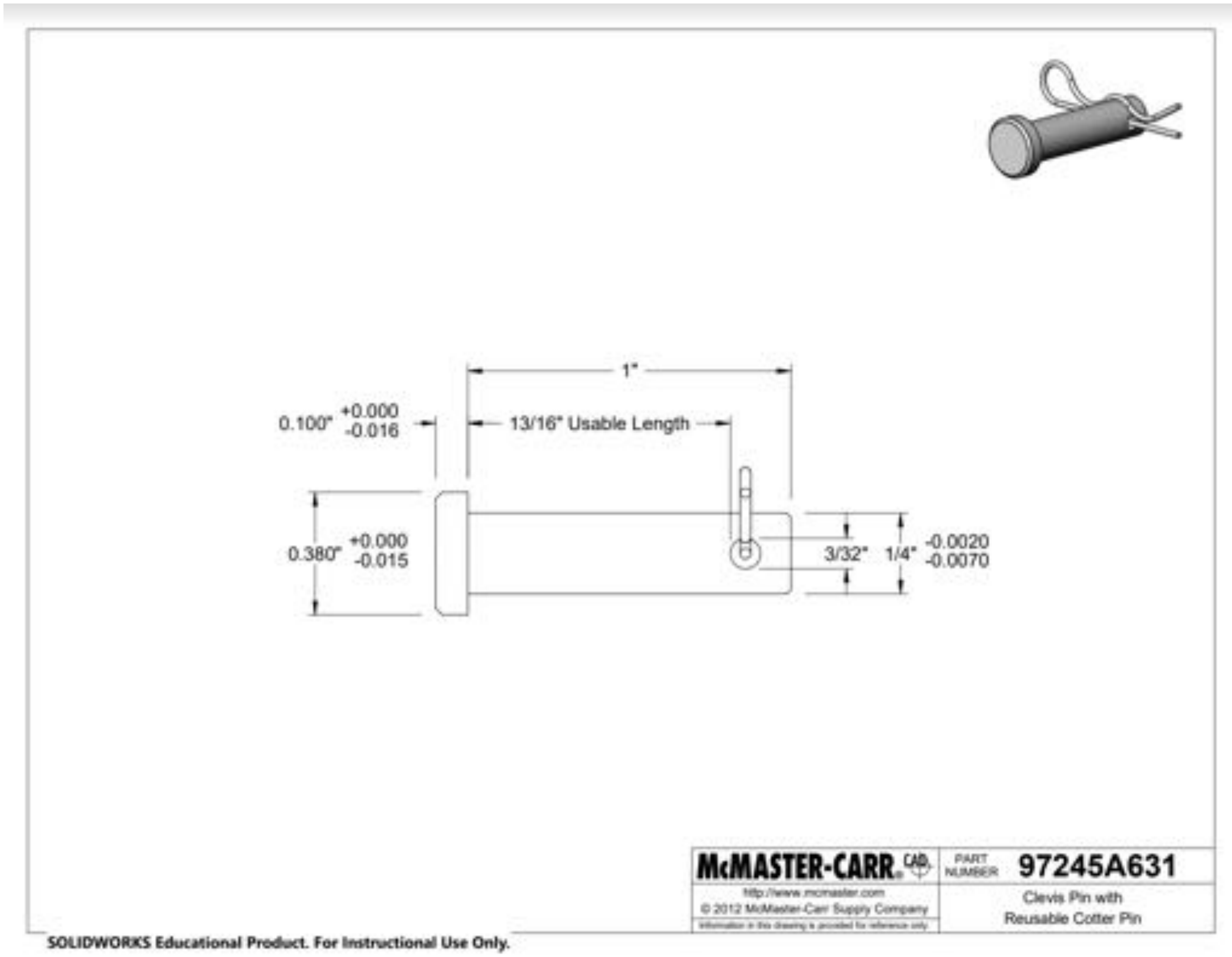


Figure 22. Drawing of the pins used in Model 1, Version 4

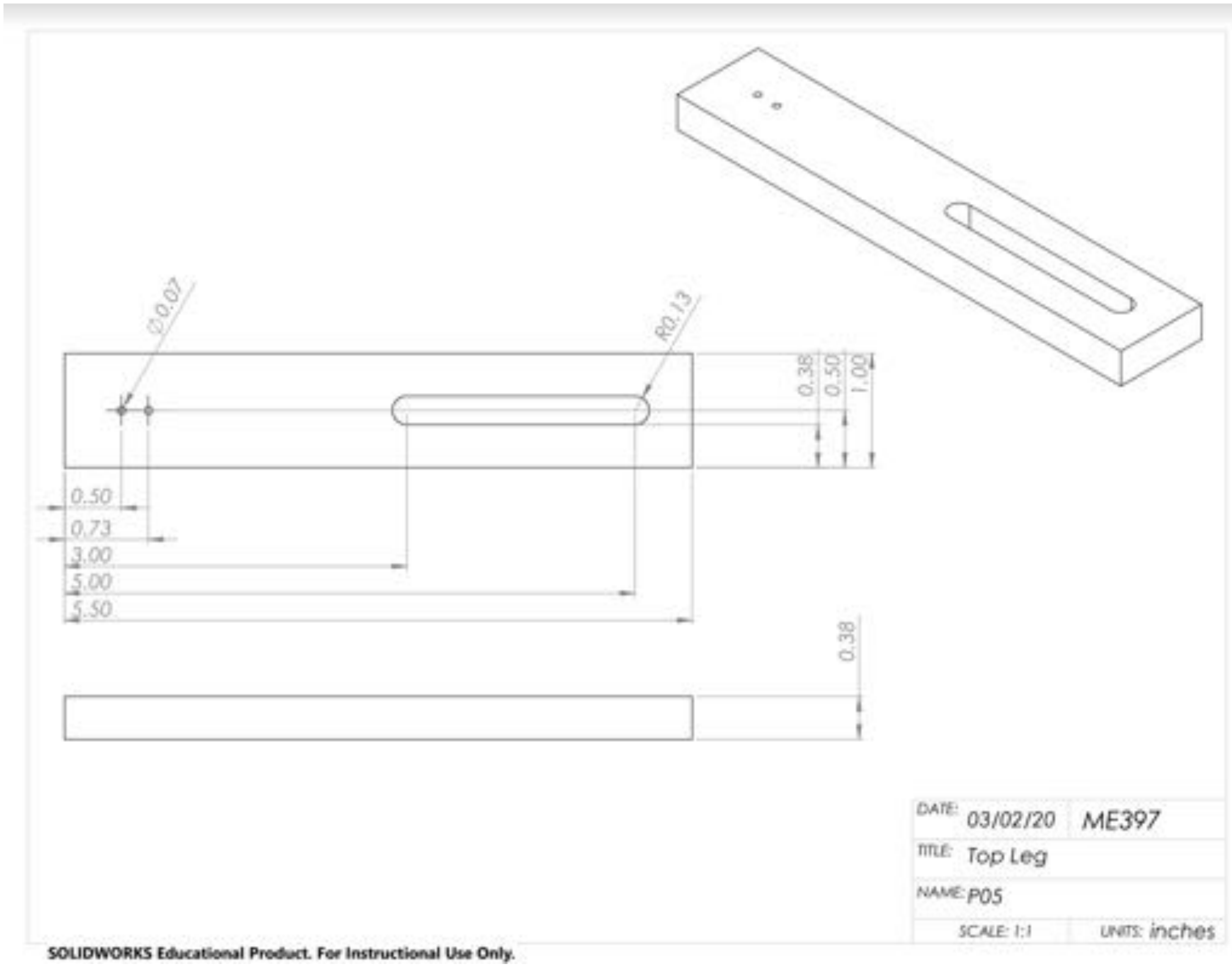


