Self-propelled Bouncing Spherical Robot

Undergraduate Honors Thesis

Presented in Partial Fulfillment of the Requirements for Graduation with Honors Research Distinction in the Department of Mechanical and Aerospace Engineering at The Ohio State University

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Abstract

Most robots that can travel on the ground are either traditional wheeled robots or legged robots. Exploring non-traditional novel robots may provide new solutions for locomotion not previously examined. Currently, self-rolling spherical robots have been designed and manufactured for hobbies, entertainment, or military uses. Similarly, various researchers have built legged robots that walk and run. Our objective in this research project was to design, build, and control a self-propelled bouncing and rolling spherical robot. While some self-bouncing wheeled robots have been built as toys, the self-bouncing spherical robot (one that looks like a ball) remains largely not explored. No one has produced a robot that can bounce continuously and can be steered without any external device to assist its movement. To achieve this goal, we plan to prototype up to three different mechanisms for bouncing. Each prototype would go through brainstorming, computer-aided design and simulation (of the bouncing), initial build, redesign, second build, and final analysis. We follow the classic design cycle: observe, ideation, prototype, and testing. We will also perform dynamic analyses of the robot to improve the design. This thesis reports on current progress towards these goals: we have designed and fabricated (and iterated) on a simple prototype bouncing ball, based on a spinning internal mass; we have performed some 2D and 3D simulations of the spinning mechanism that shows promise for the mechanism to produce persistent bouncing. Future work will consist of improving the current prototype, matching the computer simulations quantitatively to the prototype, performing design optimization and trajectory optimizations for optimal control, exploring other designs closer to hopping robots, and finally, building the ability to control and steer the robot.

Acknowledgments

I would like to first thank my research advisor, Professor Manoj Srinivasan for his belief in me and tremendous support in this research project. I really appreciate all of his guidance for both programming and prototyping on this project. It is because of his passion and enthusiasm that I can achieve so much in this project and win the finalist in the Denman Research Forum of the Ohio State University. Secondly, I would like to thank Kevin Wolf for his passionate assistance in manufacturing and his valuable knowledge of 3D printing and machining. I would also like to thank Chris Adam for his consultation with electronics and teaching for soldering skills and strategies. Thank you to Aaron Orsborn and all the student workers for assistance in Machine Shop. Thank you to Professor Ryan Harne for his suggestion for various learning resources. Thank you to Myungjin Jung and Kai for this assistant for debugging BLDC motors. Thank you to Zhiyi Jiang for his help with Simulink. Thank you to Zhihao Zhang for this consultant with the Lipo battery. Last but not least, I would like to thank the College of Engineering and Second Year Transformational Experience program for providing a substantial amount of fellowship for my research projects.

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Chapter 1: Introduction

1.1 Background Information

Animals of different kinds have different morphology to take advantage of different ecological niches in nature. Similarly, exploring new robot morphologies may help identify new robot capabilities. Here, we seek to construct a spherical bouncing robot. Many science anime, fiction, and movies have depicted versatile spherical robots, for instance, Haro in Gundam, BB-8 in Star Wars, etc (Figure 1.01).

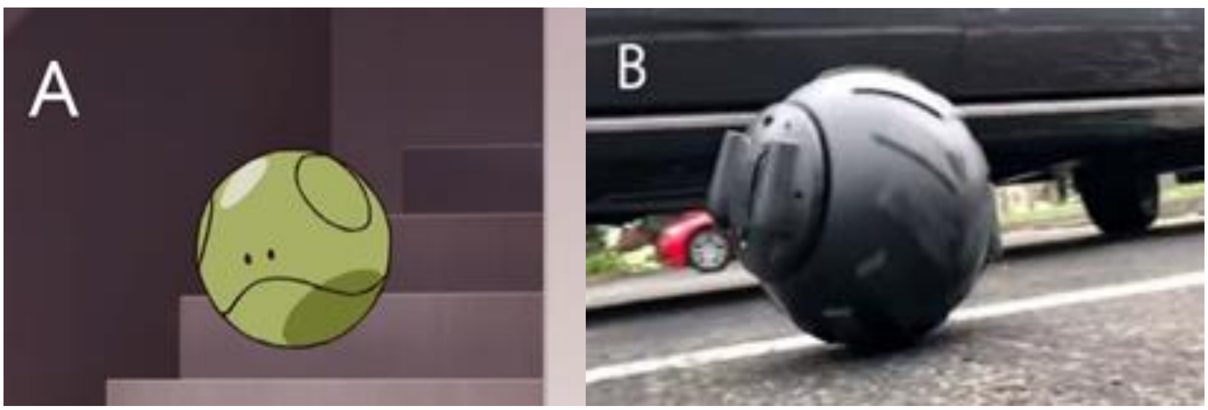


Figure 1.01: Fictional bouncing robots and real rolling robots. A) Haro robot in the Gundam series is an autonomous bouncing robot. B) Guardbot is a rolling robot used for surveillance. (GuardBot, 2018)

Here, our goal is to have a perfectly spherical robot with all mechanisms internal. Such a bouncing robot could, potentially, be more agile than a purely rolling spherical robot. The technical challenges will involve mechanical design, product development, and control system development. The primary challenge is leaping and steering of the robot with no mechanisms outside the spherical shell. My approach will be to test three different mechanisms for achieving bouncing: spinning masses, slider-crank mechanism, and a spring or a voice coil actuator. A spherical bouncing robot could be used in child daycare (as a toy), entertainment, surveillance, low gravity space exploration, etc. For instance, imagine a children's toy that just looks like an ordinary ball, but can be remote-controlled to start bouncing in place and then steering around while bouncing.

1.2 Purpose of the Study

1.2.1 Original Research Goals

We first describe ideal research goals we would pursue if we had sufficient time and resources. We envision a robot that has a relatively small size for easy storage and utility. We outline three different approaches to achieve self-propelled bouncing. For each approach, we will build computer models and perform optimizations of the controller to test feasibility. We will build prototypes of one approach, one for each approach. We will compare these prototypes along various factors to determine the best solution. Possible factors such as cost, reliability, easiness to maneuver, fabrication, and bouncing performance will be taken into consideration. Each prototype might be the best solution in a different situation and depend on the material and fabrication. My objective is new solutions for locomotion not previously examined.

1.2.2 Revised Research Goals

Due to limited time and resources, we now describe our revised research goals that take these constraints into account. Specifically, only one of the prototype ideas will be pursued by the author through multiple fabrication iterations. While the initial plan was to perform detailed trajectory optimization using 2D and 3D bouncing robot simulation, here we present progress toward such simulation but do not present progress on model-based optimization of the design. An improvised testing frame will be built to conduct testing and early results will be presented.

1.3. Design methodology

Multiple prototypes ideas will be designed. Each prototype will go through brainstorming, computer-aided design and simulation, dynamic analyses (MATLAB Simmechanics), initial build, redesign, rebuild, and final analysis.

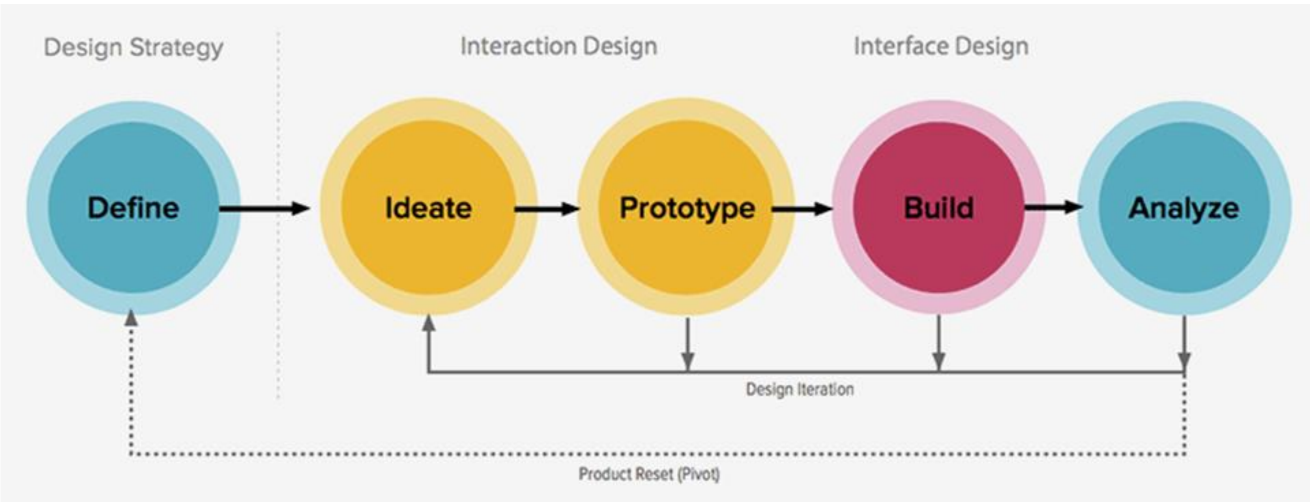


Figure 1.02. Classic design iteration cycle. (Image from Gao, 2017).

1.4 Significance of the Study:

It is important to explore such novel robot configurations as they may be more robust than either wheeled or legged robots. The potential advantages of such a robot have not been tested. The technical issues involved will challenge current design and manufacturing methods, as well as push the envelope of control methods, as 3D aerial control of a spherical bouncing robot has not been demonstrated yet (although we do not pursue 3D control here in this thesis).

1.5 Overview of the Thesis:

Chapter 1 discusses the goal, methodology, and significance of the project, including a brief literature survey. Chapter 2 discusses other related robots and inspirations from existing devices. Chapter 3 discusses the prototype ideas to achieve the goals. Chapter 4 discusses our attempts at fabricating a simple robot and our design iterations. Chapter 5 shows our road of building simulation models and designing optimization controllers. Chapter 6 concludes the thesis and outlines future plans.

Chapter 2: Other related robots and inspirations

In Chapter 1, I listed some robots that rolled or hopped. Here, I list a few other toys, robots, machines, or natural phenomena that provide further inspiration for our proposed device.

While doing research on previous spherical robots, I obtained a BB8 toy by Sphero and took it apart to get inspiration on the structure and mechanism design (Figure 2.01). One takeaway was that the structure in the bottom half of the robot was very compact and dense which results in the center of gravity of the robot being lower than the geometric center. This makes the robot's orientation stable wherever it goes. This asymmetry of the robot is also how it moves forward, constantly raising this mass to produce a forward moment.

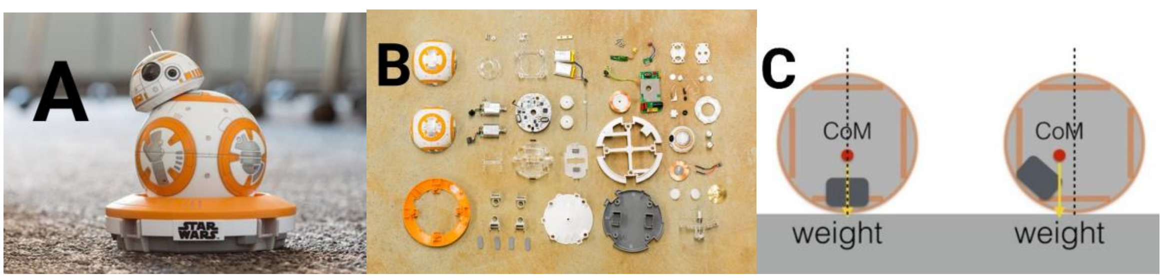


Figure 2.01: Sphero robot. A) Close up photo of Sphero BB8. Sphero BB-8 App-Enabled Droid (Torres, 2015). B). BB-8 Sphero Teardown (Evans, 2015). C) Physical diagram of the principle of the BB8 robot (Allain, 2015).

Researchers, industries, and hobbyists have made progress on achieving features such as rolling (Michaud. 2005), maneuvering (Lee, 2013), and transforming on a spherical robot (Muralidharan, 2015). However, there has been no substantial work on the self-bouncing feature for a spherical robot, which may be due to the difficulty of design, manufacture, and control. While there have not been any spherical bouncing robots, there have been some successful hopping robots with other morphologies. For instance, Salto (Figure 2.02A), a leaping robot from UC Berkeley (Yim, 2018), is able to use one leg to jump continuously and maneuver its jumping direction and ensure stable landing. The sand flea robot by Boston Dynamics uses a leg-like appendage to push-off and land with four wheels (Zhao, 2013). Figure 2.02 shows other hopping robot examples.

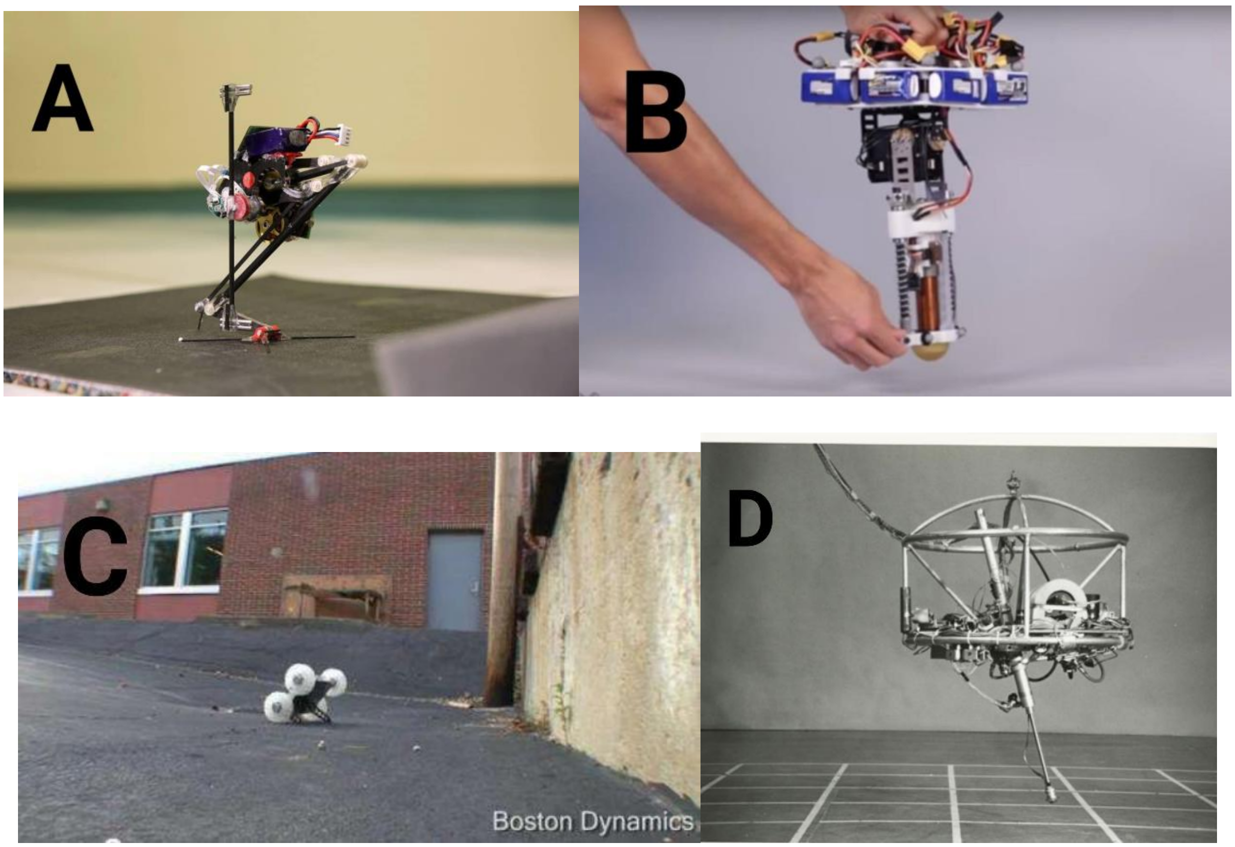


Figure 2.02: Previous jumping robots from other research labs. A) Salto from UC Berkeley (Yim, 2018). B) One-legged hopping in 3D using a linear elastic actuator (Batts, 2016).C) Boston Dynamics Sand Flea (Owano, 2012). D) 3D One-Leg Hopper by MIT Leg Lab uses one spring leg to hop instead of walk (MIT Leg Lab, 1983-1984).

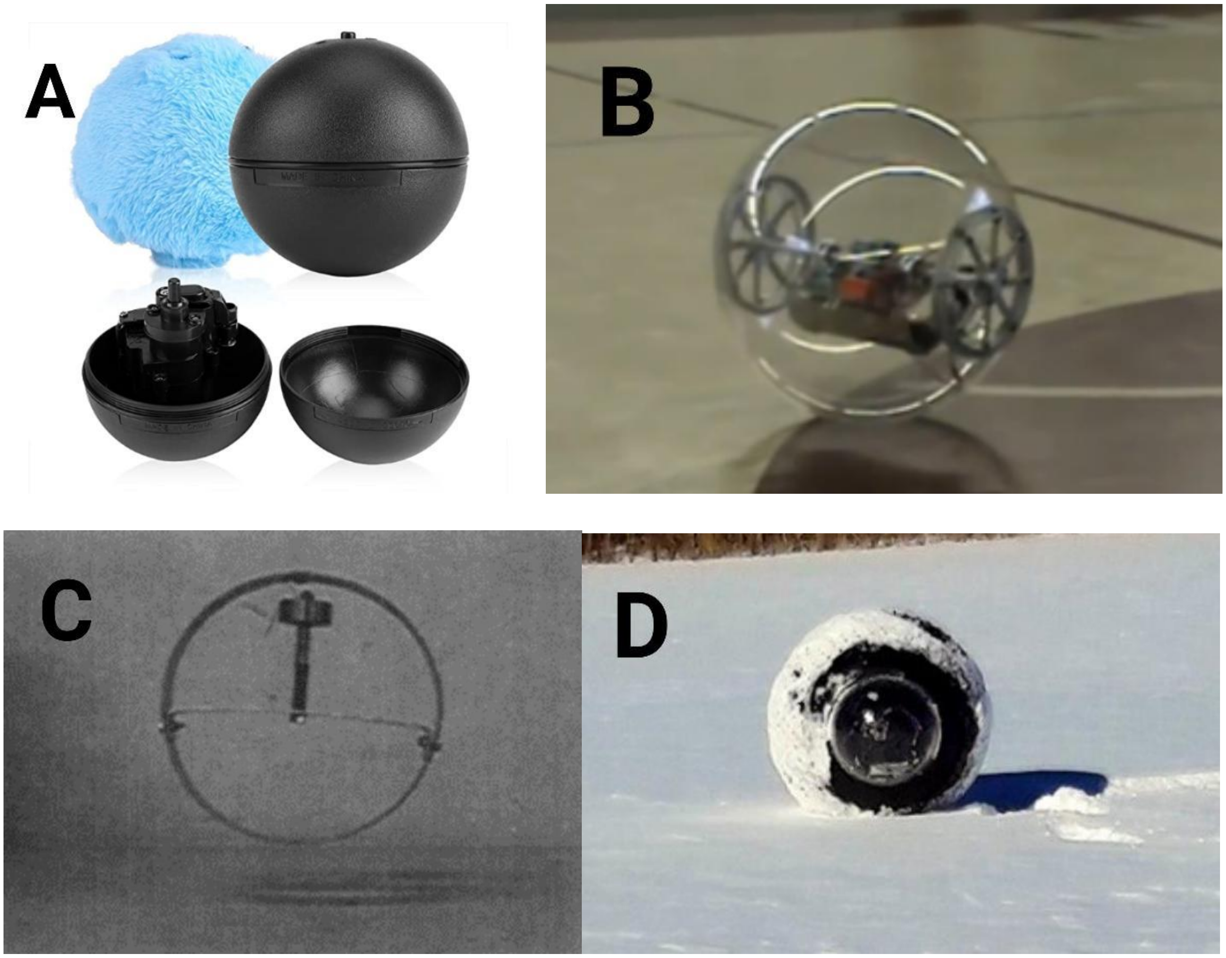


Figure 2.03: Previous projects or products on market or by students. A)Automatic dog ball & sweeping robot. (Amazon) B) Spherical Rolling Robot. (Carabis, 2013). C) Research on the climbing and jumping off a spherical rolling robot (Wang, 2007). D) Police Guard ball robot (Wang, 2016).

Figure 2.04: A) Jumping Sumo front view (Amazon). B) Jumping Sumo back views (Goldman, 2014). C) Jumping Sumo cam mechanism (Parrot. 2014).

Figure 2.04 shows a jumping robot called the Jumping Sumo, which I took apart to study its mechanism. It uses a cam and spring coil to exert a tremendous amount of pushing force on the ground in a glimpse which pushes the robot upward (Figure 2.04C). This cam mechanism could be adapted by the third prototype idea to be discussed in Chapter 3.

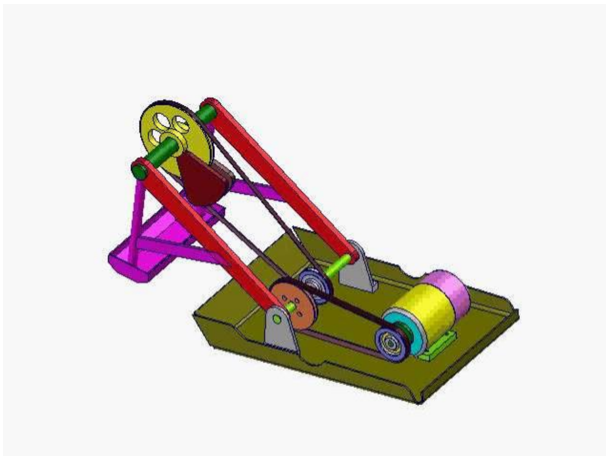


Figure 2.05: The mechanism in the soil compactor is later one my inspiration for prototype ver.2.0 (MachineTo).

Figure 2.05 shows an old-fashioned soil compactor and whose mechanisms could be adapted for a spherical bouncing robot. It uses belts to lower down the speed and increase torque. It also has a flywheel with a huge off-centered mass on one side. With the spinning of the flywheel, the moving part of the compactor can jump continuously which strikes and firms the soil.

Figure 2.06: Jumping toy.

Figure 2.06 shows a jumping toy, which uses wired plastic to create a spring that is lightweight and bouncing performance. After sufficient compression and release, the toy could jump up to one meter. The wired spring part can perhaps be potentially added to the spherical bouncing robot design, either as an internal mechanism or as something that provides springy contact with the ground.

Figure 2.07: Anti Gravity wheel. (Veritasium, 2014).

Figure 2.07 shows the principle of gyroscopic stabilization due to a fast-spinning object: principle behind this is (roughly) the conservation of momentum which could be used to stabilize the robot.

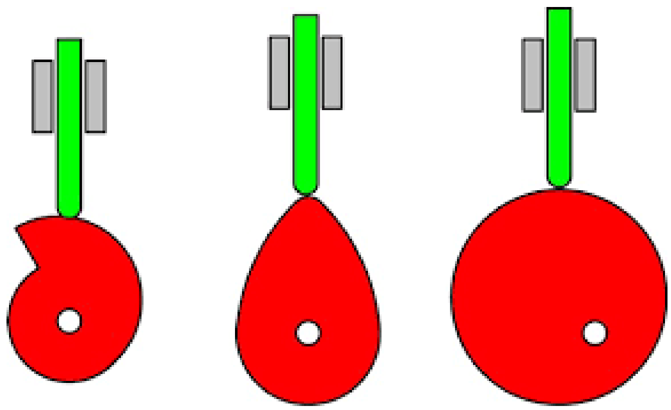


Figure 2.08: Cam mechanism with different cam shape to produce different follower movement. (Image from eduqas.co.uk).

Figure 2.08 shows a few cam mechanisms that can be a good solution to translate rotational motion into linear reciprocating motion (instead of the slider and crank mechanism as suggested in Chapter 3).

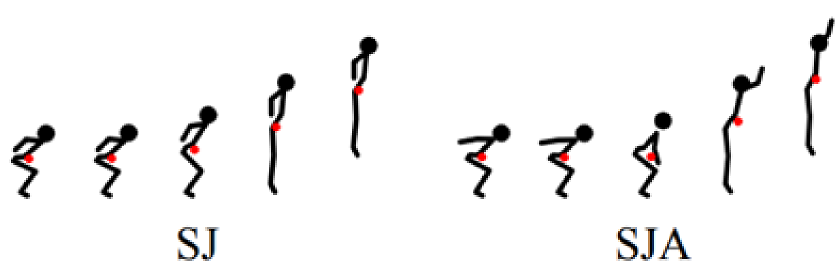


Figure 2.09: Effect of jumping height due to the swing of arms (Hara, 2006).

In the tumbling class I was taking at the Ohio State University, I realized that swinging arms can help with hopping both vertically and horizontally. Analogously, ancient Greek long jumpers used dumbbell-shaped weights called ‘halteres’ to help them with long jumps (Minetti, 2002). Such swinging of arms or additional masses is analogous to mechanisms that I am proposing in chapter 3. Further, there is a substantial biomechanics literature on `countermovement jumps’, which may also be relevant in our robot design (Harman,1990).

Finally, we note that in a passive eccentric disk or sphere (a single rigid body), given the right spin, can bounce persistently on a rigid frictionless surface, as can an an ellipsoid on a no-slip surface (Ruina et al, 2005), by avoiding collisions by rotations. However these passive motions were not stable (Ruina, Stiesberg, unpublished observations).

Chapter 3: Three basic designs: Brainstorming and Design

In this brief chapter, I propose and discuss three mechanisms that might be used to produce persistent hopping or bouncing in a spherical robot. While other mechanisms may be feasible as well (e.g., see Chapter 2), these are the primary mechanisms we initially proposed to study.

Prototype Idea 1. Pure planar rotation of an internal off-centered mass in a vertical plane such as in a vibration motor (Figure 3A). Pros: Potentially easy to fabricate and build. Cons: Cannot move in the desired direction and the center of mass is not near the center. Further, it may be harder to decouple forward motion and bouncing in this design. In any case, this is the design we pursue in this thesis: see chapter 4 for prototypes.

Prototype Idea 2. Slider and crank mechanism to move an internal mass in a linear reciprocating manner. Pros: Easy to fabricate and build. Can move in the desired direction. Center of mass near the bottom which will make the gadget stay stable inside the ball. Cons: The friction may slow down the movement of the weight. Instead of the slider crank, we can also use other mechanisms to move the reciprocating mass. E.g., a cam (as noted in Chapter 2) or using directly linear electromagnetic motors (Spring and electromagnetic voice coil, as in idea 3 below.).

Prototype Idea 3. This idea allows for reorienting the line or plane of action of the internal mechanisms in ideas 1 and 2, and this reorientation can be either active or passive. Pros: Can potentially jump in a certain direction. With the wheels on the side of the plate touching the inside wall of the ball, the gadget could stay stable inside the ball. Cons: Not easy to fabricate and build. Need to design the mechanism to auto-reload. Need a strong spring to ensure enough speed of the weight.

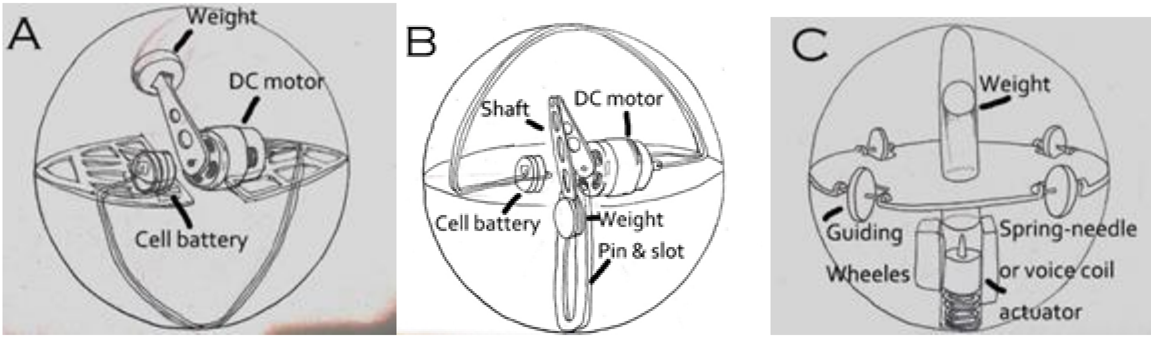


Figure 3.01 A) Prototype 1 concept sketch. Pure rotation vertically. B) Prototype 2 concept sketch. Slider & crank mechanism. C) Prototype 3 sketch. Spring or magnetic coil, with potential reorientation of the plane perpendicular to the prismatic motion.

For each of these three proposed designs, we will follow the steps outlined below: (1) Sketch basic form of the prototypes on a sketchbook. (2) Build Solidworks models to create parts and structure of the prototype. (3) Use Simmechanics to simulate the movement of the prototype. (4) Build prototypes using bought parts, machined parts, and 3D printed parts. (5) Testing the performance of the prototype. (6) Write down basic properties, examine if the prototype satisfies criteria, and analyze the strength and shortcomings. Of course, as noted, we primarily pursued prototype idea 1 in this thesis.

In prototype idea 1, superficially, we have drawn the center of the spherical shell and axis of rotation of the spinning pendulum to be coincident. This need not be the case and their relative positions could be a design parameter to be optimized.

Chapter 4: Fabrication and design iterations

In this chapter, I describe my attempts at designing and fabrication of a working prototype of a bouncing ball robot, describing multiple iterations (versions) of design and fabrication over the last few months. The current bouncing ball device as of the writing of this thesis is shown in Figure 4.01. The organization of this chapter is roughly in chronological order of the full prototype, while on hind-sight, we acknowledge that an alternate effective way of organizing the chapter could be in terms of the progression of the individual components of the device.

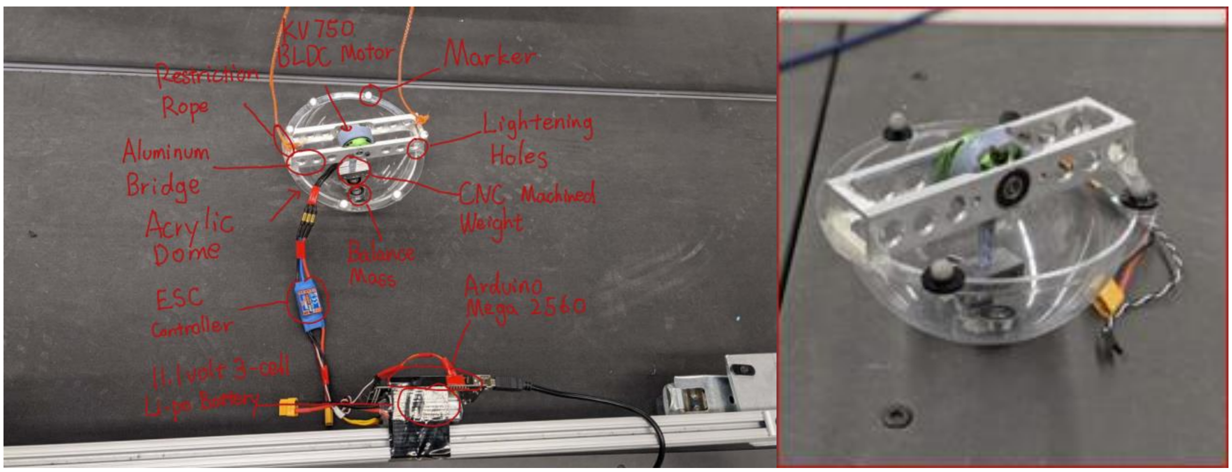


Figure 4.01. Bouncing ball robot. It contains a plastic spherical shell, to which is rigidly attached a steel bridge roughly along a diameter. The steel bridge carries a BLDC motor that spins a heavy pendulum and this spinning lifts the ball off the ground.

4.1. Prototype version 1.0.

Figure 4.02: Transparent plastic dome.

Initially, for the spherical shell, I chose a transparent Christmas decoration ball. It is lightweight and designed to be easily opened and closed. However, it was later proved by experiments that the Christmas material and structure were not sturdy enough to withstand violent continuous bouncing.

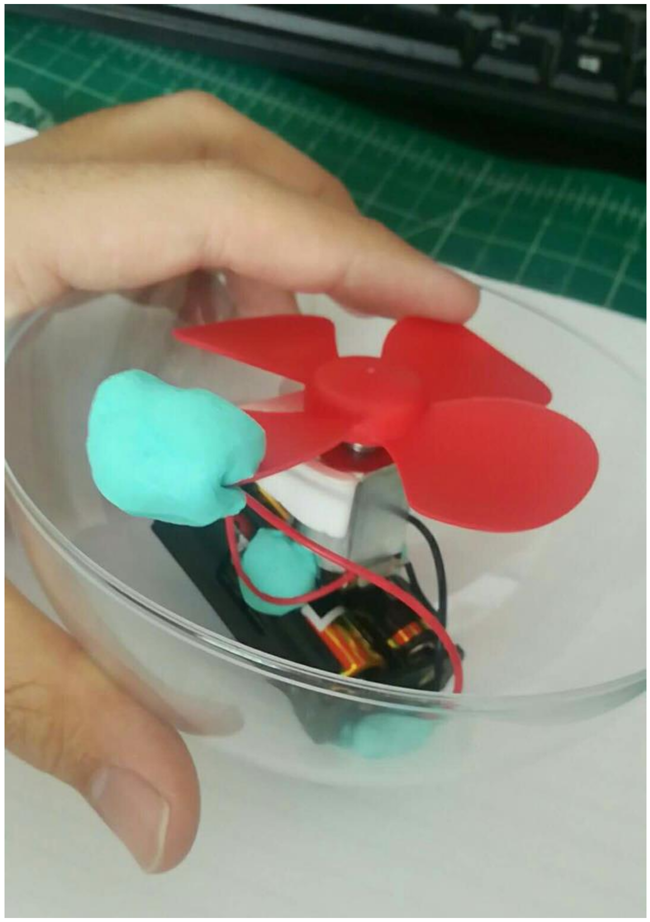


Figure 4.03: Rough initial build of version 1.0.

The first version of the prototype was made with off-the-shelf parts (Figure 4.03). The other half of the ball was taken off to show the inside structure more clearly. The off-centered mass was a gum called Blue Tack. The robot was powered by two AA batteries and the fan was actuated by an inexpensive brushed DC motor. This prototype failed to meet any goals and did not look promising. The system was too heavy relative to the off-centered mass and the fan spinning axis was not parallel to the ground. The ball did not rise off the ground but rolled erratically. This failure suggested that we needed to design and fabricate customized high quality parts.

4.02. Version 2.0.

4.02.01. Design of the Internal Structure.

Using SolidWorks, I designed a few preliminary representations of some of the parts for the robot, shown in Figures 4.04 to 4.06.

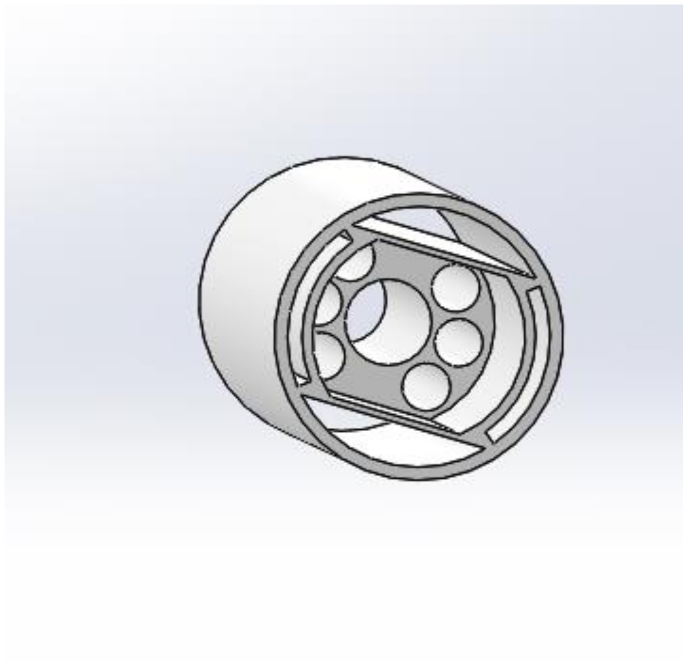


Figure 4.04: Structure to hold up the motors.

Figure 4.04 structure is designed to hold the motor in place. However, it was discarded for its complexity to fabricate.

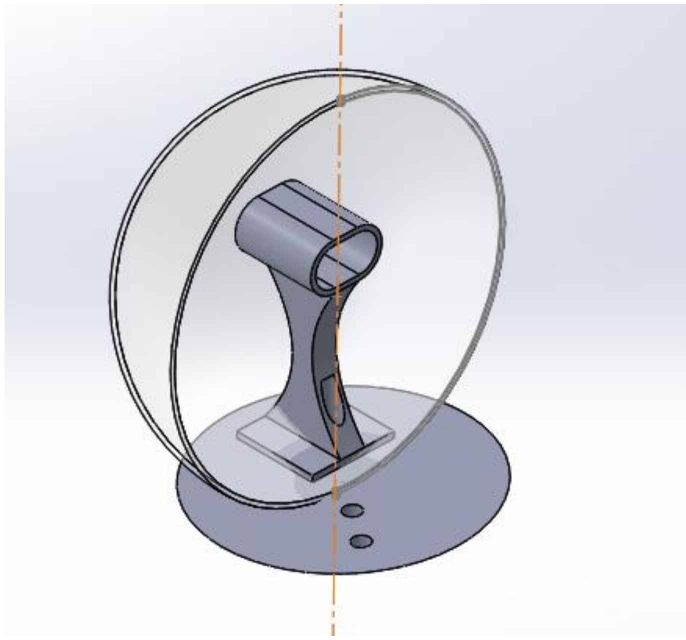


Figure 4.05: Design to lower the center of gravity.

Next, Figure 4.05 shows a concept design to have the center of gravity of the whole system lower than the geometric center of the spherical shell. One key aspect of the design was to use a convex base that fit with the curvature of the inside of the sphere (need to see Figure 4.05 from bottom up to see this). This convex not only provides stable support but also moves down the center of gravity of the whole system. Although this exact design was discarded for its complexity, the idea of using a spherically shaped mass stuck to the shell was used to lower the center of gravity of the robot.

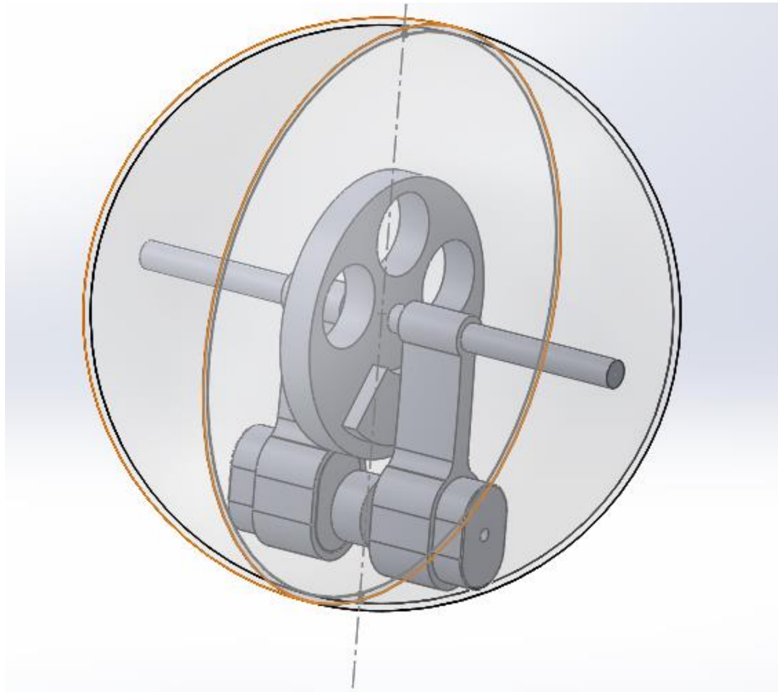


Figure 4.06: Rough concept design with the transmission mechanism adapted from the soil compactor.

Figure 4.06 shows a concept design to use the motor both as actuation and balance weight to lower the center of gravity. The big flywheel in the middle is attached with an off-centered mass and the flywheel was hollowed-out by some lightening holes. This mechanism and part design is derived from the soil compactor described in Chapter 2. It’s feasibility was validated by Solidworks animation and redesigned with more detail as in Figure 4.07.

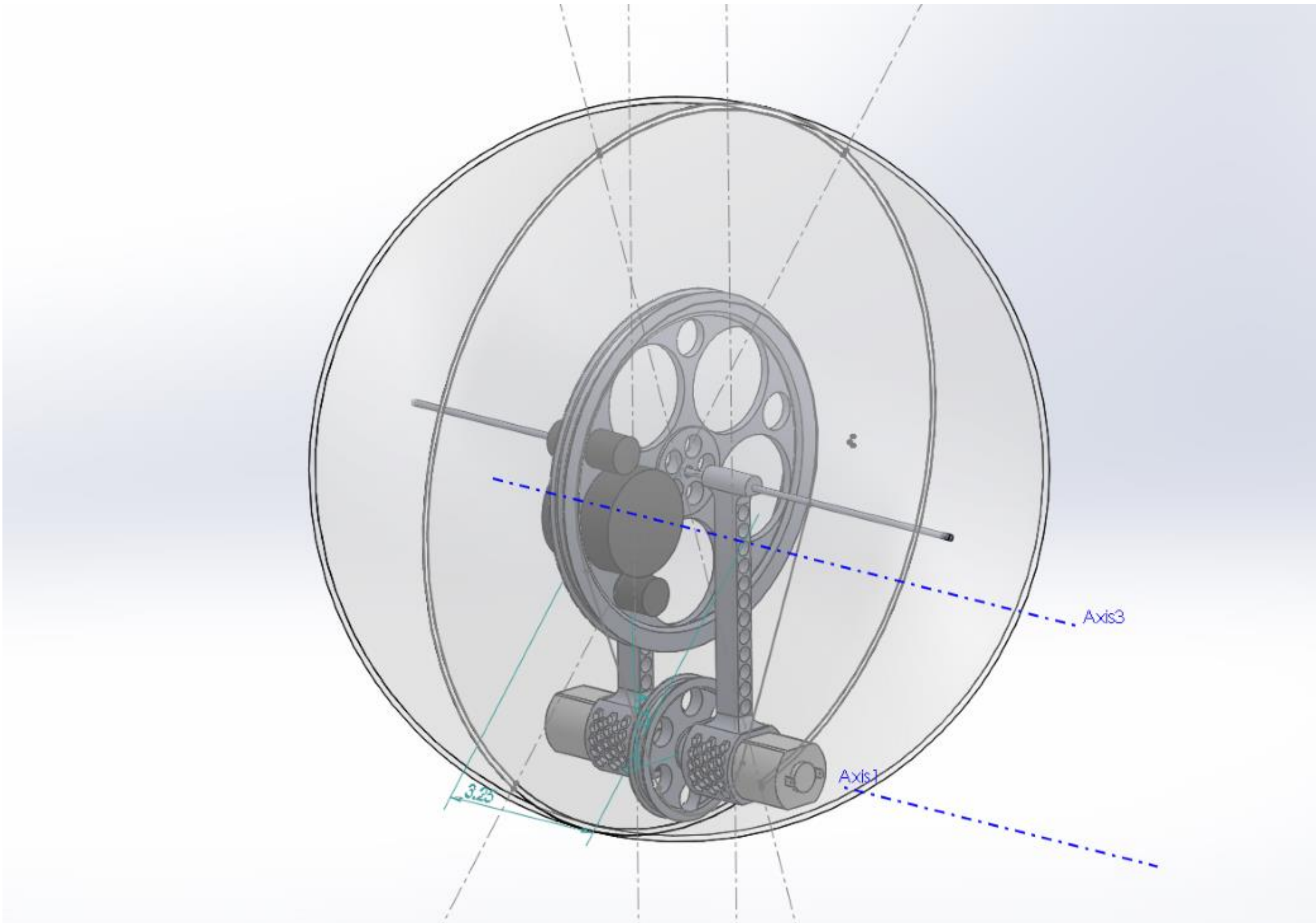


Figure 4.07: Detailed model with measured dimensions.

Figure 4.07 is a design based on measurements from existing parts we used. Each designed part had lightening holes of possibly different kinds with the intention of reducing weight while maintaining structural strength. The holes were added based on intuition and a formal structural strength calculation was not performed. After validating the fit and kinematics by SolidWorks animation, the model file type was then converted ready for 3D printing.

4.02.02. 3D Printing the Internal Structure

Figure 4.08: Anycubic photon 3D printer and SLA resin used in this project.

After some research and consultation from professionals, I chose an SLA resin-based 3D printer, namely Anycubic Photon (Figure 4.08), that was thought to be precise, reliable, and affordable for our purposes. The reason for choosing SLA over traditional FDM filament printing is due to the complex shapes of the parts I designed. The size of each part also requires the printer to print small-scaled details that FDM printers may not be able to achieve. However, due to the lack of initial experience with SLA resin 3D printing, a number of problems had emerged in the printing process.

Figure 4.09: Poor 3D prints: Initial print of the driving wheel with horizontal placement on the printing bed.

Figure 4.09 shows one of the parts I printed initially. The part was oriented in the vertical direction during the print because it reduces the overall distance from the printing bed and thus saves printing time and material. This print orientation works fine for relatively small parts except for the 1 mm hole in the middle of the wheel that was clogged by the excess resin during the curing process. The clogged hole was fixed by drilling the hole in the machine shop but it was later discovered that the friction between the hole and the pin was not enough which caused the motor to spin without carrying the wheel (it was not a sufficient interference fit).

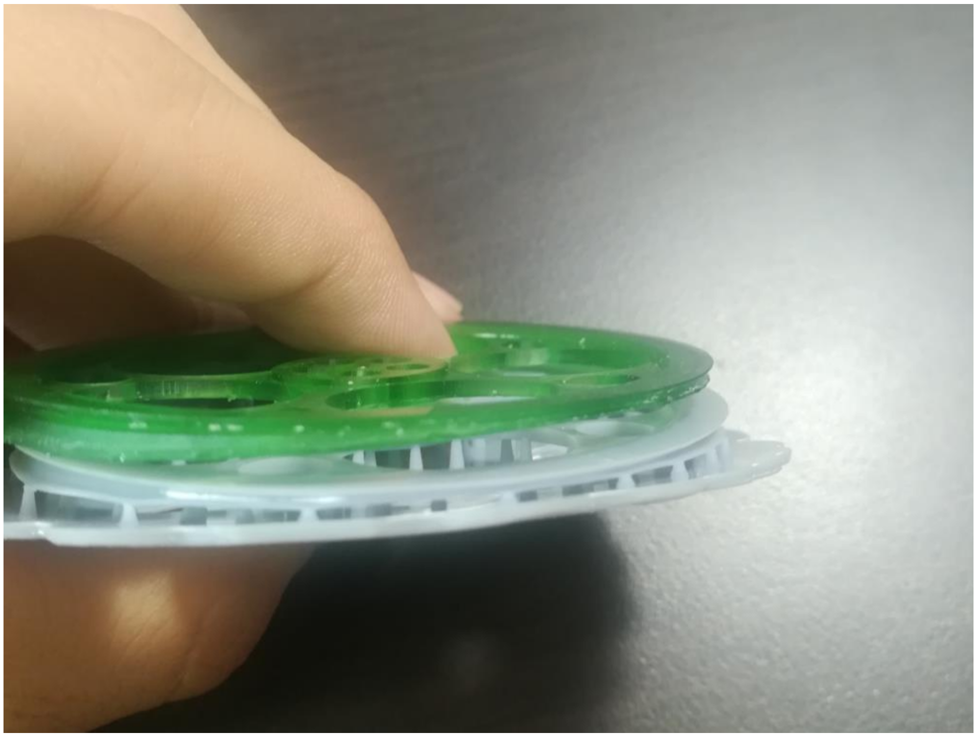


Figure 4.10: Poor 3D prints: Shrinking and warping of the large parts when placed horizontally on the printing bed.

Figure 4.10 demonstrates a major issue that I encountered when initially printing larger pieces, relating to shrinking and warping of the printed parts. It was then that I learned about printing orientation strategy. While the software for AnyCubic printer (AnyCubic Photon Slicer) did not have an auto-orient feature, I used the PreForm software from Form Labs to auto-orient my parts and then transferred that auto-orientation to the AnyCubic software. Although accurate orientation couldn't be obtained, close approximate orientations are enough to obtain prints with a high successful rate. The auto-orientation uses a printing strategy that orients large, flat parts by inclining them by 10–20º to increase the printing success rate substantially. This strategy works due to reducing the surface area of each layer which also decreased the amount of contact the print has with the resin tank (see Figure 4.11). If the surface area of each layer is too large, the print will likely to stick with the resin tank thus peeling off or falling from the printing bed.

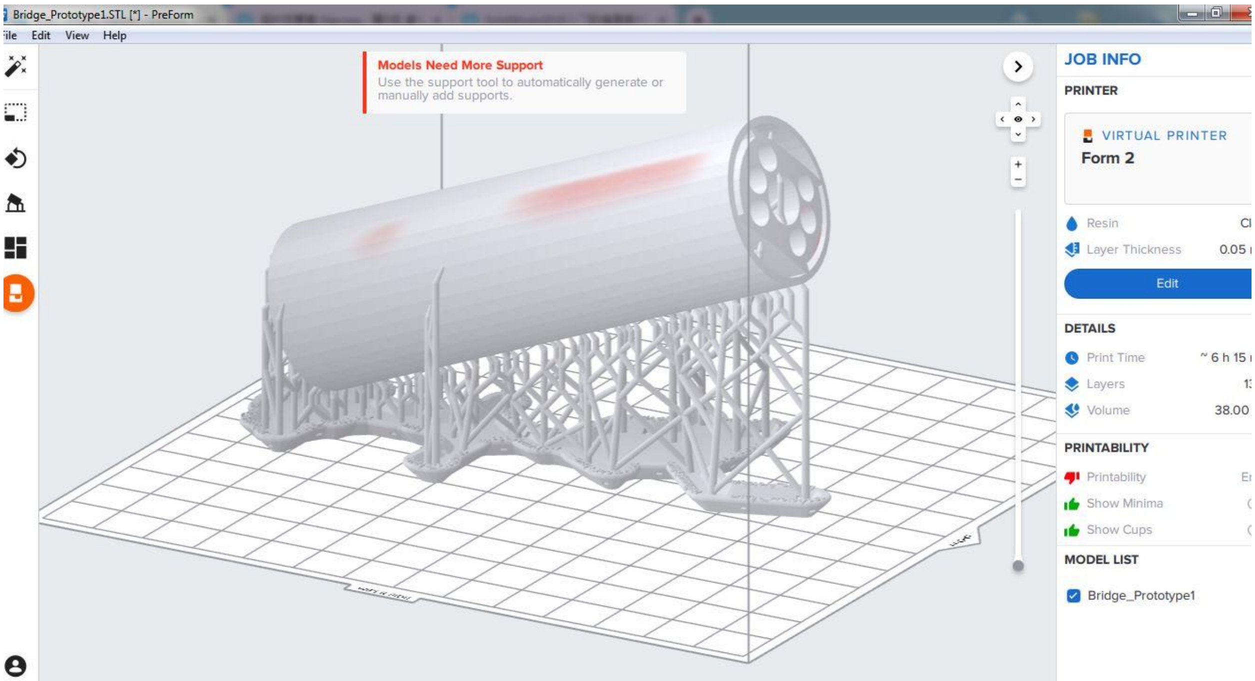


Figure 4.11: Preview of PreForm interface (software from Form Labs)..

Moreover, after perfecting and practicing good printing procedures and strategy, the printer was able to print large solid prints like the one below (Figure 4.12). With good printing practice, the designed parts are successfully printed and assembled with existing parts like motors.

Figure 4.12: Close up photo of a large piece of print just after the printing process.

Figure 4.13: One of a few successful parts with very small details.