Figure 23. Drawing of the top leg for Model 1, Version 4

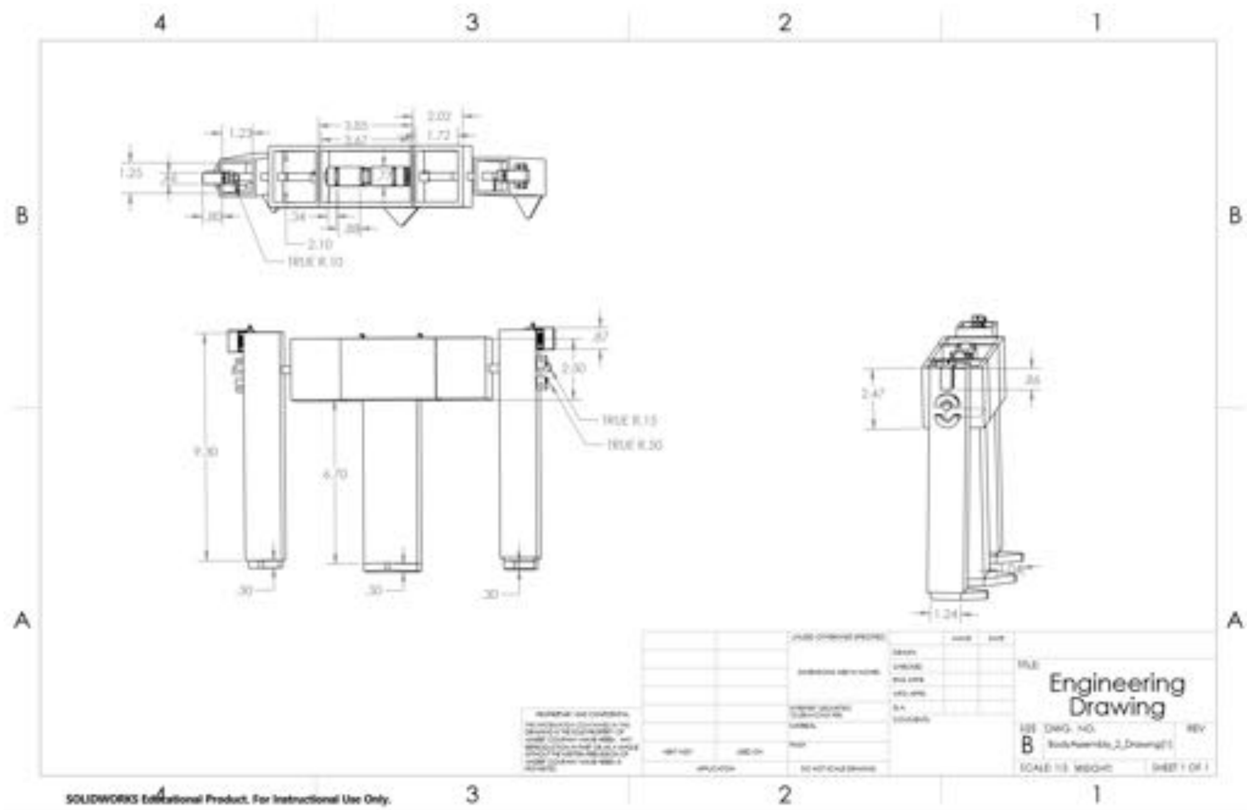