The motor I bought was an N20 DC motor. This DC motor has a larger power vs. weight ratio than a regular DC motor. Figure 4.13 shows the motor along with the pendulum part it is attached to. The grid size on the printed part (Figure 4.13) was in millimeter-scale, but the printer was still able to print and maintain its integrity

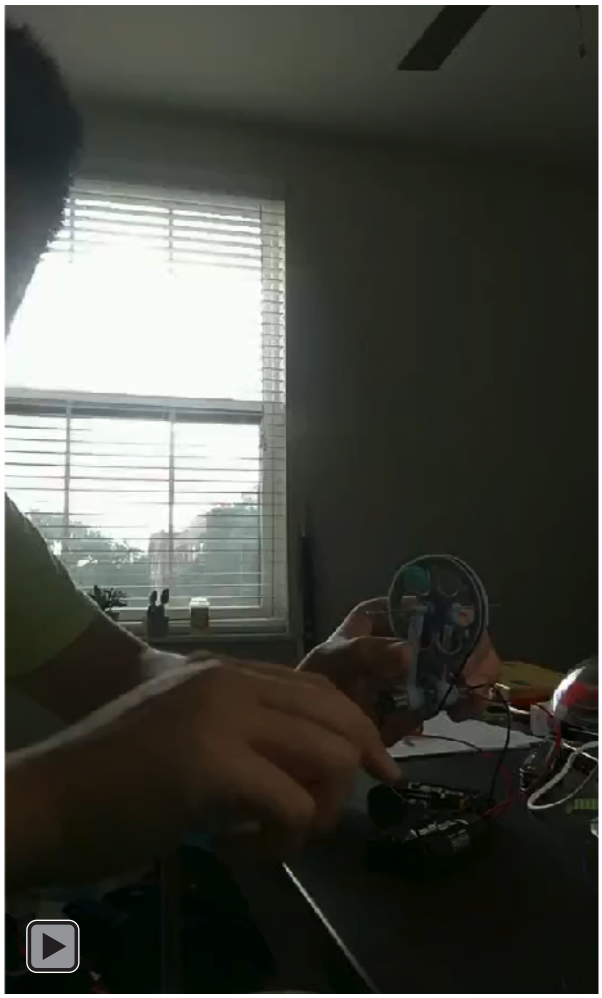


Figure 4.14: Testing the core mechanism.

Due to the resin curing process by ultraviolet light, the print will shrink in some areas afterward. Therefore, I experimented with the tolerance of the sizes of holes in order to let it fit with existing parts. Then two types of support structures were printed to test the performance of the machine without putting it into the ball.

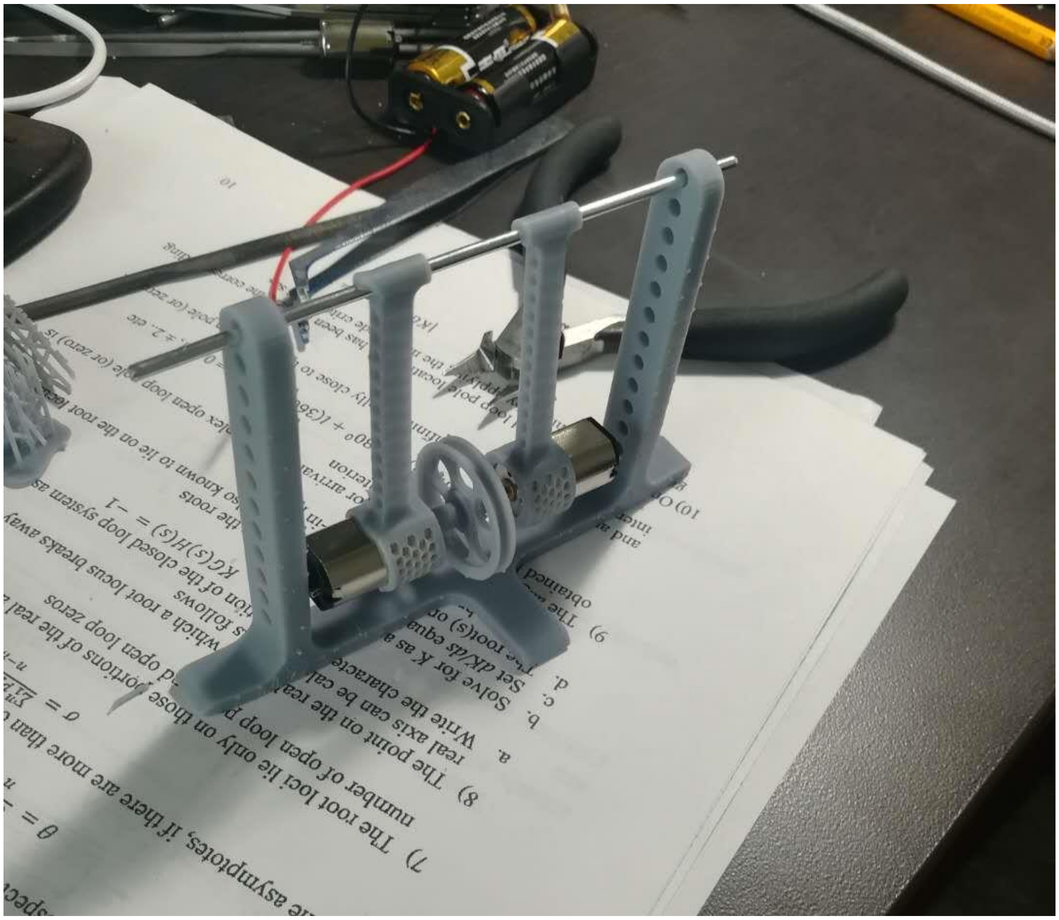


Figure 4.15: Flat support for the transmission mechanism.

To test this possible spinning solution, I built a simple support instead of a ball (Figure 4.15). This support structure has a flat bottom to stabilize the base. The purpose of this support is to hang the transmission mechanism and see how much oscillatory force can exert. In testing, the oscillatory forces looked promising, qualitatively but suggested a modified support structure.

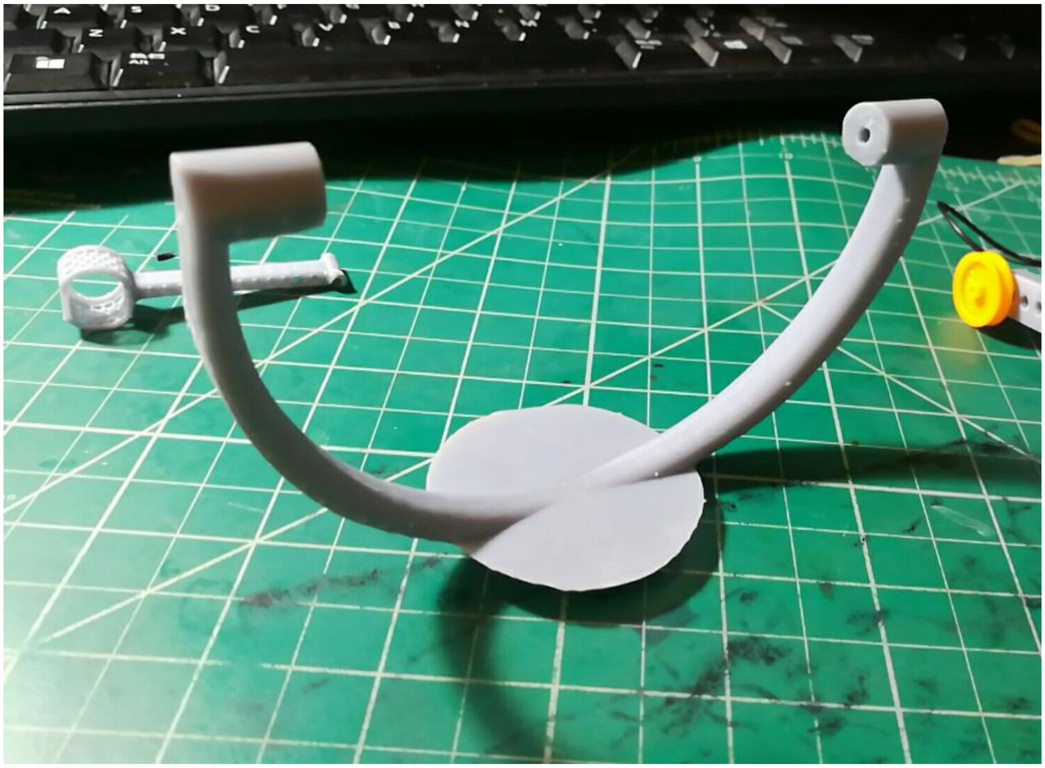


Figure 4.16: Round support to simulate spherical contact without the outer ball.

Figure 4.16 shows a modified support structure. The idea is derived from the previous design which has been discarded before the fabrication phase. The bottom has a domed shape to imitate the contact surface of the sphere. There are two ends to hang the transmission mechanism. In testing, the whole system couldn't have enough bouncing due to too much excess dead weight of the system. Moreover, due to the friction between the belt and the spinning wheel, a lot of torque and speed is wasted. Therefore, this design was put aside and will be redesigned afterward. The prototype version 2.0 was never fully put together, but we limp the various design ideas expressed in this section as version 2.0.

4.04. Prototype Version 3.0.

Due partly to the complexity and poor robustness of the designs in version 2.0, after discussions with my advisor Professor Manoj Srinivasan, I switched back to the initial idea of a simple spinning mass for prototype version 3.0.

4.04.01. Further Candidates for the Outer Shell

Figure 4.17: Metal wire cage.

Figures 4.17 to 4.19 shows a few potential alternatives I considered for the spherical shell. The metal cage ball that was light and robust, but was not chosen due to not having enough material for attaching other parts. The wiffle ball (Figure 4.18) suggested by Professor Ryan Harne seemed to have a material and shape that is good for the outer shell. However, since the balls found on the marker were all too small to fit anything else for simple prototyping..

Figure 4.18: Wiffle Ball.

Figure 4.19: Acrylic dome (Duradom/Catlabs 150 mm dome).

Figure 4.19 shows an acrylic dome (suggested by Kevin Wolf) that is lightweight and durable. This dome is used in some backpacks designed to carry cats (and the dome serves a porthole for the cat). Due to its cat-related purpose, the dome is also anti-scratch. I ordered a few different sizes and ultimately chose a 120 mm diameter acrylic dome for the spherical shell.

4.04.02. Assembling version 3.0.

Figure 4.20: Prototype Version 3.0.

Our design for prototype version 3.0 has a lightweight bridge to hold up the motors (Figure 4.20). We used a small brushless motor (company name?). Because of the limited power and a sideways roll balance problem with just one motor, I designed two slots on both sides of the bridge to double the power and balance the robot. The swinging pendular arm is a standard LEGO part (Figure 4.30). The off-centered mass is made of a few metal washers and nuts. The motors could spin apparently synchronously at high speed with relatively small weight but stop occasionally when bigger mass is attached. When spinning at high speed, the sphere was able to leave the ground by around 3 mm which was promising but perhaps not significant enough.

4.05. Prototype Version 4.0

In order to achieve higher bouncing, the next step was to upgrade each component. The most obvious problem with the previous prototype is the motors' ability to swing large masses. To have motors with relatively large power vs. weight ratio, we settled on brushless DC motors (BLDC motors). The Salto, the jumping robot by UC Berkeley, used a small BLDC motor Scorpion S-1804-1650KV. We initially chose the exact same motor for our bouncing ball (Figure 4.21).

Figure 4.21: Scorpion S-1804-1650KV Brushless DC motor.

Our approach was to control the BLDC using Arduino through an ESC (Electronic Speed Controller), with a11.1 volt 3-cell Lipo battery providing the necessary power to the motor.

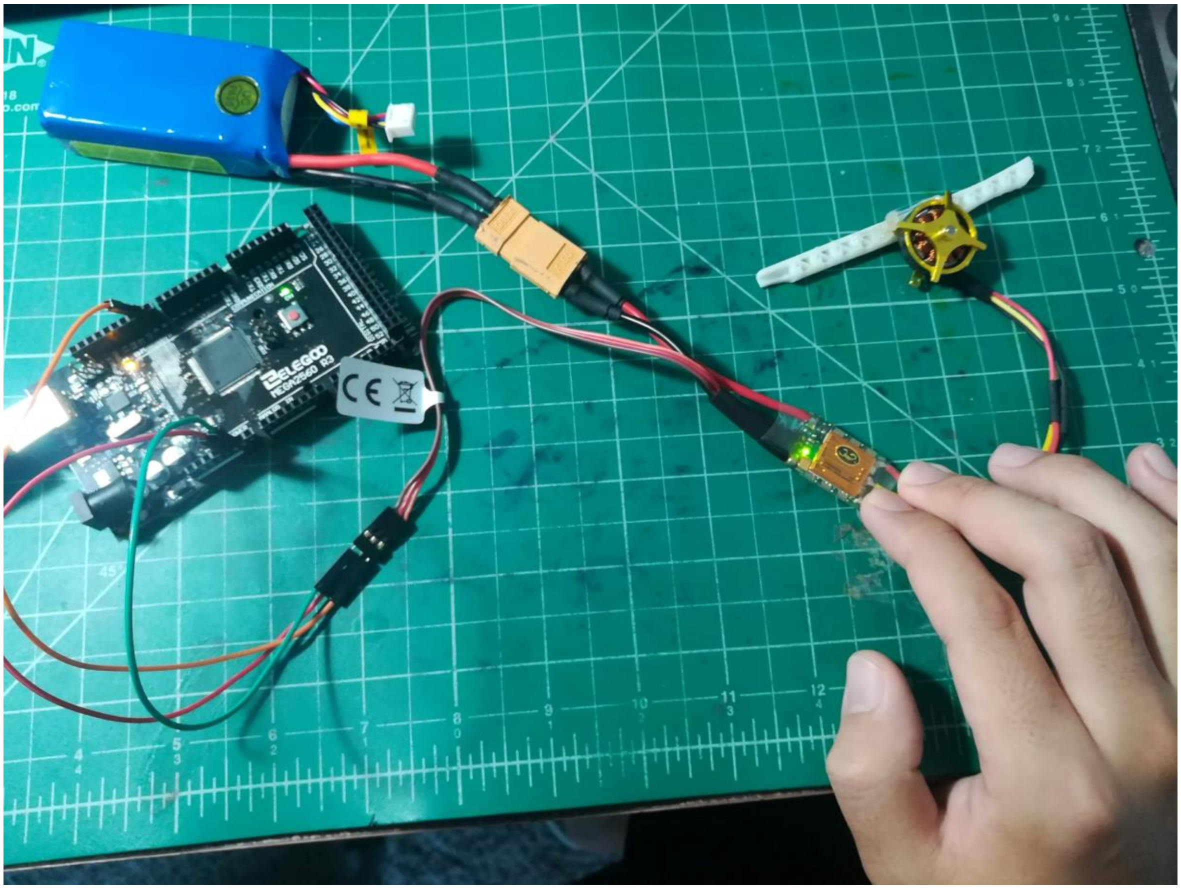


Figure 4.22 Circuit setup for BLDC motor and Arduino.

Getting the Scorpion motor to work with the arduino required fixing some compatibility issues by using a regular ESC instead of the scorpion-provided ESC (thanks to Kai and Myungjin Jung for debugging help). But after this, the scorpion motor's copper wire connections failed and the motor could not be repaired (thanks to Chris Adam for help here). Therefore, I ultimately decided to use some regular BLDC motors from MultiStar (e.g., MultiStar 750 kV, 800 kV, and 920 kV, all about 60-75 g), which have more robust construction and did not fail in any of our testing. Not knowing the performance of the motor under load condition, the motor that has the lowest torque was chosen to make the first move.

Figure 4.23: Close up view of different kinds of BLDC motors I experimented with.

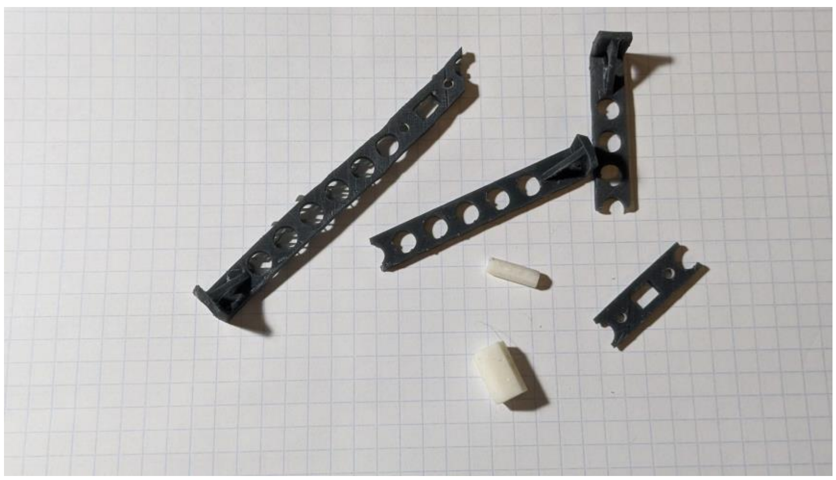


Figure 4.24: Remains of prototype version 4.0., broken due to excessive stress.

The BLDC motors were very powerful, so that with the same bridge design and modified motor connection, the bridge cracks in every test. Even when using a thick solid piece of 3D print to be the bridge, the same thing happened. Therefore, we changed the bridge material to aluminium.

4.6. Prototype Version 5.0

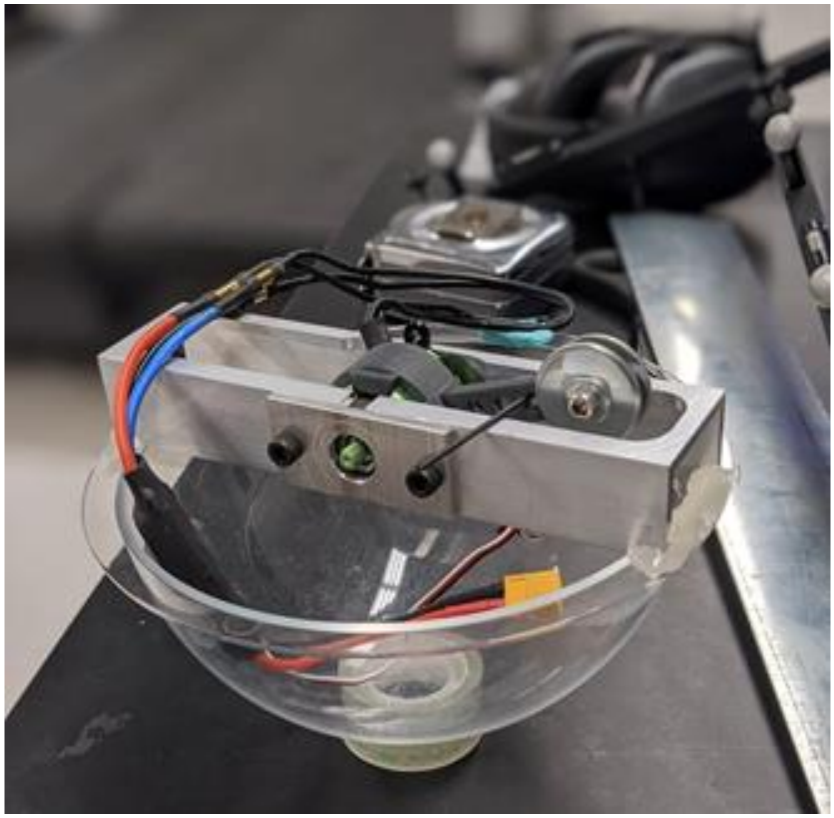


Figure 4.25: Prototype 5.0.

I fabricated an aluminum bridge to substitute the 3D printed bridge. The pendulum arm was still 3D printed due to the need for complex shape and lower weight. For the pendulum, larger washers were able to be used due to the strong torque the motor could exert. Because the BLDC motor was larger and more powerful than the DC motor, a 150mm dome was used to replace the 120mm dome which also allows the extension of pendulum length.

The prototype was then tested with only constant spinning of the motor. The robot bounced much higher than any of the previous prototypes which looked very promising, but was a little out of control as expected.

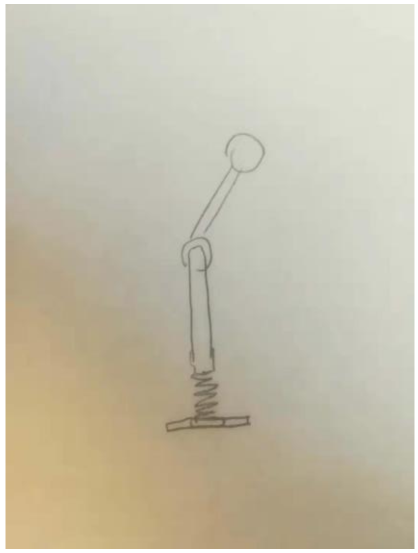


Figure 4.26: Putting a bouncy material on the bottom may increase bounce performance.

Professor Manoj Srinivasan and some fellow students suggested making the sphere or just the bottom of the ball bouncy, that is, have a larger coefficient of restitution that prevent kinetic energy loss during bouncing. Using a different ball from a different material (such as wiffle ball) was one potential solution to make the ball bouncy. However, an appropriate size of the ball was not found on the market therefore this idea was put aside. Making only the bottom surface bouncy was another potential solution (Figure 4.26). I used three different types of rubber spray (Figure 4.27) on a few extra Christmas decorations balls left (e.g., Figure 4.28). The effectiveness of the rubber was compared with a decorations ball without any spray. However, after comparison, the rubber sprays made the ball less bouncy than it used to be. This idea was put aside for future consideration, perhaps using different materials.

Figure 4.27: Some of the rubber sprays used.

Figure 4.28: One of the balls with rubber spray applied.

I drilled lightening holes to reduce the weight of the bridge significantly. After sufficient testing that proved the bridge was able to handle different loads, it was replaced by the strongest motor available. I also refined the pendulum arm design from the previous version.

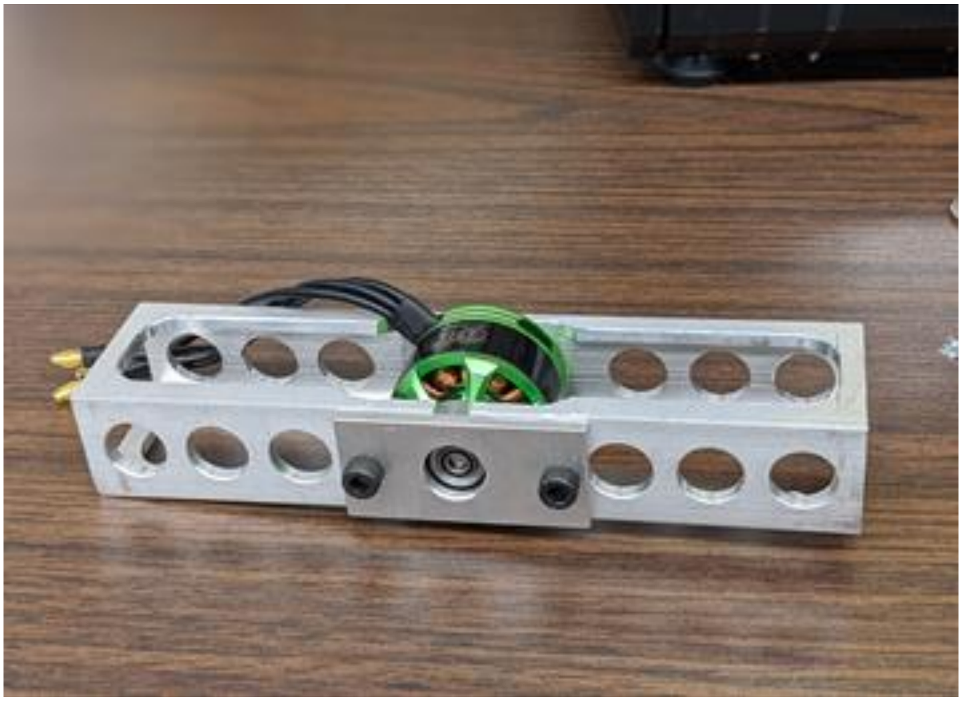


Figure 4.29: Close-up picture of the lightened bridge.

Figure 4.30: Close-up photo of the redesigned pendulum arm.

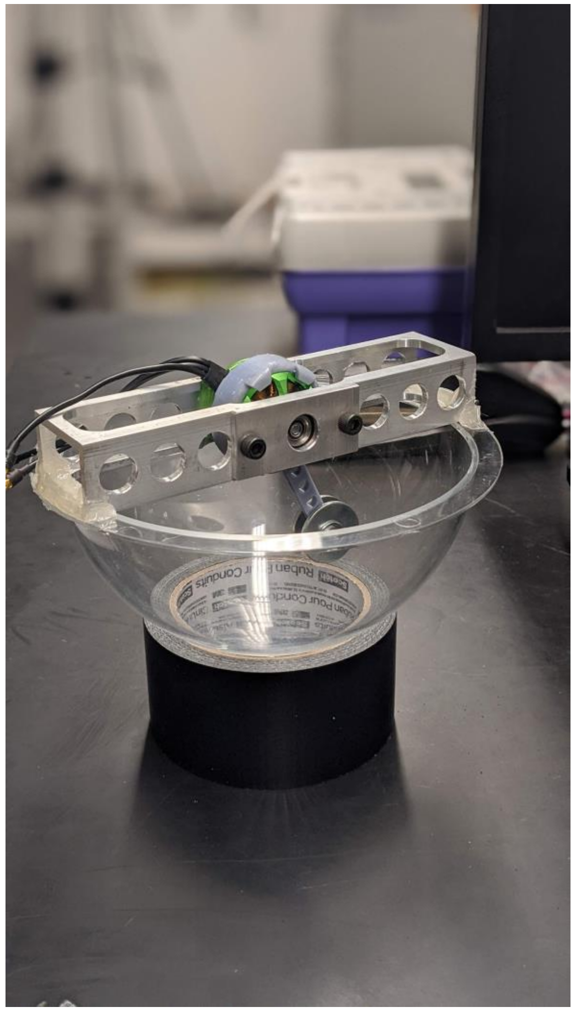


Figure 4.31: Close up after pendulum and bridge modification.