Figure 24. Drawing of Model 2

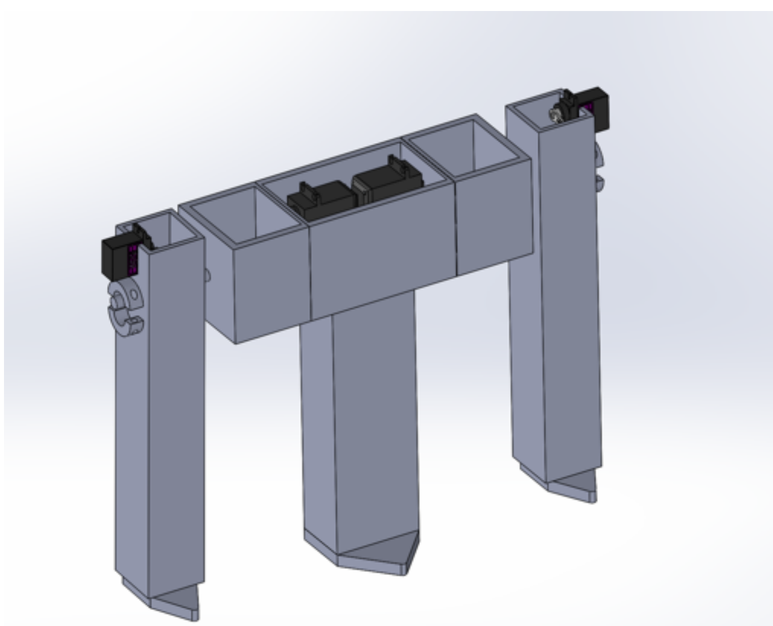


Figure 25. Isometric view of Model 2 solid model rendering

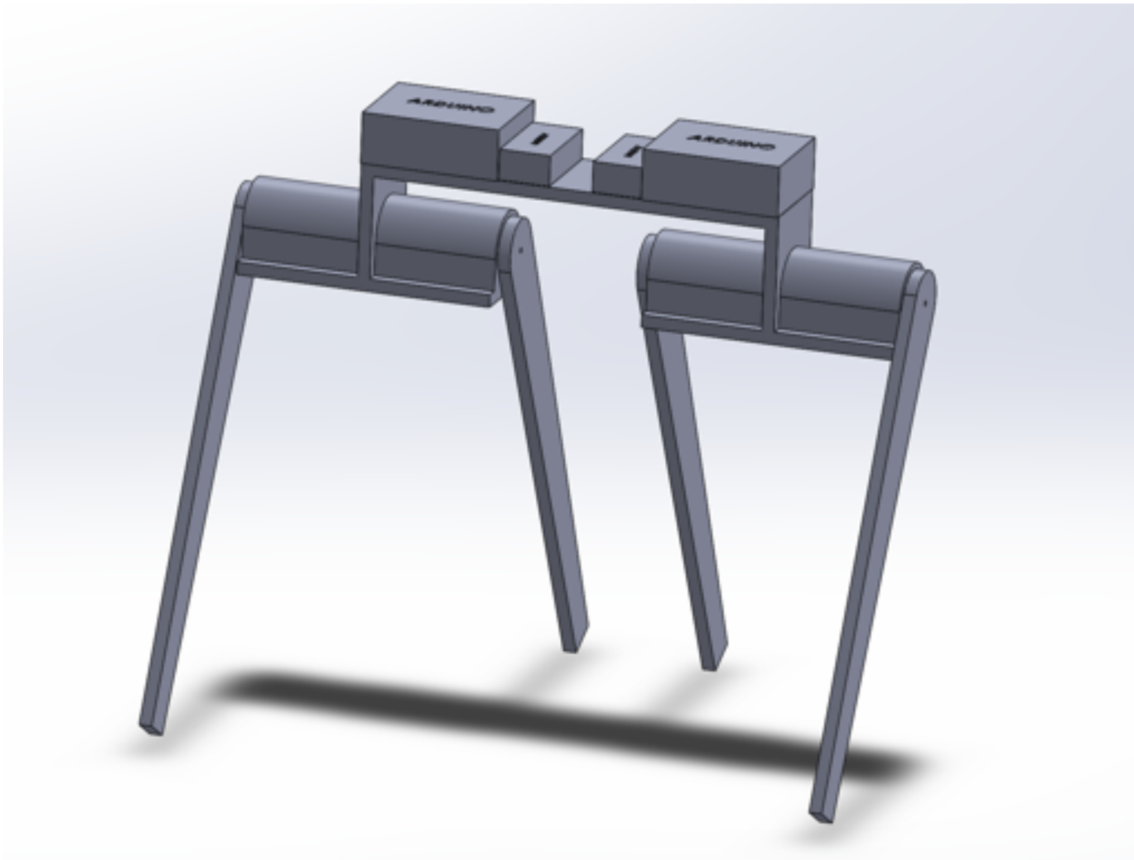


Figure 26. Solid model rendering of the original concept behind the Crutch design