After assembling the modified parts and doing testing, I found that the new BLDC motor is much stronger than the previous BLDC motor and has the ability to bear more weight. Besides, the washers I used to form the bulk of the spinning mass were not heavy enough to serve their purpose. Therefore, I designed a custom spinning mass using SolidWorks, after some research on counterbalance mass design (Figure 4.32). In order to design a more efficient counterbalance, the weight distribution should be as far away from the center as possible in order to obtain higher torque and momentum. Kevin Wolf suggested I split the spinning mass design into two pieces, which not makes it both easier to machine and to assemble on the robot. Wolf helped machine the part with the CNC machine.

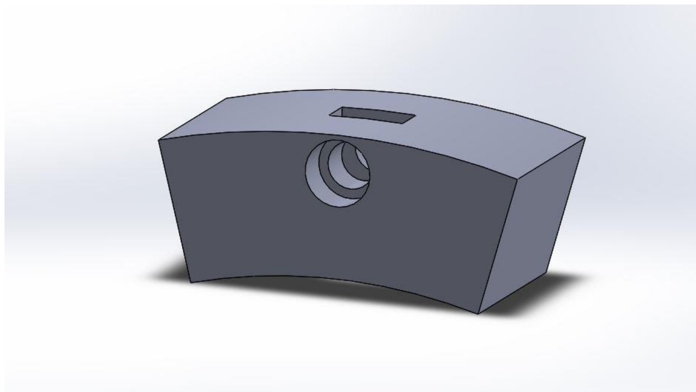


Figure 4.32: Initial customized counterbalance mass.

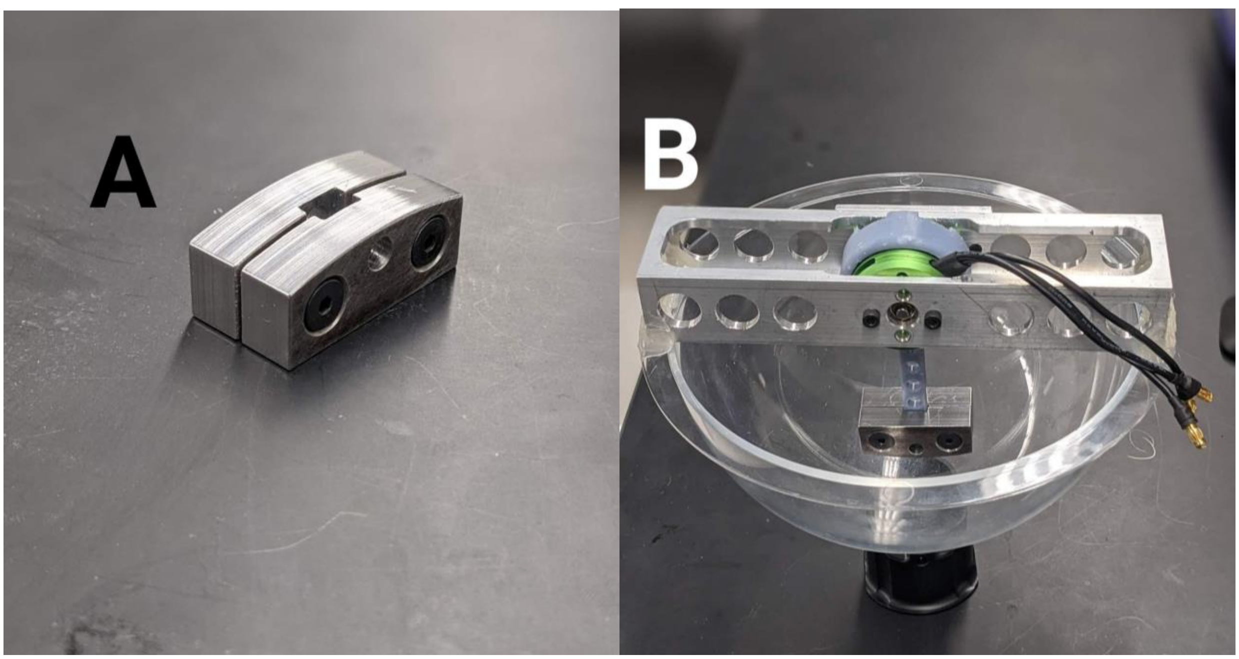


Figure 4.33: A) Close-up photo of the CNC machined carbon steel mass. B) The robot with a mass attached.

After a few trails of testing with the new machined mass, a much better performance was observed. But it came with another problem. The weight of the mass was much higher which resulted in the robot exhibiting uncontrollable bouncing. Therefore, I used an additional mass stuck to the bottom of the ball to lower the center of gravity than the geometric center. The principle is the same as a roly-poly toy (Figure 4.34), which has a center of gravity lower than the geometric center therefore gravity always pulls the object towards a stable state.

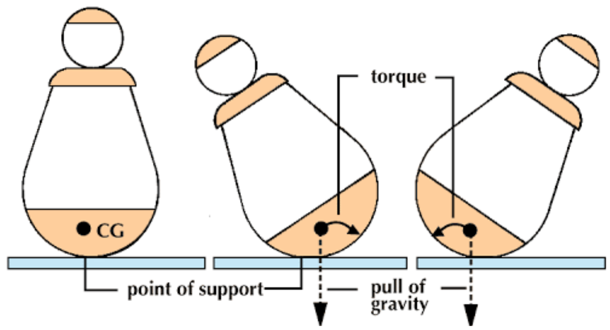


Figure 4.34: Roly-poly toy. (BRITANNICA KIDS).

4.6. Testing the bouncing robot

Only limited testing of the robot was done before the lab had to be closed down due to COVID-19 university lockdowns.

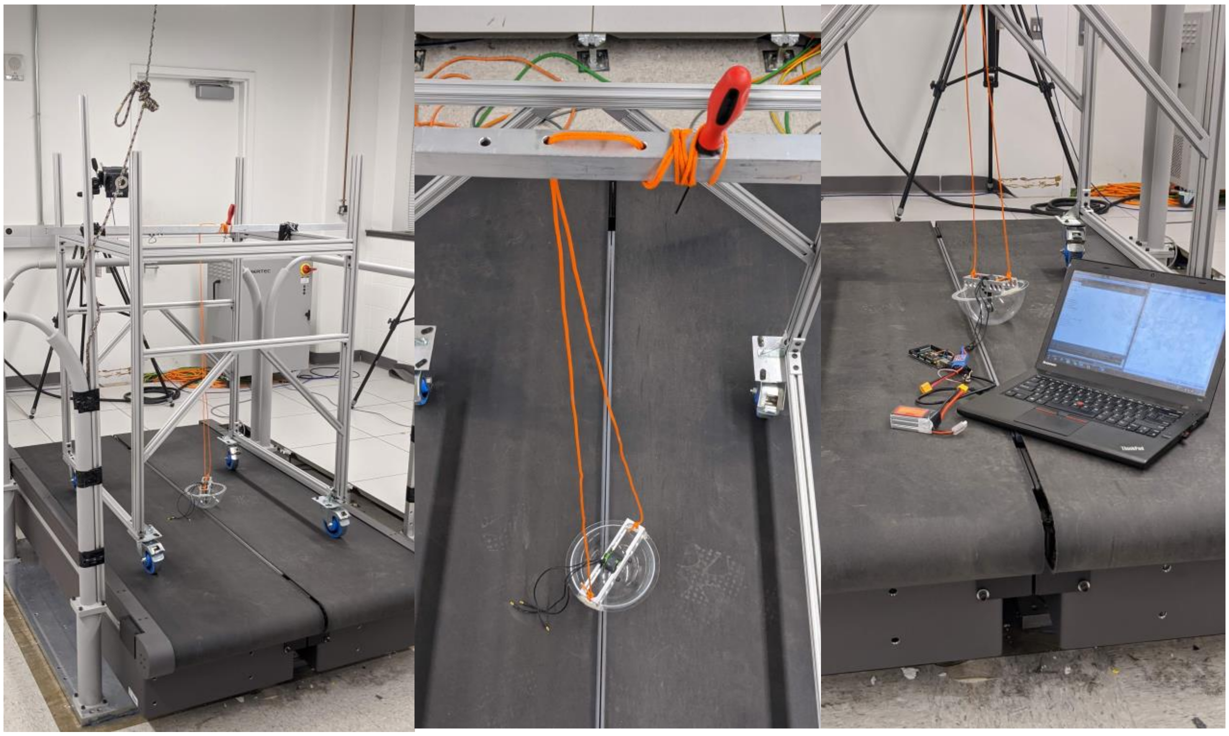
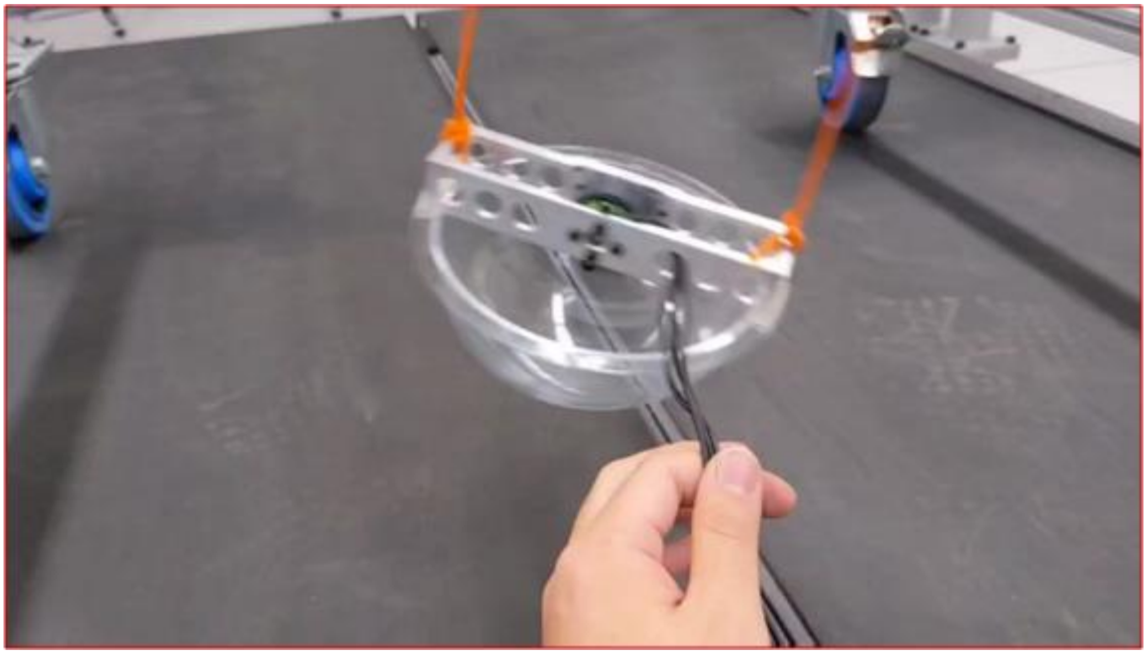


Figure 4.35: Different perspectives of the initial test setup. The ball is resting on a force-instrumented treadmill (which can measure forces on it). We tie both sides of the bridge with a loose rope to limit the horizontal movement of the ball.



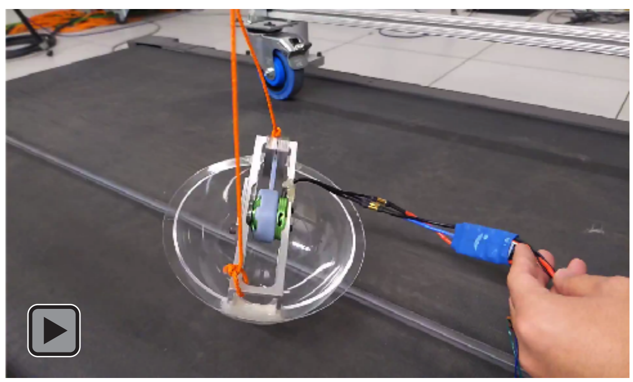


Figure 4.36: One frame from the robot bouncing video.

This is the experimental setup of the bouncing robot in the Movement Lab. The robot was tied with a thin rope on both sides and attached loosely on a cart to not restrict the movement of the robot but to prevent it from jumping off the treadmill. The cart was put on the treadmill which has force sensors under it and surrounded by Vicon motion capture cameras.

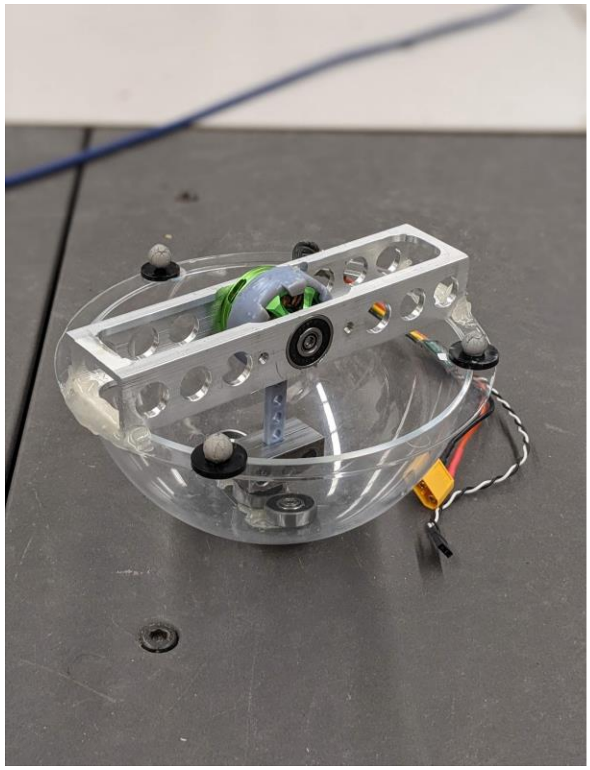


Figure 4.37: New machined mass and bottom weight added. Spherical reflective motion capture markers are also shown.

Besides the robot itself, at least three reflective markers were added to let the Vicon Motion Capture system track the position and orientation of the robot. However, the markers were not very reliable to capture due to many possible reasons. One reason might be the shining motor, bearings, and bridge are introducing interference in the reflective light of the markers. Another might be the bars on both the cart and the treadmill were blocking the reflection of the markers and couldn't be received by the camera. After removing all the bars on the treadmill, the markers were steadier than before but still not reliable enough, possibly because of the accelerations involved.

The testing was then switched to measuring force using the force sensors on the treadmill. Each session lasted 10 seconds while the robot did continuous bouncing. The results were collected and plotted by MATLAB. The plots show positive and negative with average close to 0 N. Of course, negative normal reaction forces (downward forces) from the treadmill are not possible. No such negative forces are seen during the treadmill's normal function for biomechanics experiments, such as walking. It is likely that this phenomenon of qualitatively incorrect forces reported by the treadmill is due to the fast time-scale of the impact forces on the treadmill (say, happening over a small duration ΔT) and the treadmill may have a lowest natural frequency that is smaller than $1/(\Delta T)$; that is, the treadmill vibration dynamics, specifically the treadmill "bouncing back" or "ringing" may create these negative forces. In order to validate that hypothesis, I used a tripod and stab the treadmill to achieve a sharp force stroke. The result shows a similar pattern to the bouncing data. Although this experiment was put aside for further consideration, it was discovered that the treadmill, originally used to measure the force of people's feet walking, was not able to capture fast time-scale impact forces accurately. It may be possible to fix this issue by performing a `system identification' of the treadmill (that is, model it as a mass-spring-damper system) and then infer the actual forces that are consistent with the reported forces or vibration. The data and plots could not be displayed in this thesis due to lab closure.

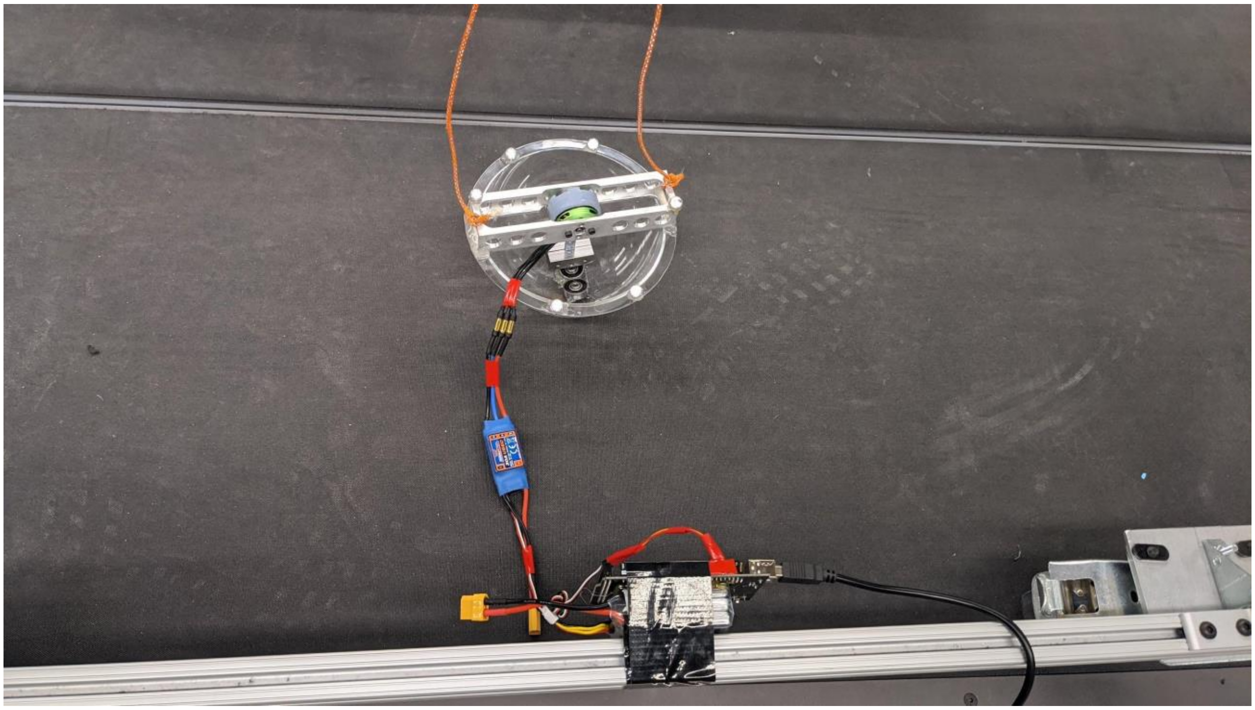


Figure 4.38: Improvised testing assembly.

Due to time and budget constraints, the power and control circuit was improvised with a battery and an Arduino board wrapped on the beam of the cart by duct tape, rather than incorporating them within the ball or have a more polished finish. The connection between each port was also reinforced by duct tape to prevent tears.

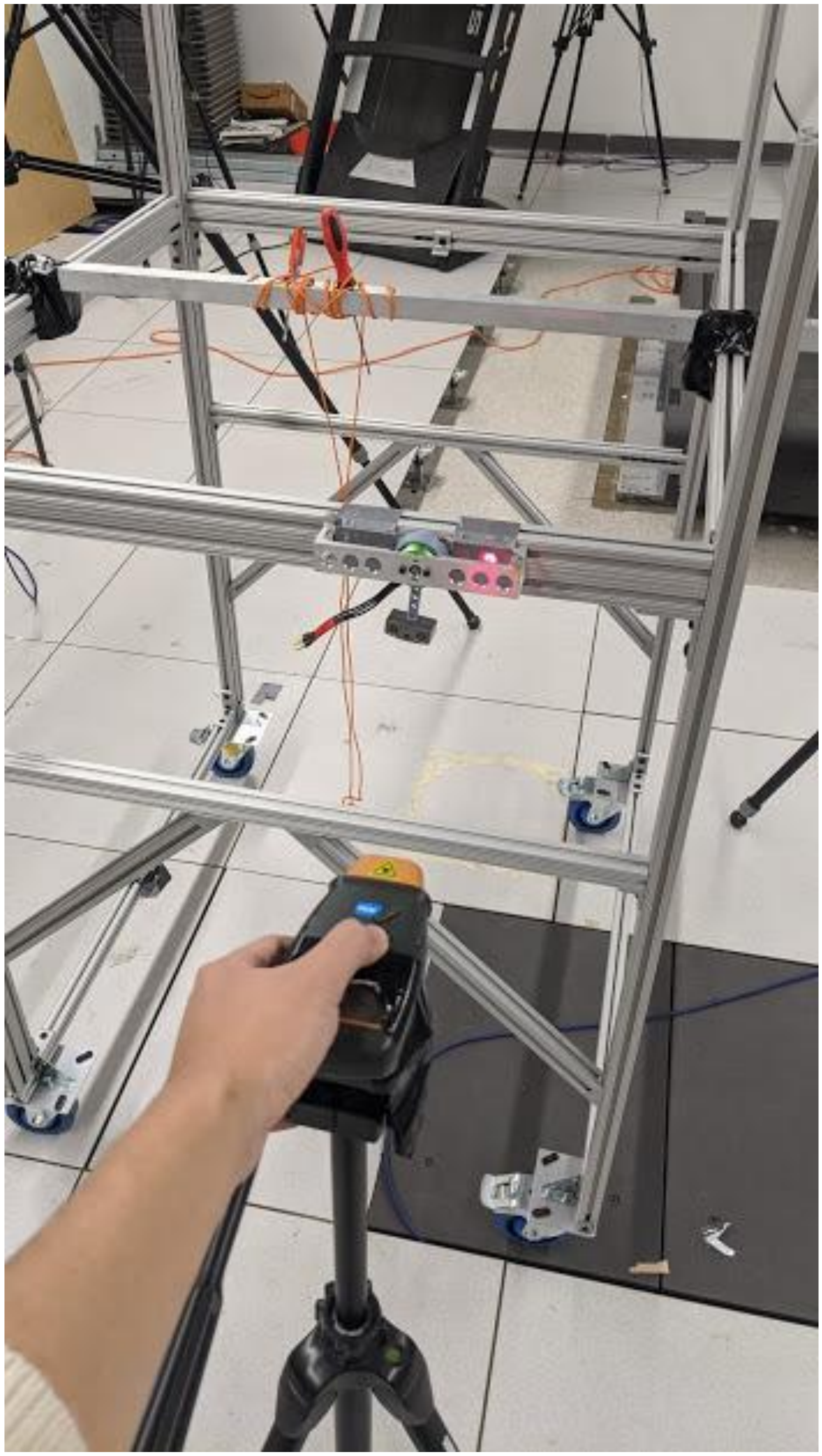


Figure 4.39: Using a tachometer to measure the speed of the pendulum under different power outputs.

Due to the mass attached to the motor, the motor had a much lower loaded speed compared to the speed setting with the mass attached. Using the borrowed tachometer from the measurement lab along with a tripod (Figure 4.39), the actual revolution speed was measured for multiple speed settings. The arduino ESC servo library allowed speed values from 55 to 57, where 55 was the lowest speed value. At the lowest speed setting of 55, we measured a corresponding speed of 130-140 rotations per minute and a speed setting of 57 corresponded to 150-160 RPM. This test was to have a benchmark to have a rough estimate of the speed under load. At these lowest spinning speeds, the ball bouncing was already a few centimeters and seemed uncontrollable, so we did not test higher spinning speeds.

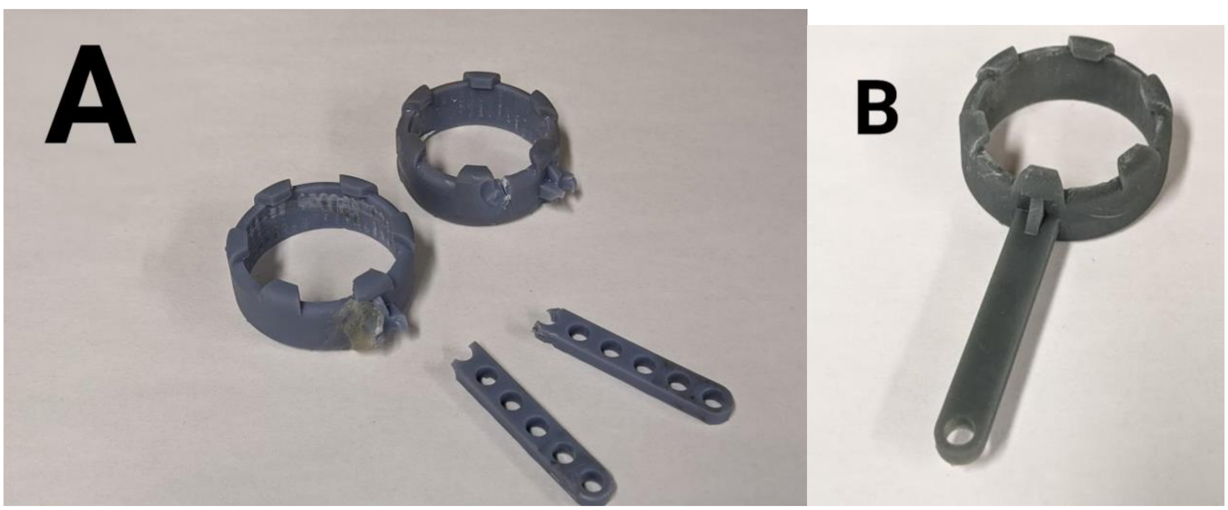


Figure 4.40: Broken arm parts copies and a modified arm part, thicker and without lightening holes to avoid failure in future runs.

During testing, the arm part of the pendulum broke three times (Figure 4.40). The two broken parts both broke in the rim and the intersection of the rim and arm. The breaking of the arm was a critical failure of the part. The failing point was always near a cross-section with a lightning hole, where the cross-sectional area was the least. The failures were also close to the base of the pendular arm where the “centrifugal forces” of spinning the mass would be largest, and perhaps also enhanced due to stress concentration. To prevent such failure, I decided to eliminate the holes. The weight is a primary concern for this part compared to the overall weight of the robot and it is more important to prevent mechanical failure. In some cases, the circular part holding the motor also cracked, likely due to insufficient clearance with the motor, and this issue was solved by increasing the diameter of the rim.

In addition to spinning the motor at a constant speed, I also tried to modify the Arduino code to achieve a better spinning pattern: my goal was to alternatingly spin the motor and then stop the motor for a very short amount of time and restart soon after. Due to the nature of the BLDC motor, the motor could not be brought to a complete stop immediately during the spinning process, thus, a longer “stop” time was needed. Eventually the following simple code was used to vary the speed of the motor within a cycle, alternating between powering the motor (ESC.write(55)) and letting the motor coast (ESC.write(0)).

```
void loop(){

        ESC.write(55);

        delay(100);

        ESC.write(0); // or ESC.write(50)

        delay(500);

}
```

Unfortunately, due to lab closures, we did not experiment further with this strategy of altering the speed of the pendulum within a cycle to achieve better bounce performance and better control of the bouncing ball.