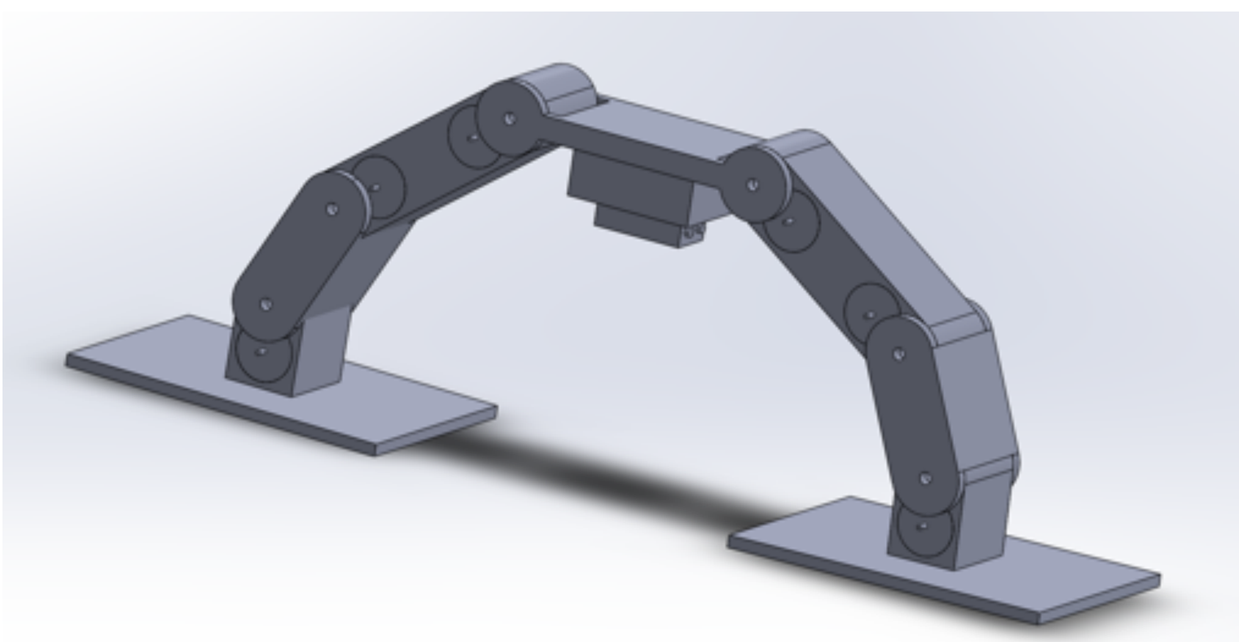


Figure 27. Solid model rendering of the original concept behind the Sidestep design

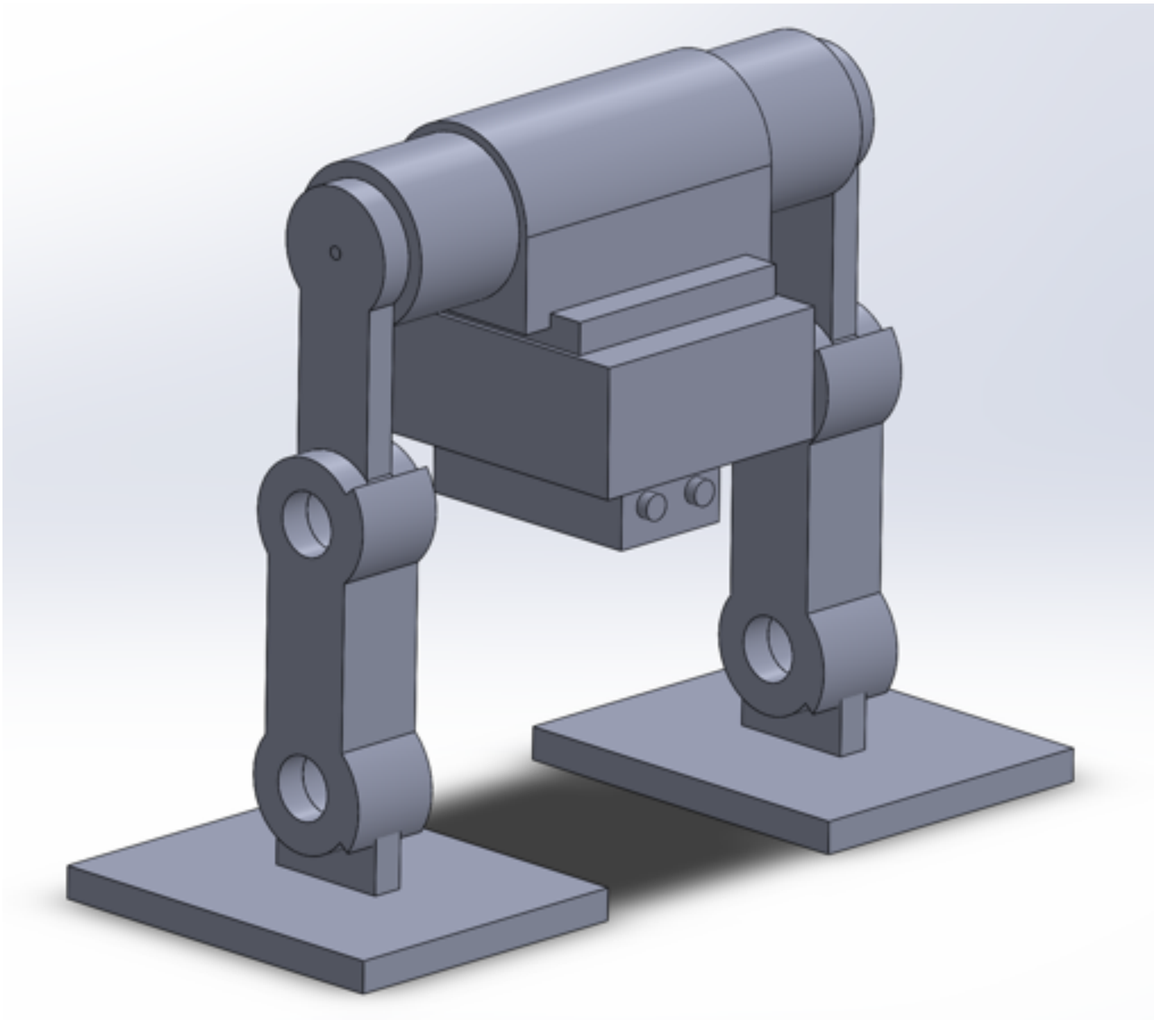


Figure 28. Solid model rendering of the original concept behind the Walker design

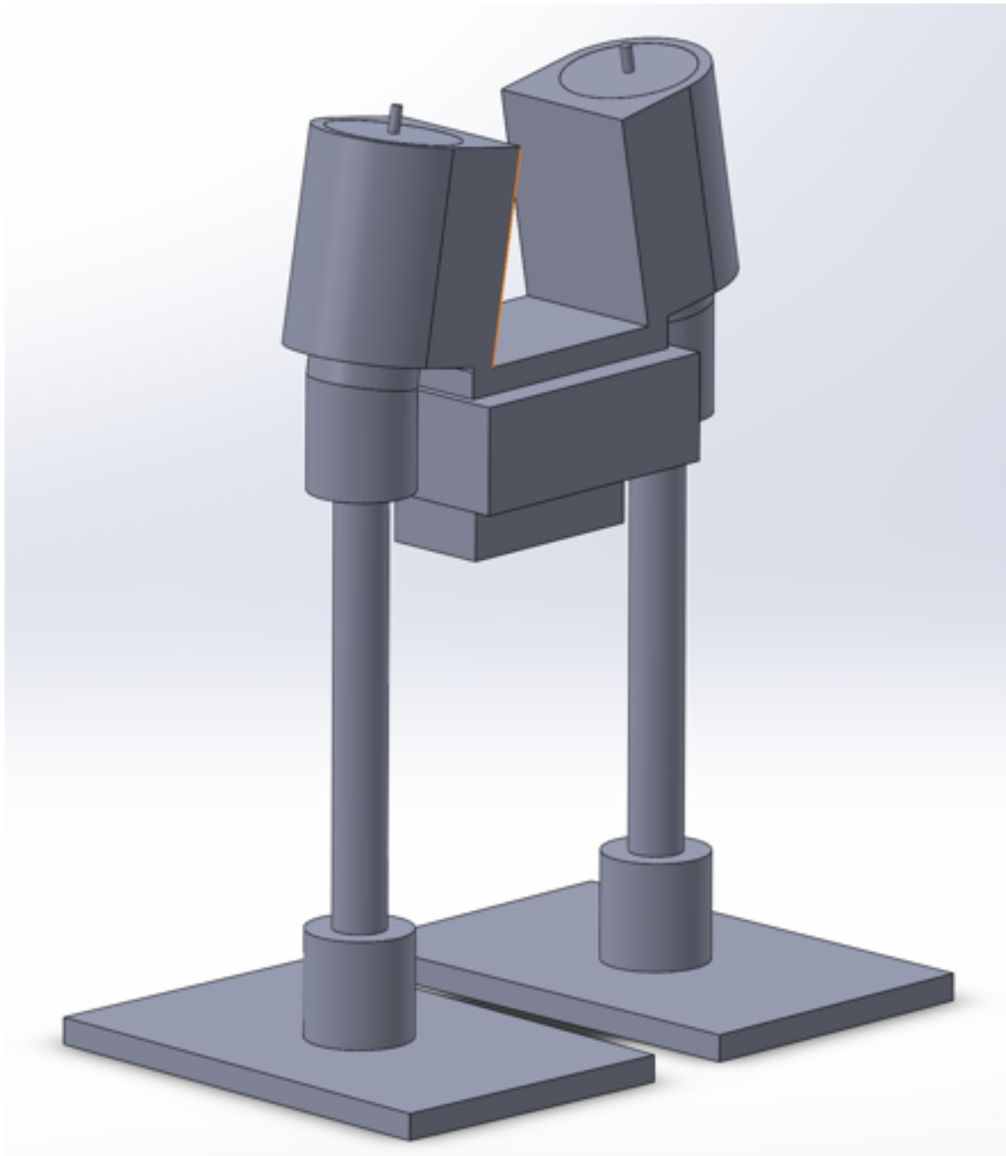


Figure 29. Solid model rendering of the original concept behind the Wobble design