Chapter 5: 3D Computer Simulation and Controller Testing

Before formally doing computer simulations of the bouncing ball, I outlined a way by which the ball would bounce continuously, hypothesized a spinning and bouncing spinning and bouncing synchronization pattern. See Appendix A for some early conceptual drawings and some simple calculations for the minimal conditions on the spin angular velocity for sphere take-off. The basic idea of the bouncing ball is that a spinning mass requires a centripetal force: when this centripetal force is downward on the spinning mass, the equal and opposite reaction on the spherical shell is upward and it can produce an upward force to lift the shell off the ground.

A variety of software is used in academia and industry for simulating 3D multibody dynamics: for instance, Co-sim, Adams, Design Simulation Technologies, MATLAB’s Simscape, etc. Of course, one can also directly write the equations of motion and solve the differential equations, for instance, using ode45 in MATLAB. Here, we used the Algodoo, MATLAB, and Simscape Multibody to make progress on building a computer simulation of the bouncing ball robot.

5.1. 2D simulations in Algodoo.

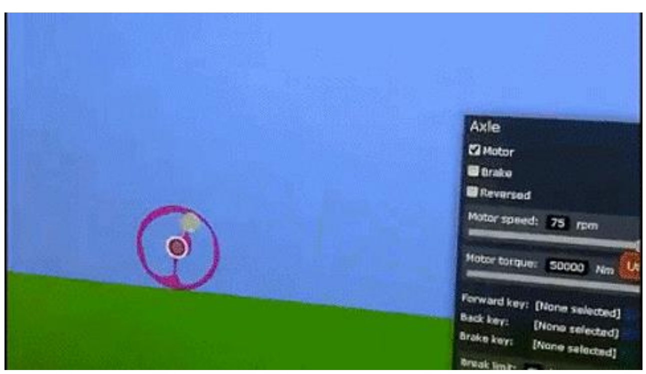


Figure 5.01: Snapshot of bouncing ball simulation in Algodoo.

Algodoo is a simple easy-to-use software that can do various 2D physics-based dynamic simulations with rough sketches; it also has simple ways of actuating parts (e.g., motors and gears) and can simulate contact, bouncing, and even simple fluid mechanics. The program, used to create simple games, is simple enough that one can set up a multibody simulation in less than two minutes.

I created a circular disk (representing the ball), hollowed the interior and left a beam across a diameter. To this beam, I attached an axle with a motor in the center of the beam and attached a thin rod on the motor with a relatively large ball with high-density specifications. The direction and speed of the motor could be controlled by the panel on the right as seen in the figure (Figure 5.01). With reasonably high speed and torque on the motor, the system could do very high bouncing. One problem with the model is the robot was not controllable and the spinning pattern did not synchronize with the bouncing pattern (Figure 5.02).

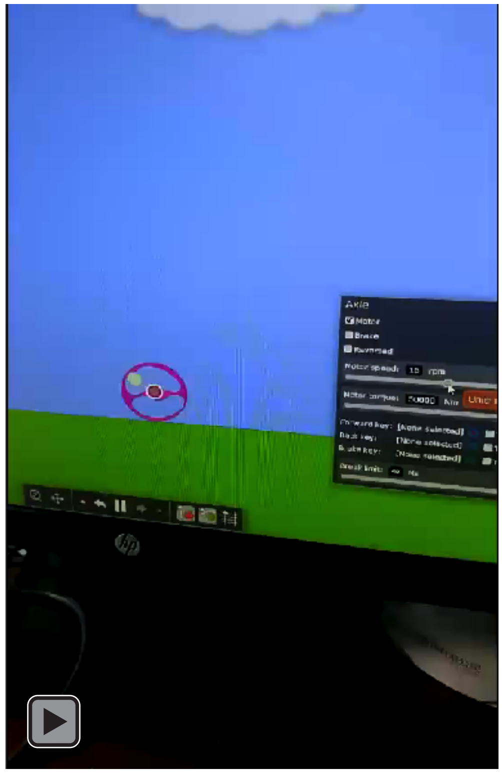


Figure 5.02: Animation of the simulation.

Thus, these simple simulations show promise that the spinning mechanism can produce consistent bouncing, even if the bouncing may be chaotic. However, there are a few limitations to this simulation. First, the simulation was done in 2D space, which means there were no sideways balancing issues factored in (roll stability). Second, the physical property of the elements in the simulation couldn't be modified, i.e., spring stiffness and coefficient of restitution of the ground. Therefore, we sought a simulation in which we have control over the physical properties of the various model components. These Algodoo simulations were not pursued further, due to its limitations as a quantitative scientific tool.

5.2. 2D simulations using MATLAB

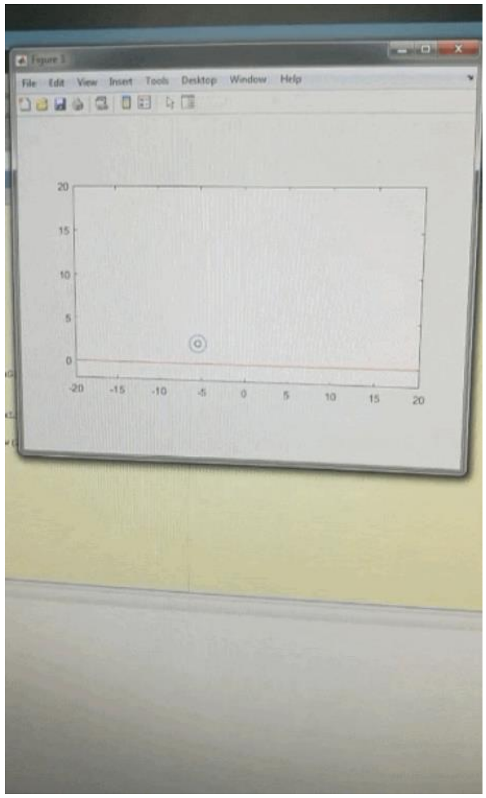


Figure 5.03: A snapshot of 2D bouncing simulation using MATLAB.

I explored directly writing the equations of motion for a 2D version of the system and solving the resulting differential equations in MATLAB using ode45. The equations of motion were obtained by drawing free body diagrams for each rigid body and writing Newton-Euler equations for each free body diagram. The contact with the ground surface was modeled by a spring and damper, which gets activated only when the circular shell touches the ground. This is a work in progress: while the simulation often produces bouncing animation (Figure 5.03), there were some un-physical features of the bouncing suggesting that the simulations need to be improved.

5.2. 3D simulations using Simscape Multibody

5.2.1. What is Simscape multibody

Simscape Multibody is a product under MATLAB-Simulink, formerly called SimMechanics, is a software that can provide multibody 3D mechanical system simulation environment for simulating objects such as robots, automotive vehicles, and aircrafts. The parts can be models with either simscape blocks or importing CAD model files. The multibody system can be described by defining the properties of the rigid bodies, joints, constraints, force elements and sensors. Simscape Multibody automatically solves equations of motion for the system. Other parameters like masses, densities, inertias, joints, constraints, and controllers can be manipulated and modified. Simscape Multibody can be called programmatically from within MATLAB. Features such as functions, variables, and expressions can be programmed in MATLAB and used by SimScape.

5.2.2. Model details

Diameter of the sphere	150 mm
Weight of the spinning mass	27 g
Dead mass (spherical shell + motor + bridge)	311 g

5.2.3. Results so far for spinning actuation

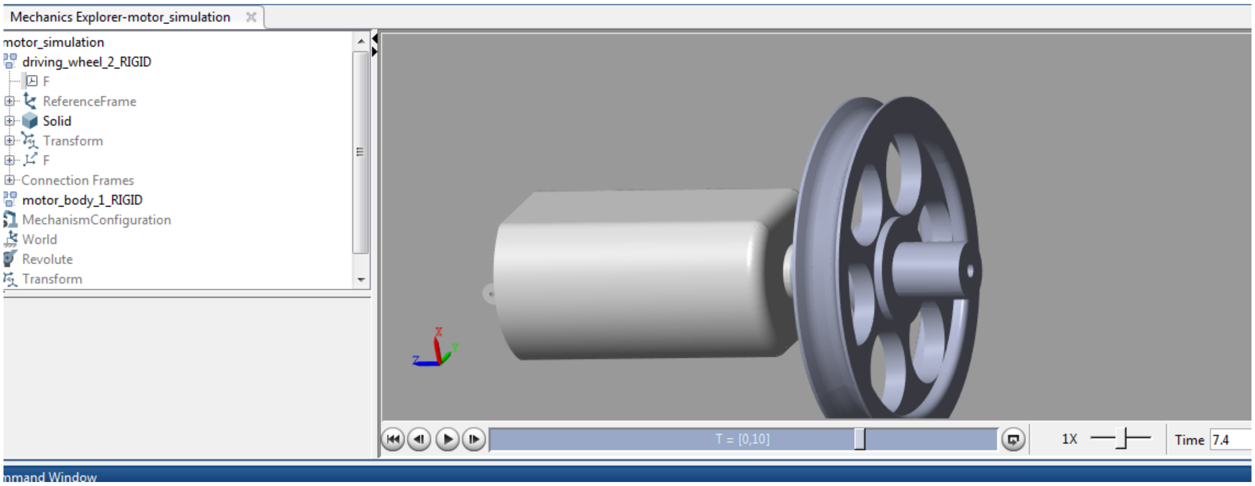


Figure 5.04: Imported CAD model of prototype ver 2.0. into SimScape multibody.

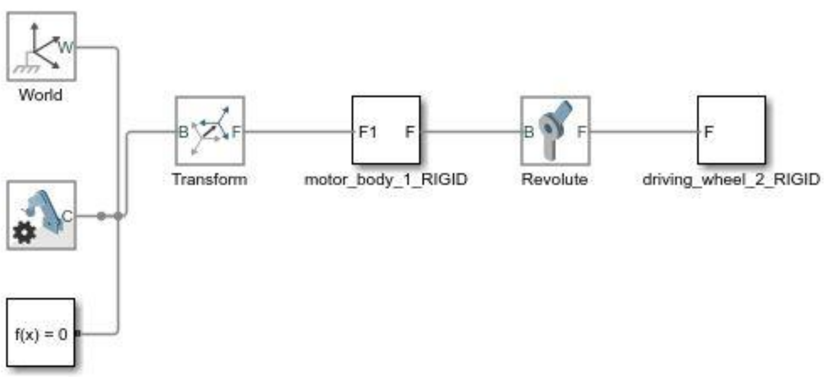


Figure 5.05: Automatic generated SimScape multibody block diagram by imported CAD model of prototype ver 2.0.

For the first version of the simscape model, I created a 3D model in SolidWorks and then imported into SimScape, at which time SimScape will automatically create block diagrams with parts, joints, and constraints. However, the logic of these imported block diagrams was not reliable and therefore had to be adjusted manually.

Figure 5.06: Imported CAD model of prototype ver 3.0. Into SimScape multibody.

Figure 5.06 shown above is a snapshot of the simulation for prototype ver 3.0, created by importing SolidWorks files. The robot was successfully assembled but the contact between the ball and the floor was not modeled, so the robot just fell through the floor. It was decided to substantially simplify the simulation so as to enable incorporating the ground contact.

We used the Simscape Contact Forces Library (2019b) to model the contact forces between the spherical shell and the ground, partially adapting the provided Simsacpe example code, Coll3D_01_Ball_Plane_Fixed.slx. The Simscape model was created directly in Simscape (rather than import from SolidWorks to eliminate compatibility issues). The spherical shell is attached to the ground by a 6DOF bushing joint, where the contact forces kick in when the sphere makes contact with the ground. We attached a revolute joint directly to the sphere. A revolute joint is a one degree of freedom joint (also called a hinge joint), which is what we want for the motor joint. Under actuation, the joint had a constant torque input using a physical signal constant. Initially start with zero or very very small torque. Under internal mechanics, the joint had some small damping, so that the spinning mass does not spin and get to infinite speed.

We then attach a spinning mass to the revolute joint through an intermediate 'rigid transform' to the revolute joint (Figure 5.07). For the rigid transform, under 'rotation', choose the default 'none'. Under 'translation', select 'standard axis', axis +X, offset = L/2, where L is the total length of the pendulum to be attached (spinning object, see next step below). The L/2 is basically saying that the pendulum is attached to the ball center so that the center of the pendulum is L/2 away from the ball. We then attach a 'rigid body' (the spinning object) to the rigid transform. For the spinning object, we chose 'brick' with length = 0.75 of the ball, say. Dimensions = L, L/10, L/10, where L = length of the spinning object. I choose L = 0.75 R, where R is the ball radius. For the 'sphere', make 'opacity' = 0.1, so that I can see the spinning object within the sphere. R = ball radius.

We initially gave zero initial conditions for the revolute joint, both position and velocity. However, this caused a problem with singularity in the equations, solved by having minimal non-zero initial velocity. For the bushing joint that connects the sphere to the ground in the code, the 'state targets', namely initial conditions were set to were set to zero for X and Y prismatic primitive, specifically the velocities, so that the ball starts with zero initial velocity in the X and Y directions. The 'Z prismatic primitive' is set to a non-zero position target = 3 m, the initial height of the object. To start the ball exactly in contact with the ground, one can the initial ball height exactly equal to the ball radius.

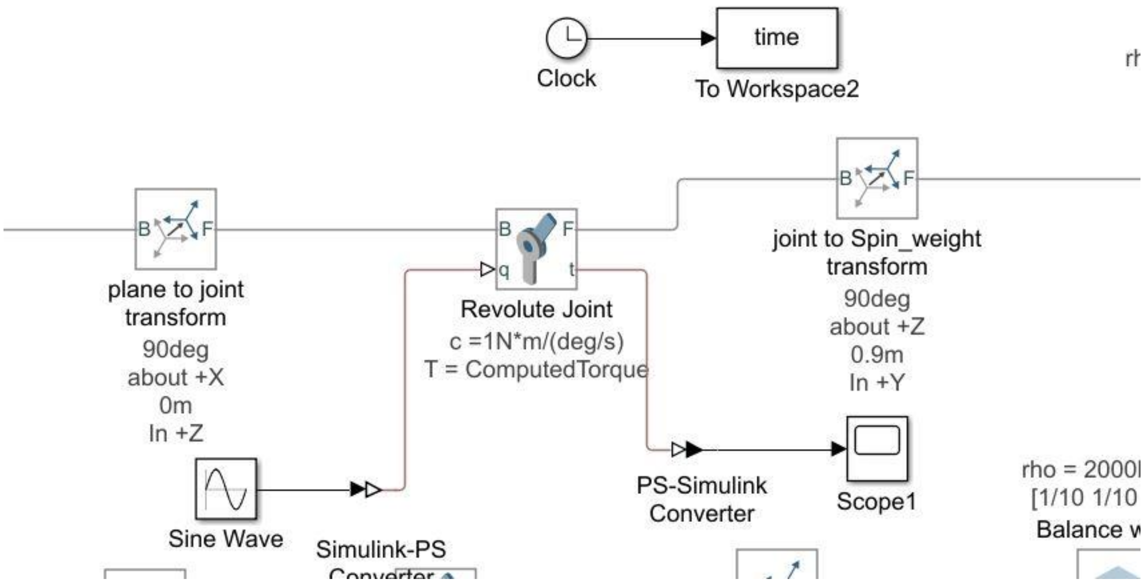


Figure 5.07: Zoom-in of the tree structure of Simulink Diagram.

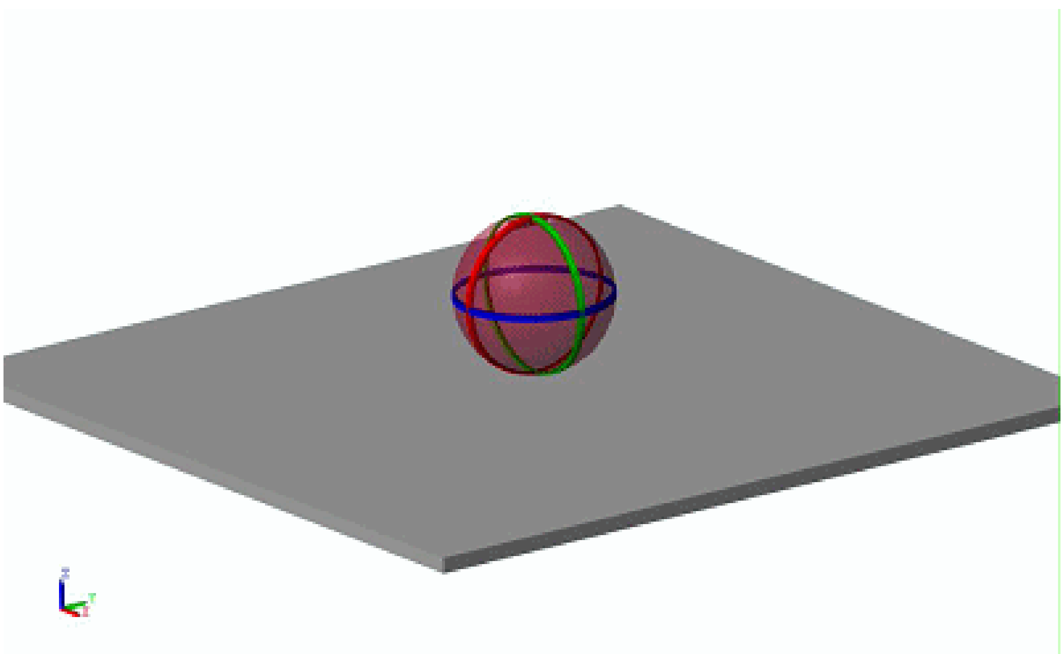


Figure 5.08: Simplified model with spinning mass for balancing.

This is the animation of the first successful simulation build on the contact simulation example. There is one off-centered mass in the ball spinning with respect to an axis. The response of the ball was not predictable.

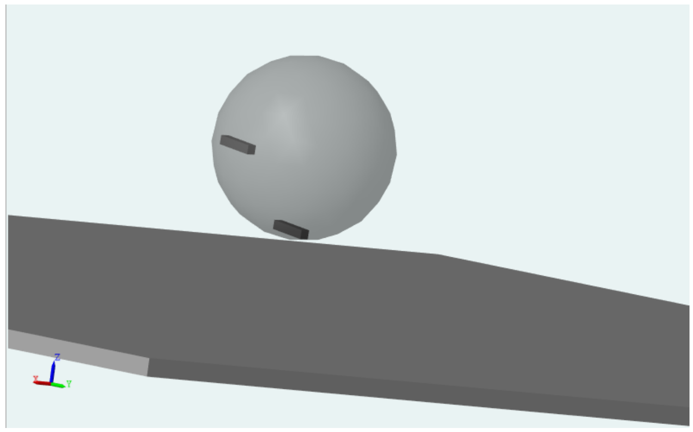


Figure 5.09: Simplified model with spinning mass for balancing.

In order to increase the stability of the robot, I added an extra weight stuck to the bottom of the robot to lower the center of gravity like the principle of a roly-poly toy. The bottom mass was set to a reasonable value to stabilize the ball but not significantly affect bouncing performance. Moreover, the appearance like the color and stripes was changed and removed for better observation. Overall, the ball exhibited persistent bouncing in the presence of continuous spinning, although the bouncing motion was erratic with the spinning not synchronizing with the bouncing. Sometimes, Simscape would produce a gimbal-lock error, presumably due to an Euler-angle singularity.

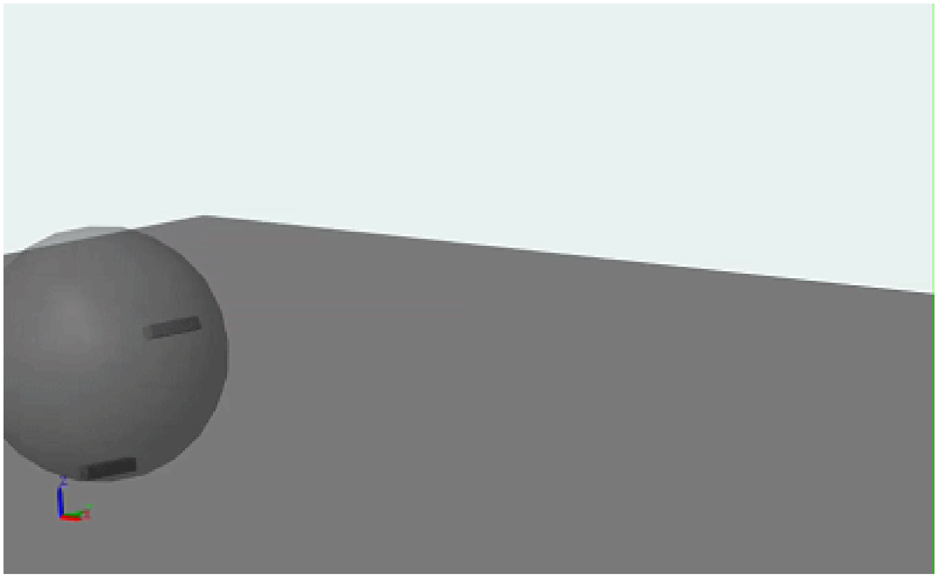


Figure 5.10: Simplified model of spinning mass with bottom mass for balancing.

5.2.4. Other attempts

I briefly attempted to vary the control input as a function of time. To generate the desired motion (position) of the pendulum, I combined different shapes of signals to get close to the desired signal shape. However, the drawback is the time and interval did not match the natural frequency of the ball. Therefore, a feedback controller was needed to tune and match the bouncing pattern. We can imagine two kinds of controllers:

1) feedforward control -- where I change the spinning velocity as a function of time, periodic in time, but with different speeds for two halves of the spinning stroke. This will be a simpler way compared to feedback control

2) feedback control -- use the state of the ball or state of the spinning object somehow to estimate when the spinning mass should go up versus down. For instance, use an accelerometer to detect contact with the ground, and then, trigger a motion of the mass somehow after that.

Due to the complex and unpredictable nature of the simulation and due to the many parameters present, tuning the parameters and the spinning pattern was not easy to do manually. We decided to perform “trajectory optimization” (e.g., Srinivasan 2011) to obtain the optimal control of the spinning to produce maximal bouncing, but this remains a work in progress. The rest of the figures in this chapter, Figures 5.11 onwards present snapshots of some work in progress and the various preliminary results from some of this work.

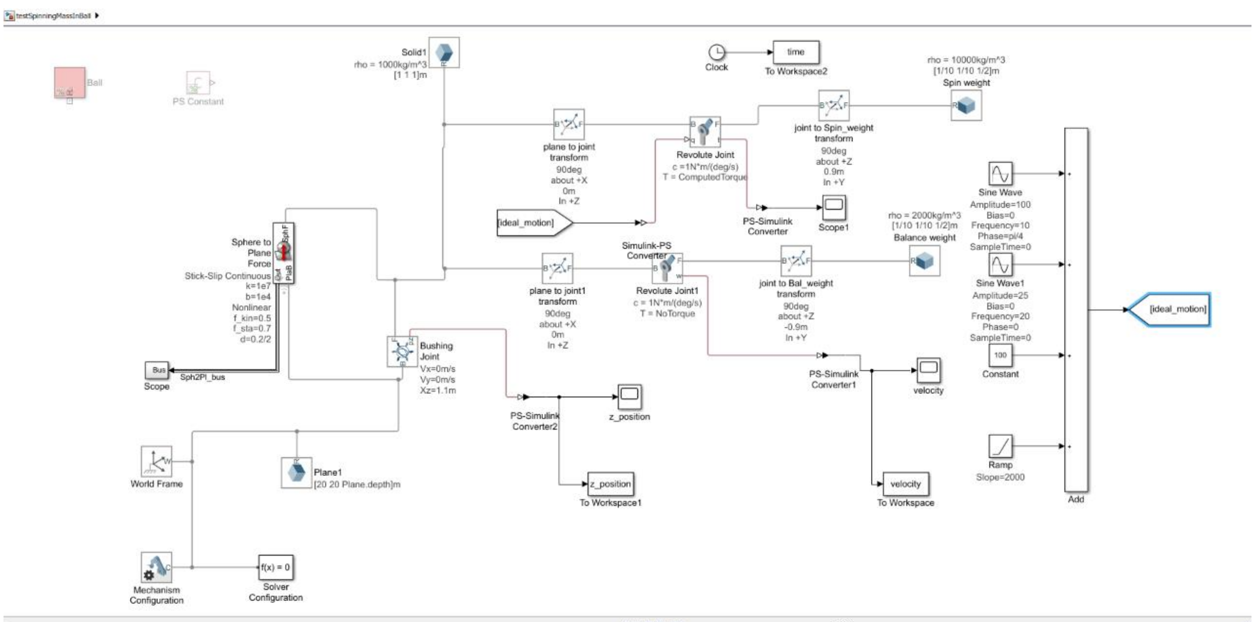


Figure 5.11: Work in progress: Overall block diagram with manually tuned ideal spinning pattern.

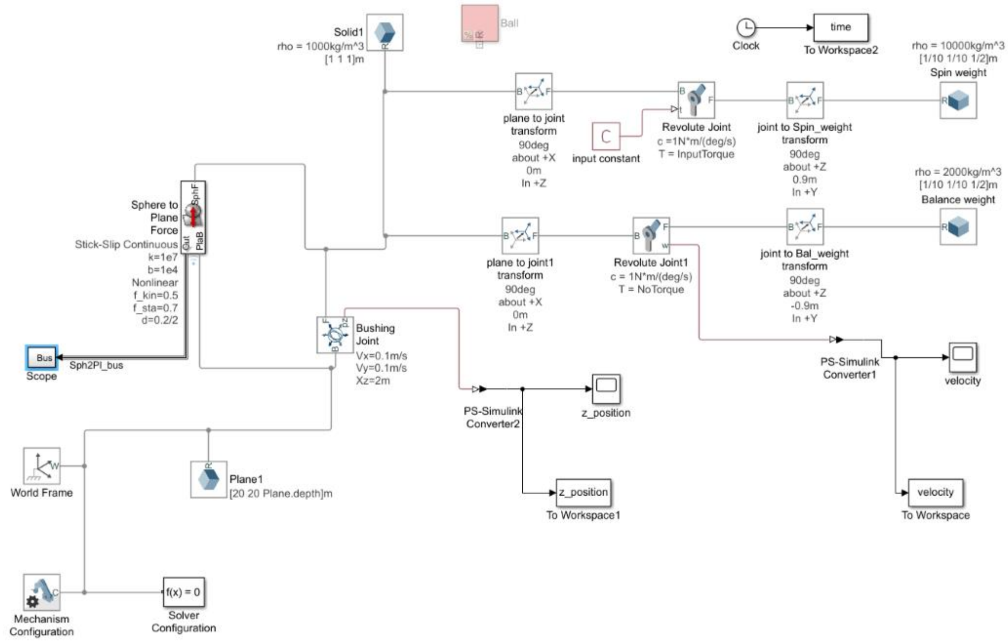


Figure 5.12: Complete SimScape block diagram without feedback controller.

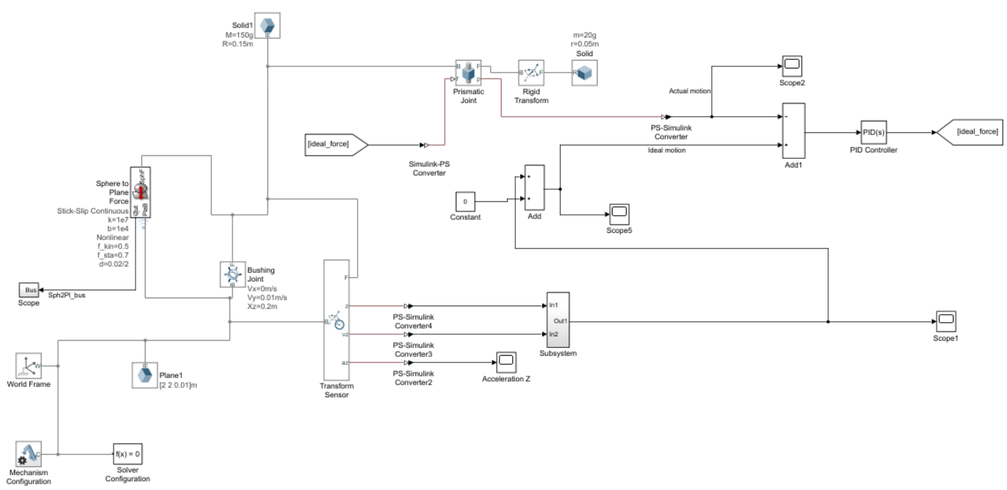


Figure 5.13: Complete SimScape block diagram with feedback controller.

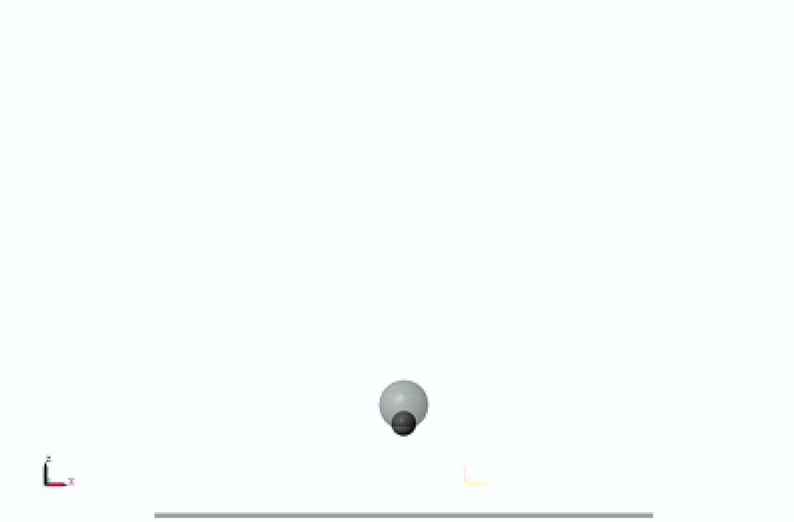


Figure 5.14: Work in progress: A prismatic (as opposed to revolute) version of the actuation was built, showing some early success.

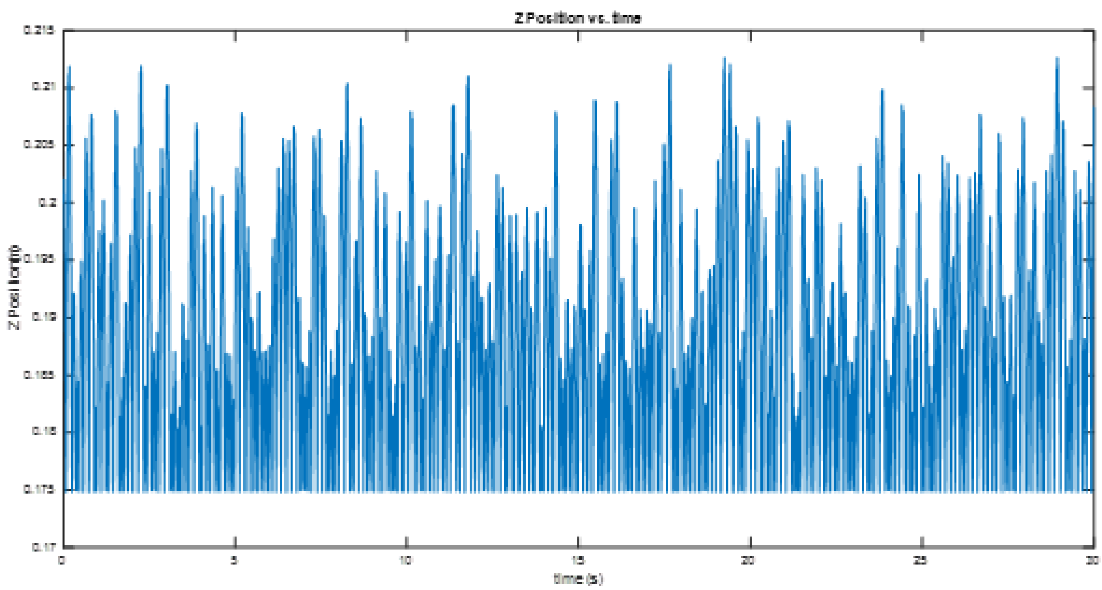


Figure 5.15: Work in progress: Prismatic actuation. Bouncing ball height for 30 sec.

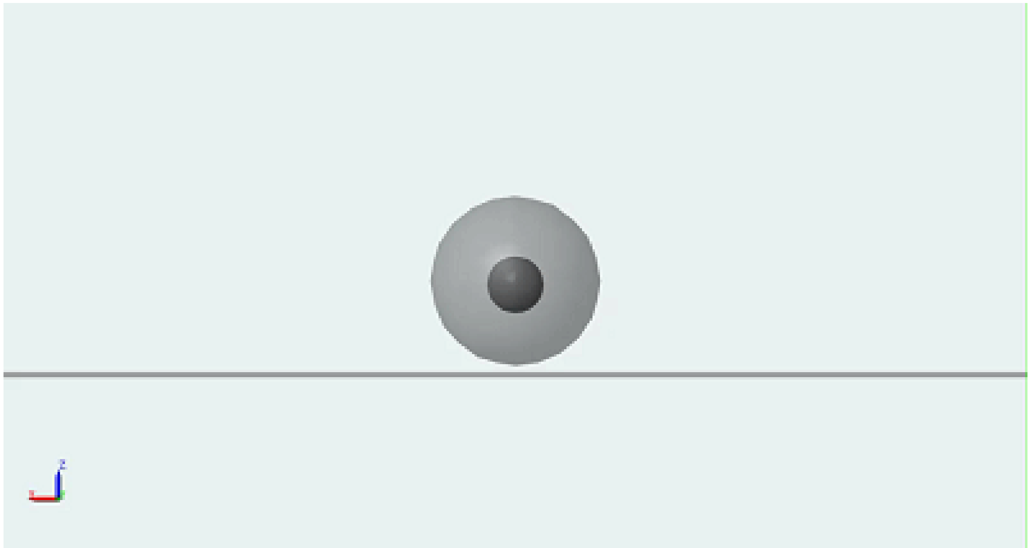


Figure 5.16: Work in progress: validation of the prismatic approach for bouncing with realistic physical parameters.

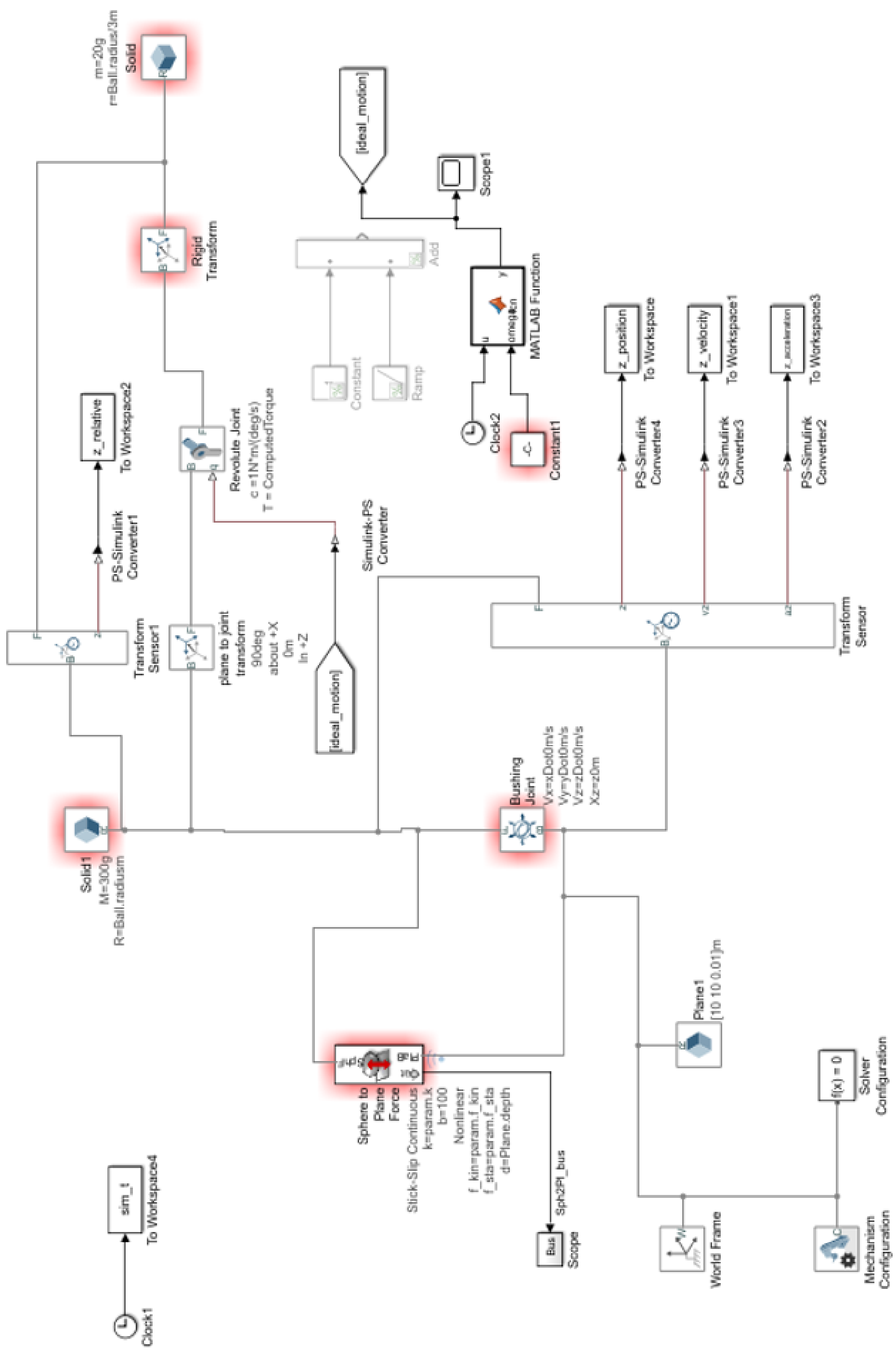

Solid
m=20g
r=Ball.radius/3m
[ideal_motion]
Scope1
Rigid
Transform
Add
MATLAB Function
Constant
Ramp
Clock2
Constant1
z_position
To Workspace
z_velocity
To Workspace1
z_acceleration
To Workspace3
PS-Simulink
Converter4
PS-Simulink
Converter3
PS-Simulink
Converter2
z_relative
To Workspace2
PS-Simulink
Converter1
Revolute Joint
c =1N*m/(deg/s)
T = ComputedTorque
Simulink-PS
Converter
Transform
Sensor1
plane to joint
transform
90deg
about +X
0m
in +Z
[ideal_motion]
Transform
Sensor
Solid1
M=300g
R=Ball.radius
Bushing
Joint
Vx=xDot0m/s
Vy=yDot0m/s
Vz=zDot0m/s
Xz=z0m
Sphere to
Plane
Force
Stick-Slip Continuous
k=param.k
b=100
Nonlinear
f_kin=param.f_kin
f_sta=param.f_sta
d=Plane.depth
Plane1
[10 10 0.01]m
sim_t
To Workspace4
Clock1
Sph2Pl_bus
Bus
Scope
World Frame
f(x) = 0
Solver
Configuration
Mechanism
Configuration

Figure 5.17: Work in progress: Overview of the whole lastest Simulink diagram.

Chapter 6: Conclusion and Future Work

This chapter describes the contributions, additional applications, future work and summary of the work done in this research.

6.1 Contributions

This ambitious project had numerous aspects, namely, design, fabrication, computer simulation through multiple modeling paradigms, optimal control, etc. Due to the numerous aspects of this ambitious project, the author could not complete the original research goals. These numerous which can be taken over by other researchers to improve, upgrade, and perfect the project.

We fabricated a simple and robust bouncing ball device after about six prototype iterations and this device exhibited persistent bouncing. More work needs to be done to go from this prototype to make the bouncing periodic and synchronous, make the bounce height higher, and make the bounce controllable.

Similarly, we showed feasibility of a persistent bouncing robot, first through an algodoo simulation and then using MATLAB 2D simulations and Simscape 3D simulations. However, the latter two simulations should be considered works in progress, with some debugging and fine-tuning required for reliability. Once these reliability issues are resolved, we should do parameter sweeps to examine the effect of parameters. We also need to complete testing frameworks in which the actuation is time-varying or feedback controlled to more clearly see the effect of these different control approaches.

6.2. Significance of the robot and additional applications

We have explored the feasibility of a novel robot configuration. It is important to consider novel robot configurations as they may potentially have advantages over traditional configurations (such as legged or wheeled robots). This novel robot, when complete, has the potential advantage that all the mechanisms could be internal, but the potential advantages of such a robot have not been tested. One possible advantage is having an air-tight body. Unlike traditional wheeled or legged robots, this robot could be less prone to get dust and liquid into its electronic and mechanical components.

Second, due to the nature of its movement, the robot may have some potential advantages for certain terrain. For instance, high bumps on the road may be traversed better by a bouncing robot than a rolling robot.

The rolling and bouncing may be most useful as an entertainment toy for children, and perhaps pets: indeed, for such purposes, a periodic and perfectly controllable motion may not be essential. However, for such situations, it is important to have a safety-first approach and make sure that the robot cannot injure the person, being capable of avoiding a human or an animal. Perhaps the bouncing motion will be useful in low gravity space. For use as a surveillance robot, however, the robot needs to be very quiet, so that bouncing aspect may make it less useful in that context.

Finally, this novel robot raises technical issues that will challenge current design and manufacturing methods, as well as push the envelope of control methods, as 3D aerial control of a spherical bouncing robot has not been demonstrated yet.

6.3 Future Work

As noted, the author here explored numerous aspects of the problem of building a spherical robot. For future researchers who continue this project, the recommendation will be to tackle only one aspect of this project. This can be divided into designing new locomotion ideas, building generations of prototypes based on existing designs that previous researchers could not complete, perfecting existing prototypes by upgrading components, building test contraptions and conducting tests, completing working simulation models and optimization of controllers, design of nonlinear controllers, performing stability analysis of the 3D bouncing in place or with forward movement, etc. Future researchers could also complete building prototypes of cam, slider and crank, and coil mechanisms that the author envisioned but failed to complete due to the time constraints. New alternative materials could also be pursued to reduce the weight and meet strength, including exploring other off-the-shelf parts. The shape design of the supporting parts could be optimized in order to reduce the weight of the part while maintaining structural property.

Due to time, material, and budget, the author could not build a complete testing framework. However, a complete and strong testing framework is essential for testing to eventually produce reliable results. Furthermore, different optimization strategies should be tested to produce the best results for the bouncing.

References

Note that the image citations are in a separate reference list in Appendix B.

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Muralidharan, Vijay, and Arun D. Mahindrakar. "Geometric controllability and stabilization of spherical robot dynamics." IEEE Transactions on Automatic Control 60.10 (2015): 2762-2767.

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Srinivasan. Fifteen observations on the structure of energy optimal gaits in many simple biped models. Journal of Royal Society Interface, 2011.

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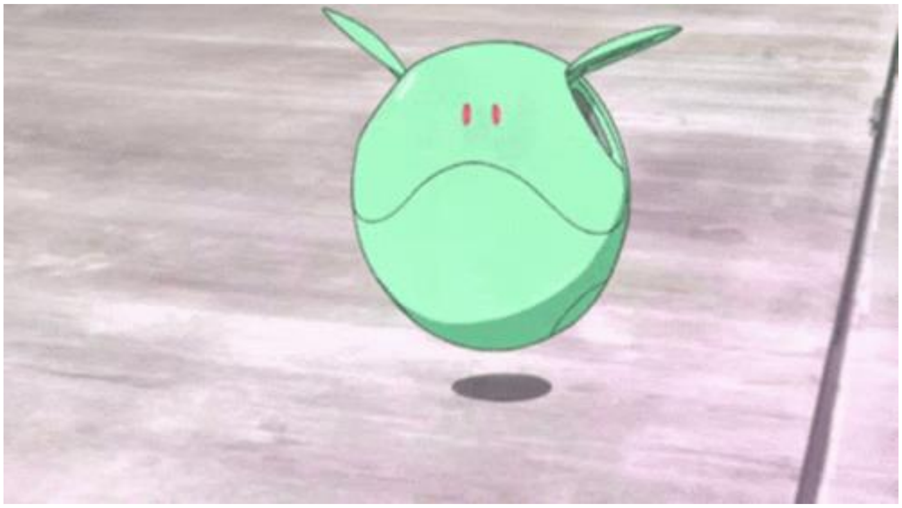
Yim, Justin K., and Ronald S. Fearing. "Precision Jumping Limits from Flight-phase Control in Salto-1P." 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018.

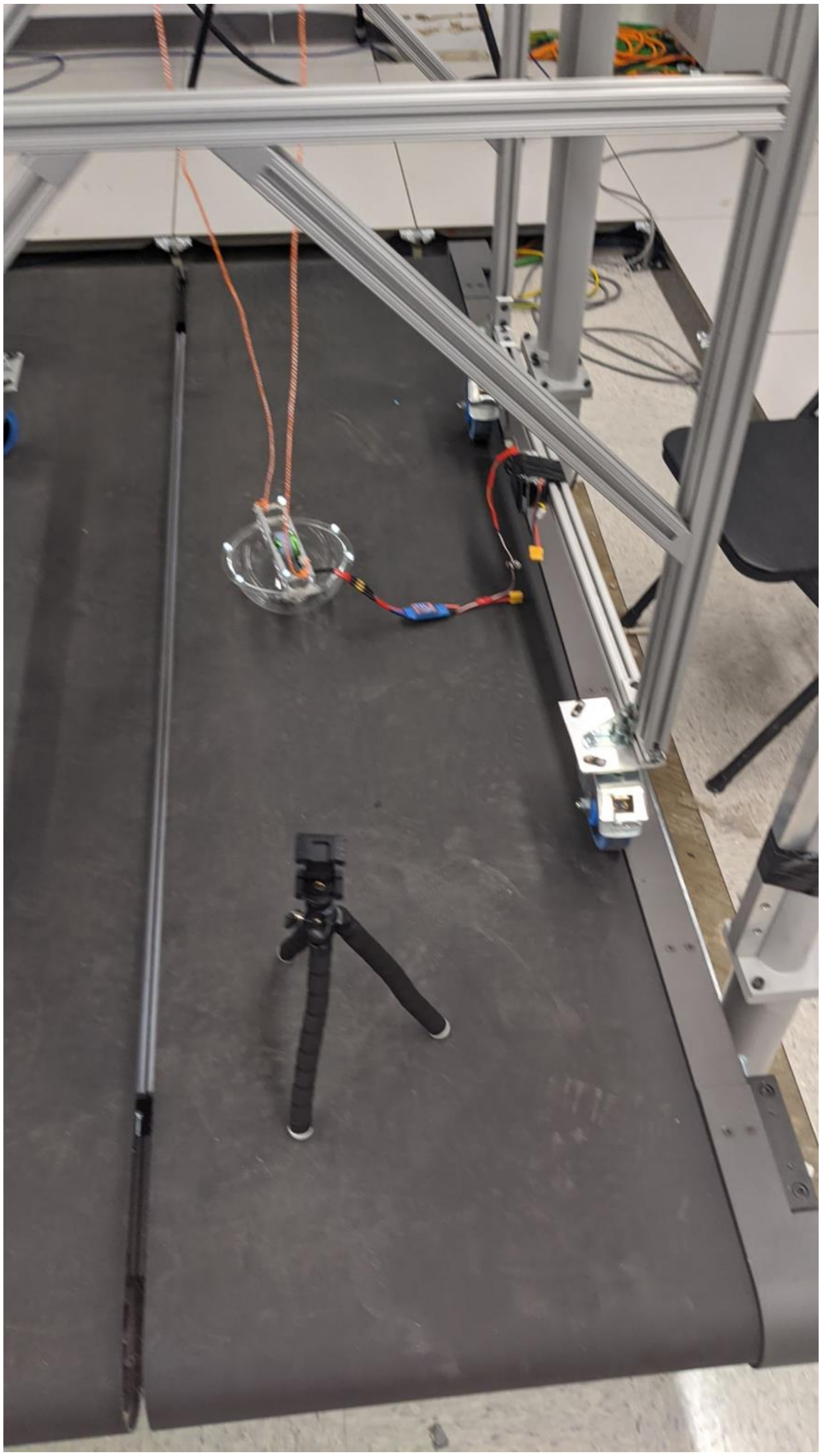
Zhao, Jianguo, et al. "Controlling aerial maneuvering of a miniature jumping robot using its tail." Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on. IEEE, 2013.

Appendix A

This appendix has miscellaneous figures, snapshots, notes, etc. that did not belong in the main manuscript. Some of these may be removed in the next version of this thesis.

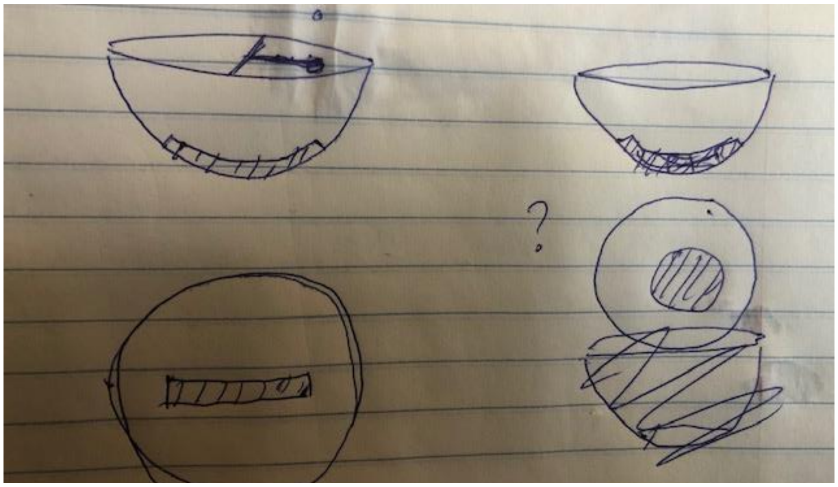


Example of Haro in anime



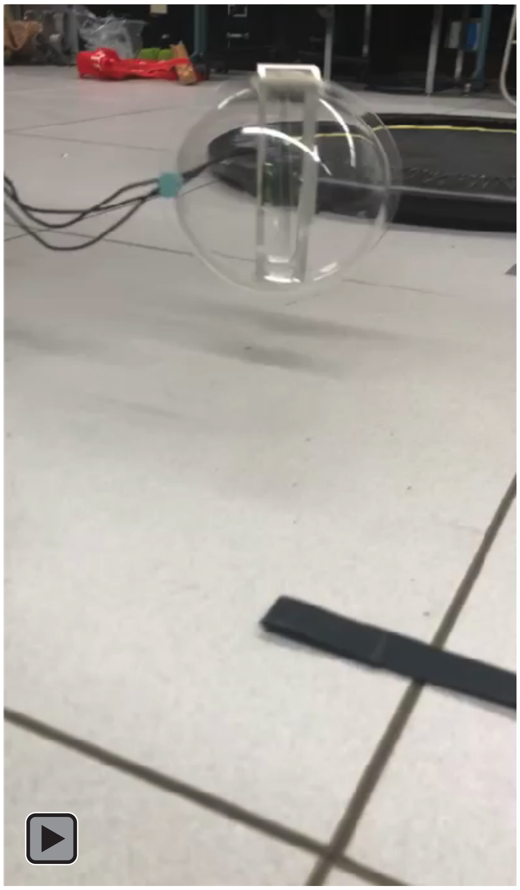
Video shooting setup

How to fasten the motor

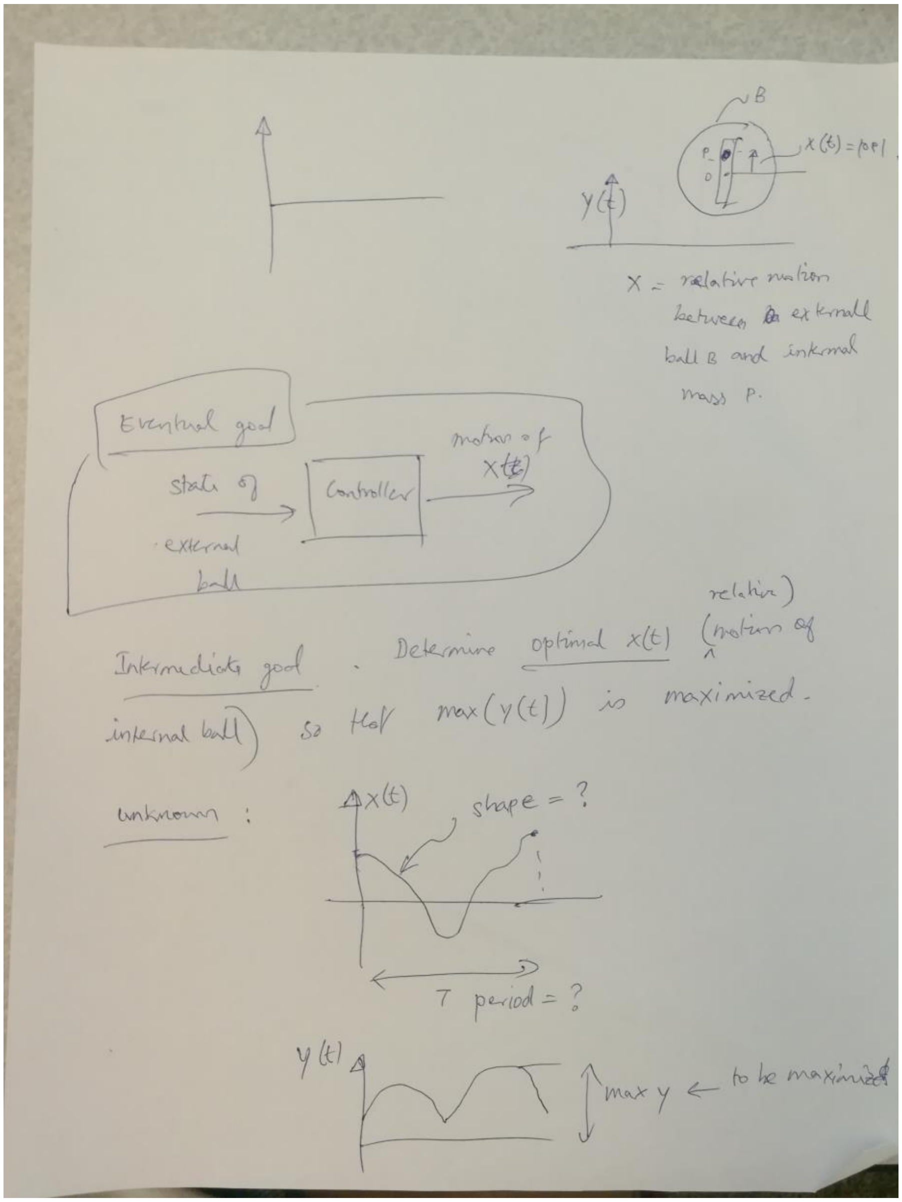


Bottom mass design

Hand-held compactor

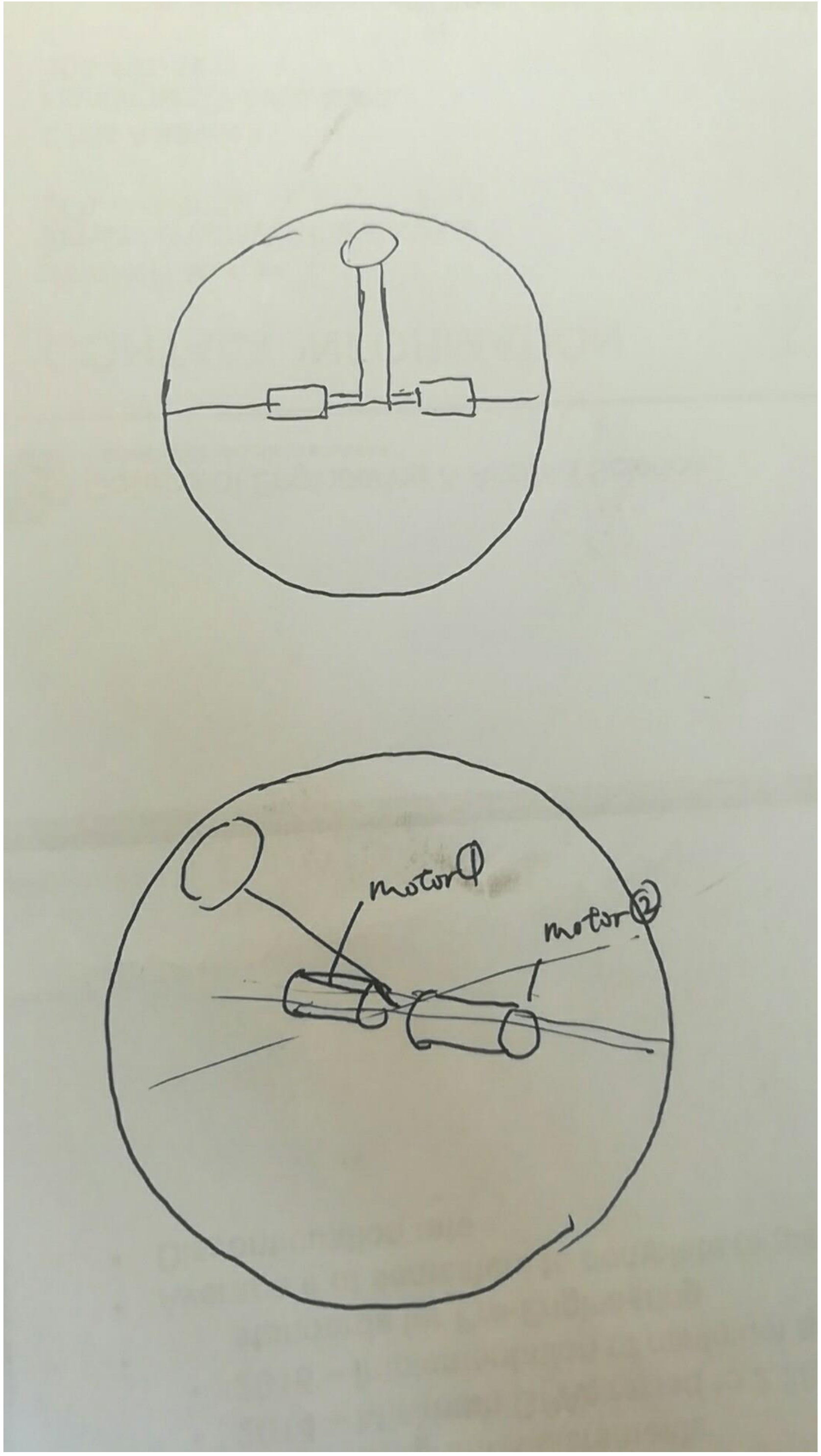


Initial test after assembly

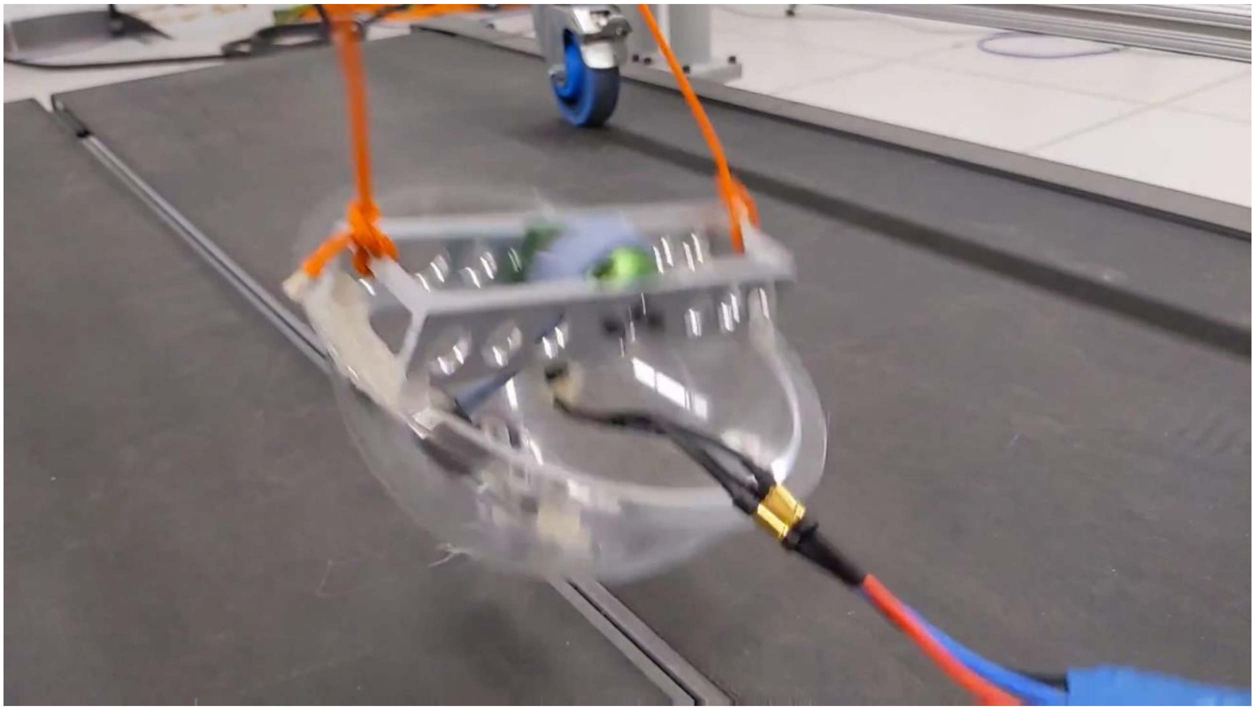


Notes from discussion

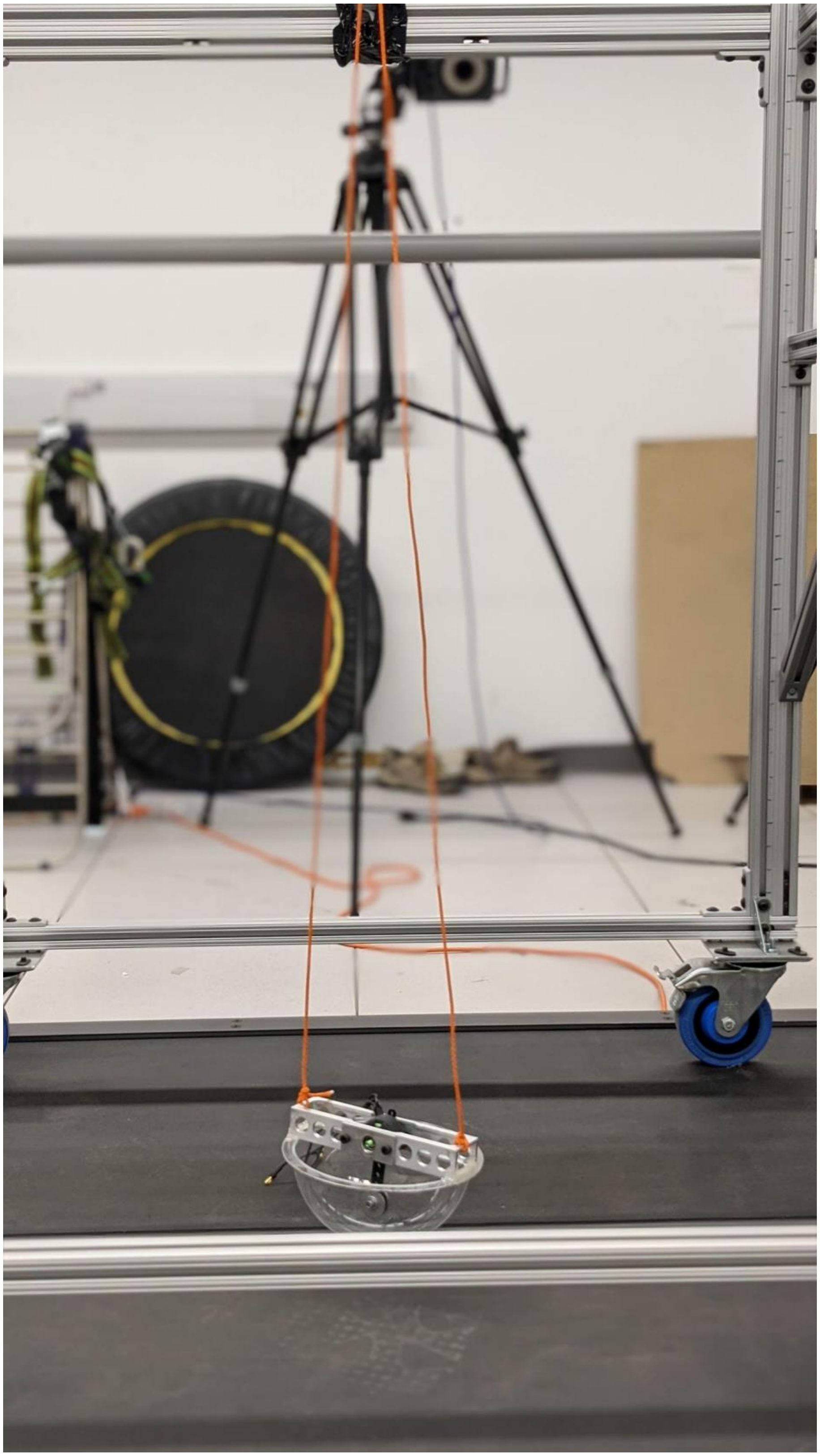
Extra resin of color grey



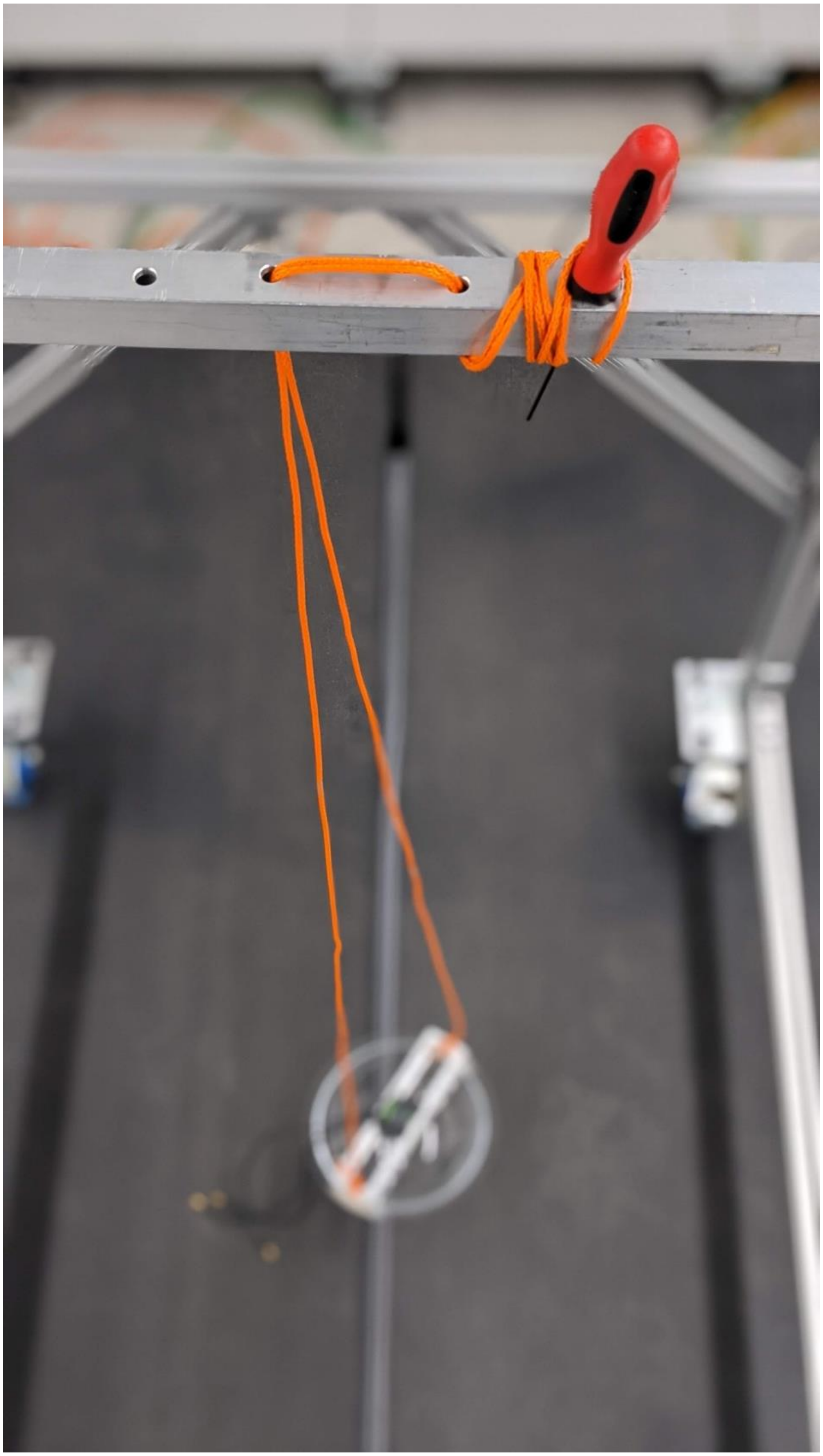
Design concept of prototype 3.0



Frame capture of final prototype bouncing

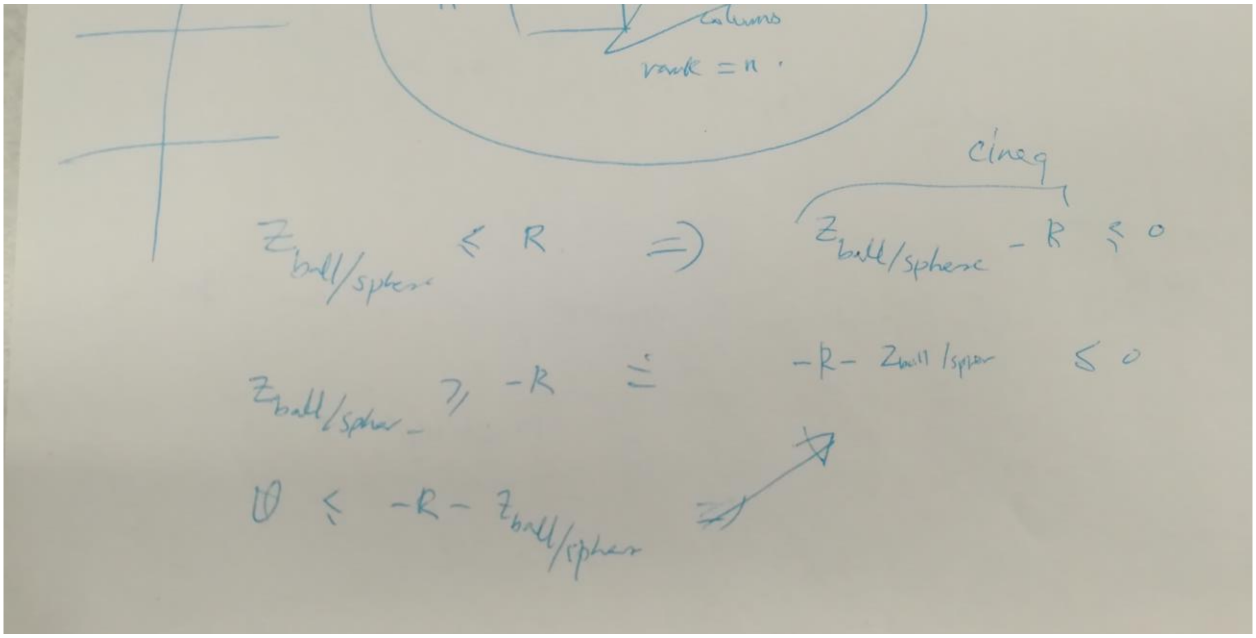


Side view of testing setup

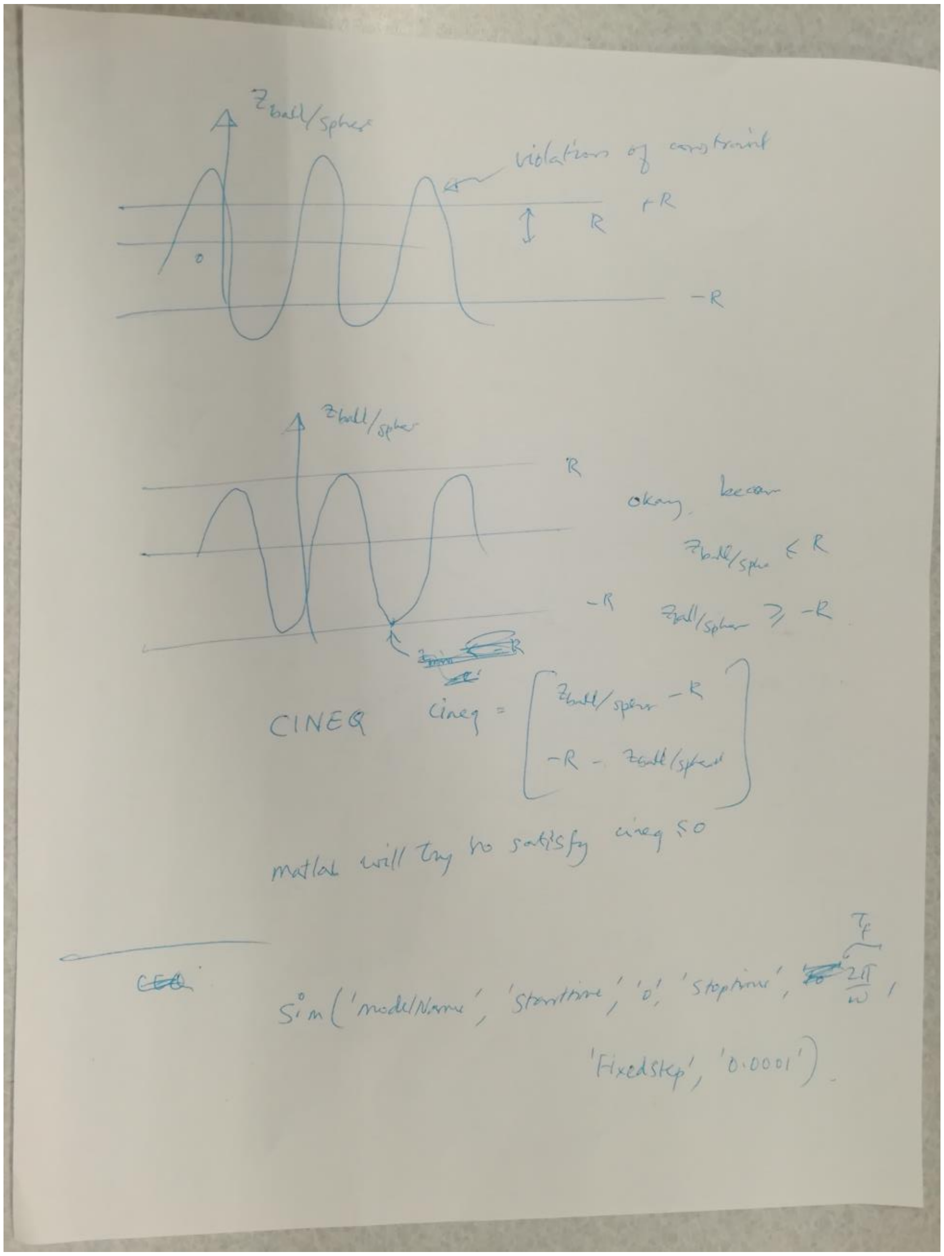


Top view of testing setup

Testing of prototype 1.0



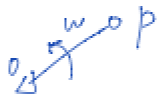
Note from discussion



Note from discussion

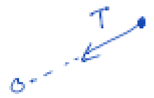
Stress calculation

Consider a mass P attached to a pivot O by a massless bar OP.



OP spins with a angular velocity ω. Ignore gravity for moment.

Then drawing FBD of P



the tension force along OP is the only force use polar coordinates

$$\bar{a} = -r\omega^2 \hat{e}_r + r\dot{\omega}\hat{e}_\theta \quad (\dot{\omega} = 0)$$

$$\sum \bar{F} = m\bar{a}$$

$$\Rightarrow \quad -T\hat{e}_r = m(-r\omega^2 \hat{e}_r$$

$$T = mr\omega^2$$

Tension along the bar is the "centrifugal force" $mr\omega^2$

If the bar OP has cross-sectioned area A the axial stresses

$$\sigma_{axial} = \frac{T}{A} = \frac{mr\omega^2}{A}$$

average tensile strength (yield strength?)

σ_{yield} of ABS $= 28.5$ MPa $= 28.5 \times 10^6\ N/m^2$

of PLA $= 56.6$ MPa $= 56.6 \times 10^6\ N/m^2$

Note from discussion

Estimate σ axial for your m, w, R and A
and see if it was close to σ yield

___ what is the minimum area needed
so that

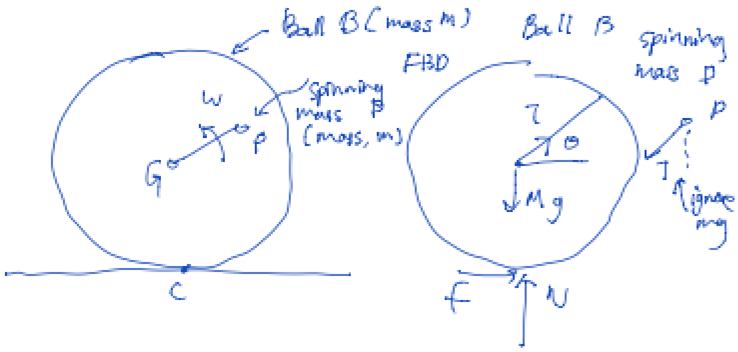
$$\sigma_{yield} = \sigma_{axial} ?$$

$$A = \frac{m r w^2}{\sigma_{yield}}$$

Make effective area, say 3 times bigger so
that you can have a factor of safety = 3

Simplification: ignoring gravity, ignoring that op
has mass too etc.
but a factor of safety = 3 will take care of such
things

Note from discussion



- Assume that that the big ball mass M is in contact with the ground and not yet moving

Let us

- Assume that w is high enough that we can ignore mg in computing force T

  Then $T = mrw^2$ (as in previous PDF)

- Report M, m, r for your robot

  what is the minimum w for the motor?
  What is the rating and what w does it actually spin at (based on video or IR sensor)?

- When $\theta = 90°$

  $T - Mg + N = Ma_y$ (because the big mass is not yet lost contact)

  $-N + Ma_y = T - Mg.$

Note from discussion

The big mass starts losing contact when $N=0$ and starts moving upward when $T > Mg$

ie, $mr\omega^2 > Mg$

$$\omega^2 > \frac{Mg}{mr}$$

$$\boxed{\omega > \sqrt{\frac{Mg}{mr}}}$$

Can we estimate this ω based on your robot's mass M, g, m, and r? ?

Is this ω smaller than your minimum motor speed?

Of course, this is a very simplified calculation

Actually, if are want to include the weight of the small mass

when $\theta = 90°$ P $\downarrow mg$ $\downarrow T$

$$T + mg = mr\omega^2$$

$$\boxed{T = mr\omega^2 - mg}$$

Then when we want

$T > Mg$, we have

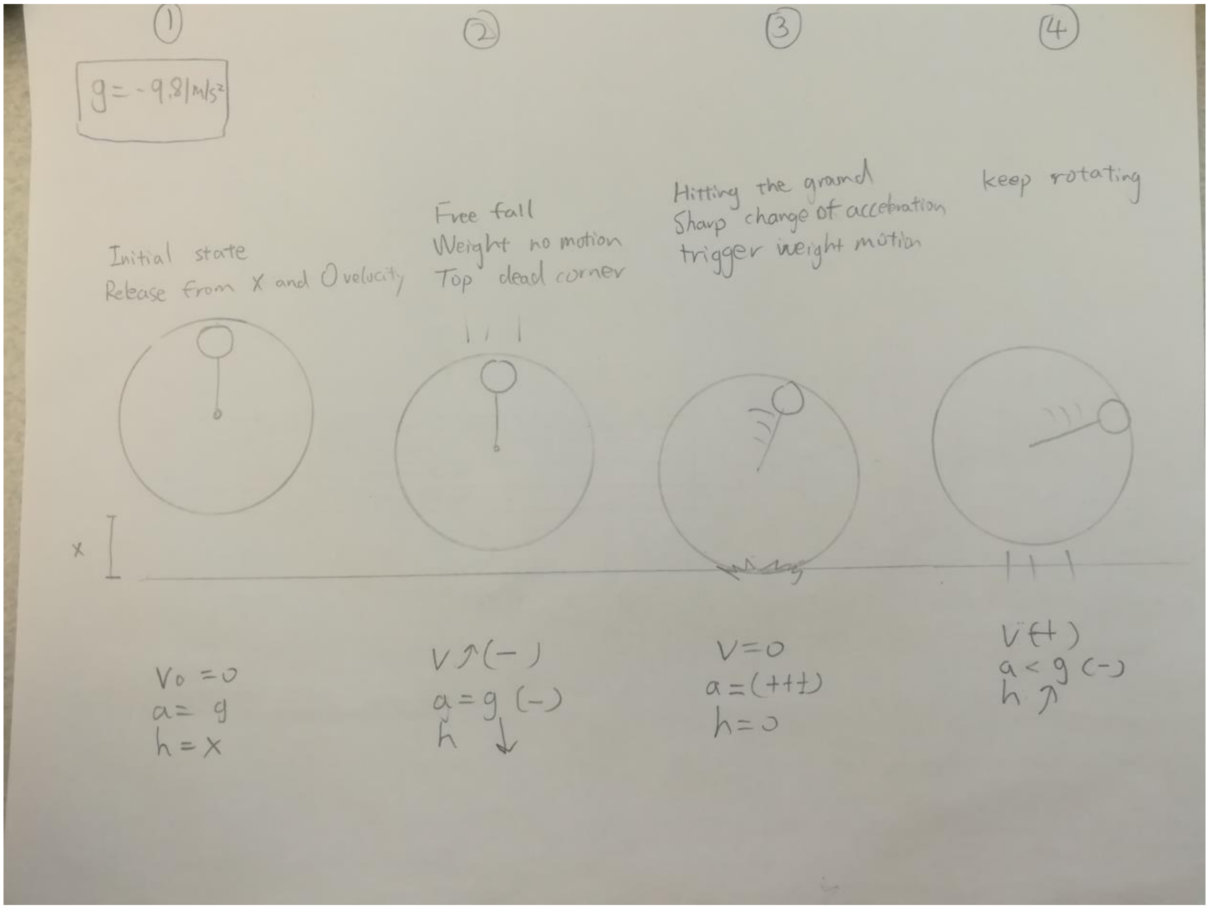
$$mr\omega^2 - mg > Mg$$

$$mr\omega^2 > (M+m)g$$

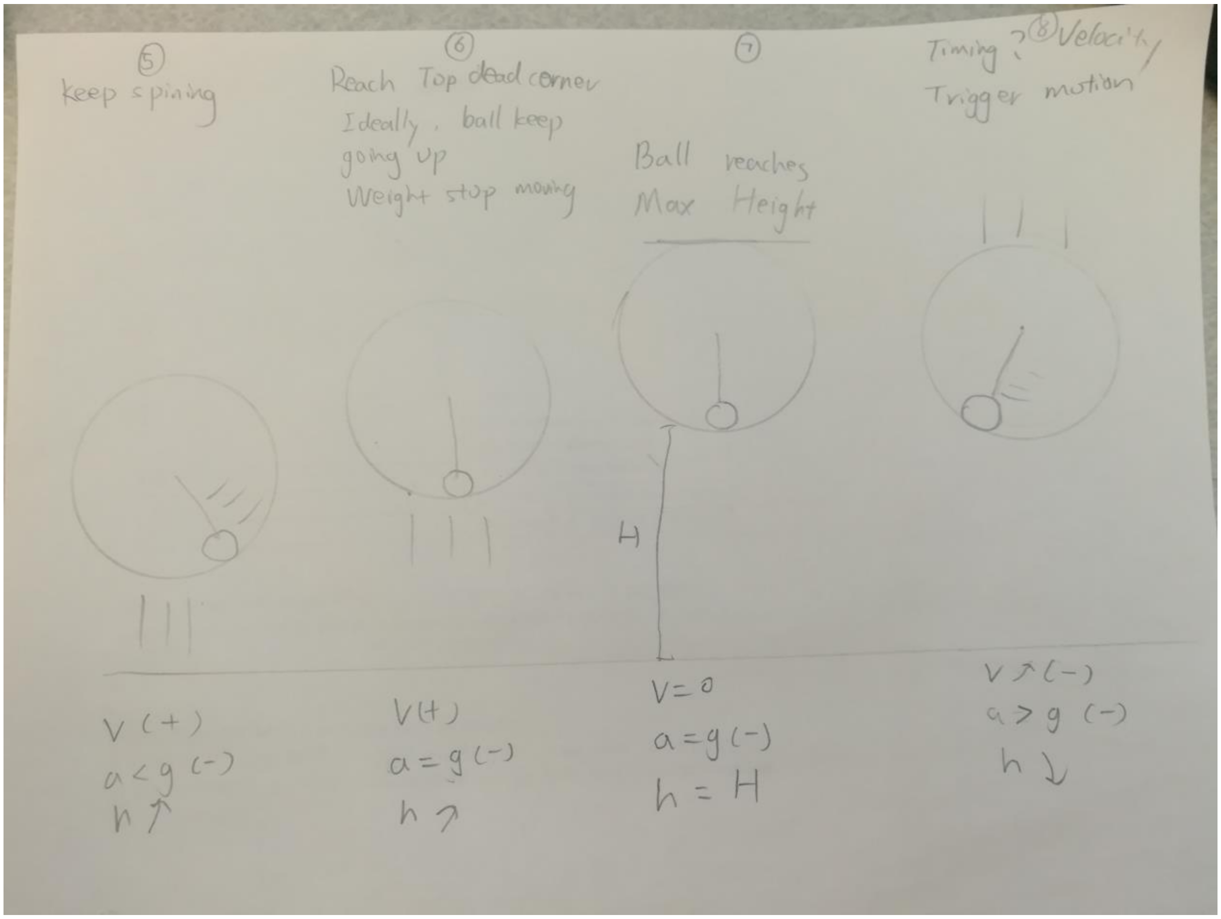
USE this formula insted?

$$\boxed{\omega > \sqrt{\left(\frac{M+m}{mr}\right)g}}$$

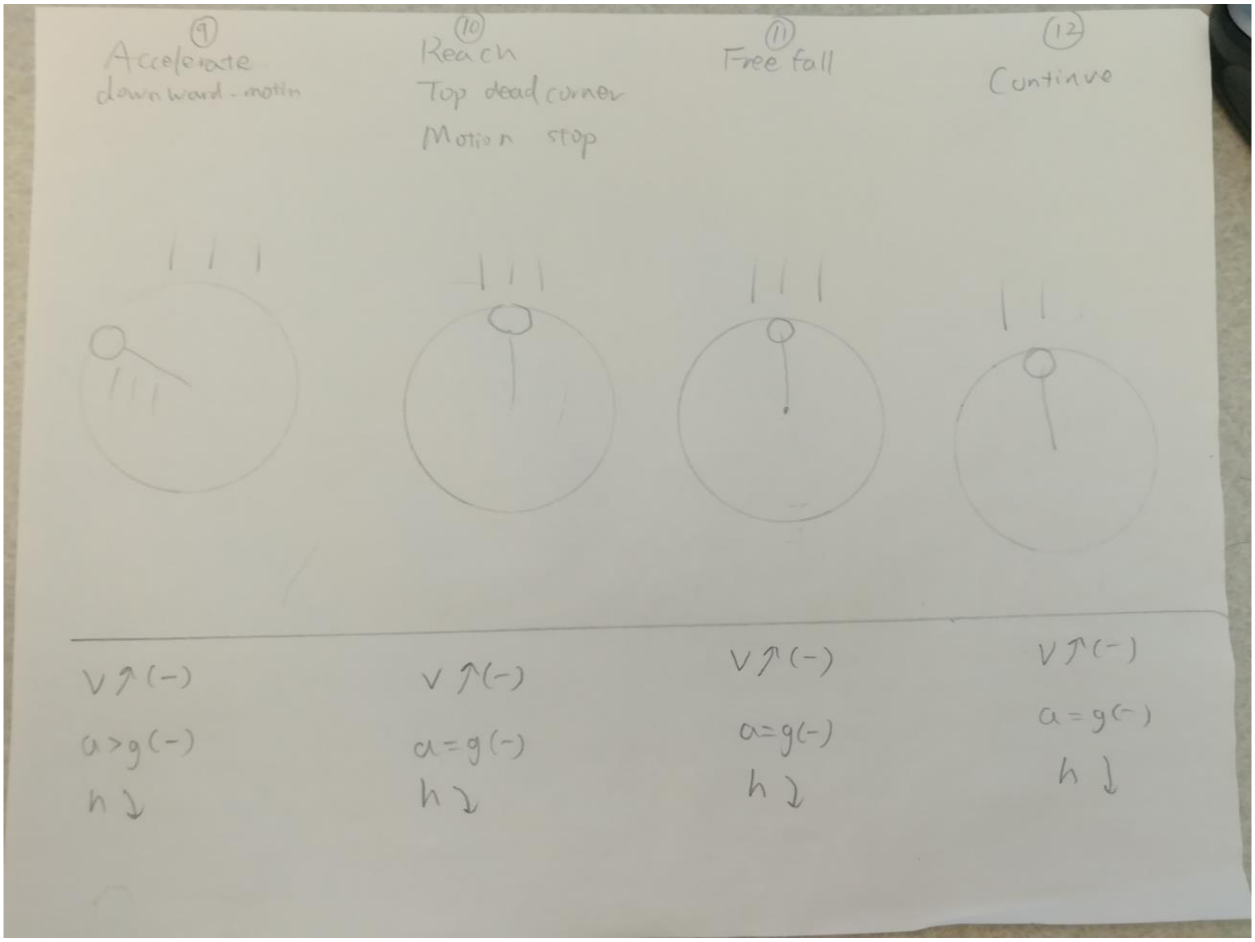
Note from discussion



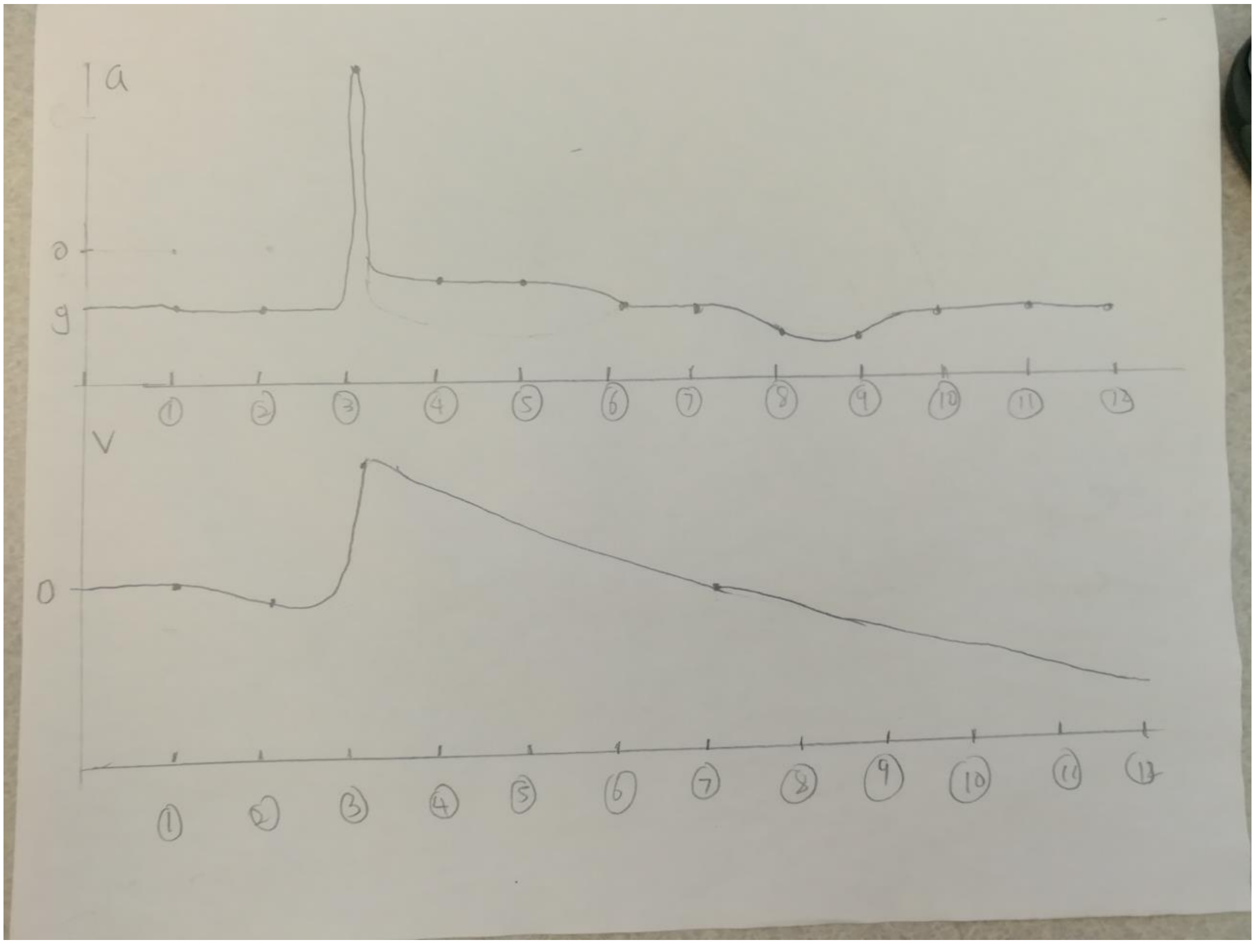
Early conceptual drawings by the author for the bouncing and synchronization pattern



Early conceptual drawings by the author for the bouncing and synchronization pattern



Early conceptual drawings by the author for the bouncing and synchronization pattern

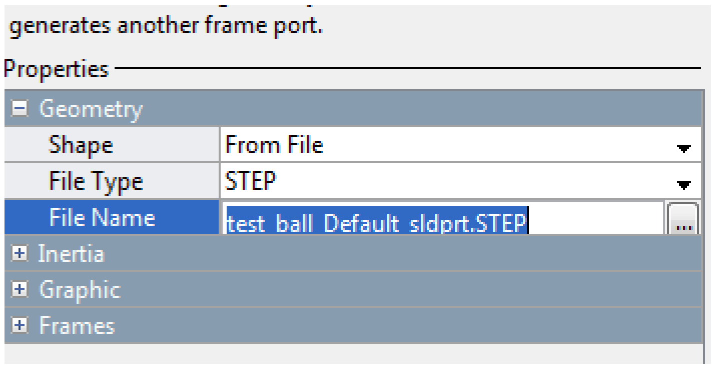


Velocity and acceleration of deal bouncing pattern.

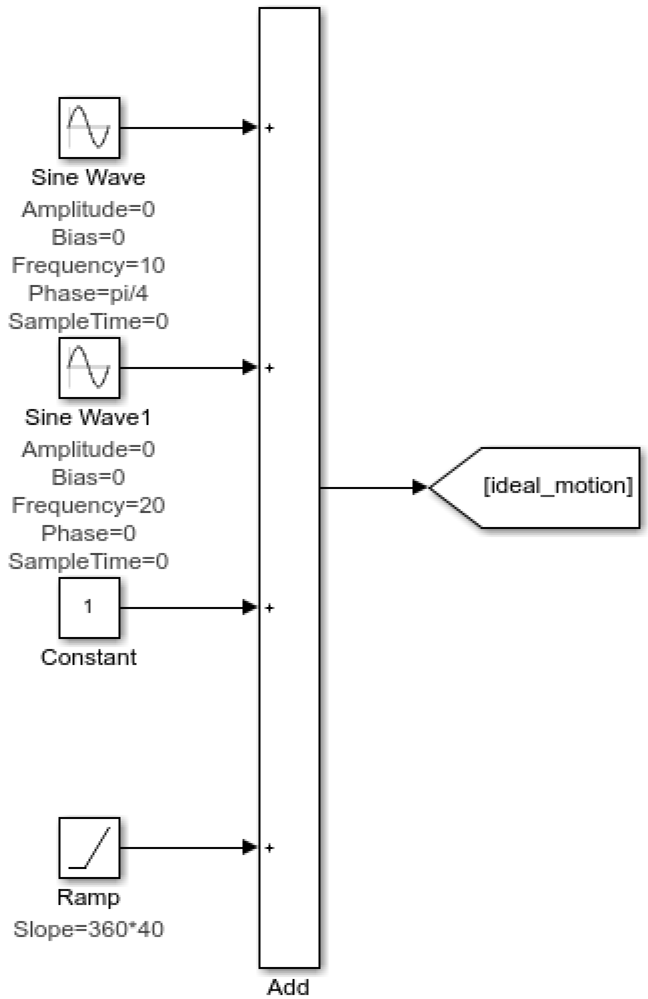
As shown in the diagrams above, ideally if the spinning pattern and bouncing pattern synchronized, the robot would get maximum bouncing height possible. In an ideal scenario, say when the weight almost reaches the top end (the compression force is too weak to hold the spring), the spring stores enough energy and rebounds the sphere, subsequently, the weight passes the top end and swings down which further highers the ball. When it reaches the bottom end, the motor breaks and right before the ball hits the ground, the arm swings upward to compress the spring.

I remember I changed all the file directories after copying the files. If it wasn't changed for some reason, you can click the rigid body block and change it in your directory. I've copied all the STEP files (SolidWorks parts) along with the program so if you could hook them up it would be good to run.

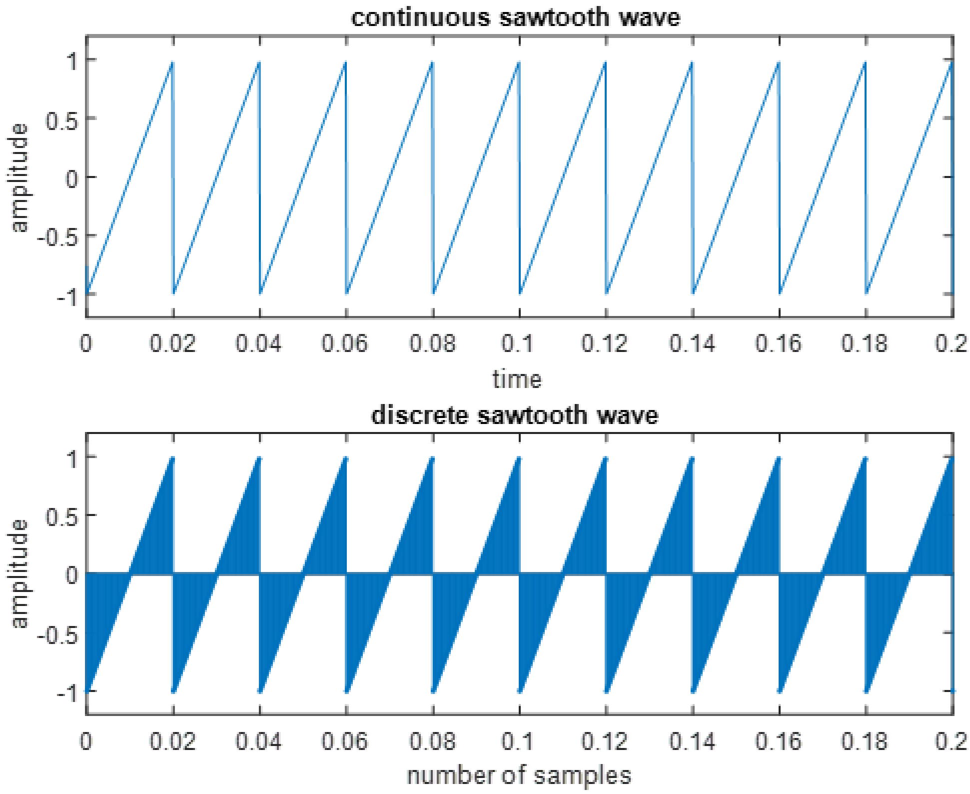
Here is where to change the directory.



Importing SolidWorks files



Approach to combine different signal shapes to imitate the ideal spinning pattern.



Approach to input force/motion to imitate the ideal spinning pattern.

Appendix B

This appendix lists the list of webpages from which illustrative photographs in the thesis have been drawn from (assuming fair use for educational purposes).

Figure 1.01: GuardBot's HARV 95 ROBOT ROLLING UNDER CAR. GuardBot. 2018

https://www.youtube.com/watch?v=sMpPw9x4mvs

Figure 1.02.(From student to professional. Vicky Gao. 2017.https://medium.muz.li/from-student-to-professional-2bccb86f77a2)

Figure 2.01: Sphero robot. A) Sphero BB-8 App-Enabled Droid Review.Timothy Torres. 2015.https://www.pcmag.com/reviews/sphero-bb-8-app-enabled-droidB) BB-8 Sphero Teardown. Dave Evans.2015. https://www.fictiv.com/blog/posts/bb-8-sphero-teardown C) The Physics of How That Star Wars BB-8 Toy Works. Rhett Allain. 2015. https://www.wired.com/2015/09/physics-star-wars-bb-8-toy-works/

Figure 2.02: C)Sand Flea robot is set to leap into reconnaissance (w/ video). Nancy Owano. 2012. https://phys.org/news/2012-03-sand-flea-robot-reconnaissance-video.html

D) 3D One-Leg Hopper. MIT Leg Lab. 1983-1984. http://www.ai.mit.edu/projects/leglab/robots/3D_hopper/3D_hopper.html

Figure 2.04: A)Parrot Jumping Night MiniDrone - Buzz (White). Amazon. https://www.amazon.com/Parrot-Jumping-Night-MiniDrone-White/dp/B0111O8VNQ B) Parrot MiniDrone Jumping Sumo review. Joshua Goldman. 2014.https://www.cnet.com/reviews/parrot-minidrone-jumping-sumo-review/C)How to replace Jump Mechanism on Parrot Jumping Sumo. Parrot. 2014. https://www.youtube.com/watch?v=1nePU5mz8Z4

Figure 2.03: A)Magic Roller Ball Toy,Cute Rolling Vacuum Floor Sweeping Robot Cleaner with 4pcs Colorful Covers Set. (Amazon). https://www.amazon.com/gp/product/B07D7RX8QT/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1 B) Spherical Rolling Robot. David Carabis. 2013. https://www.youtube.com/watch?v=LmvUkbdXNbM D) Real life robotic ball drone has been tested by US marines and is like devices in Jurassic World and the BBC The Prisoner. Brian Wang. 2016. https://www.nextbigfuture.com/2016/11/real-life-robotic-bll-drone-has-been.html

Figure 2.05: Gravel Soil Compacted High Technology Frog Compactor. MachineTo.

http://www.machineto.com/gravel-soil-compacted-high-technology-frog-compactor-10106361

Figure 2.07: Anti Gravity wheel. Veritasium. 2014. https://www.youtube.com/watch?v=GeyDf4ooPdo

Figure 2.08: Cams. eduqas. http://resource.download.wjec.co.uk.s3.amazonaws.com/vtc/2016-17/16-17_1-

4/website/category/4/functions_of_mechanical_devices/function_of_mechanical_products/media/documents/cams.pdf

Figure 2.09: The effect of arm swing on lower extremities in vertical jumping. Mikiko Hara, Akira Shibayama, Daisuke Takeshita, Senshi Fukashiro. 2006. https://www.sciencedirect.com/science/article/abs/pii/S0021929005003647

Figure 4.29: Roly-poly toy. BRITANNICA KIDS. https://kids.britannica.com/students/assembly/view/53661