"Never tell me the odds!"
-Han Solo

A Mynock Design Report

Millennials' Falcon
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1 Executive Summary

In a galaxy far, far away….

...the *ME112: Mechanical Systems Design* students were tasked with keeping mynocks[1] from damaging visiting ships with their electrical pulses in a humane way. The robotic mynock would be responsible for jumping off the ground autonomously and sticking to the hull of the "Millennium Falcon" within five seconds of being activated, thus indicating to other Mynocks that the spaceship was already claimed. We took inspiration from the unfolding legs of frogs as they jumped into the air.

When designing our robot, we initially focused on height and stability. This led us to a six-bar linkage system with connecting sets of gears at the top and bottom of the robot to reduce degrees of freedom. However, weight reduction, center of gravity and a release mechanism later became our priorities, and we shifted from the six-bar linkage to a five-bar linkage design. The five-bar design decreased the mass of the lower half of the robot, allowing for a much higher and more efficient jump. The five-bar linkage system was also far more similar to actual frog jumping behavior.

Our final design used a Tamiya 6-Speed motor box with a 1300.9:1 gear ratio, as seen in Figure 1.1. It ran at 9 volts and 0.75 Amps from one battery while loading. Our design performed successfully after several attempts in which it jumped just short of a meter on demonstration day. We made adjustments to increase the spring constant of our robot after which it successfully latched onto the hull of the Millenium Falcon. Our decision to rapidly prototype different versions of our mynock helped us to quickly build a robot that jumped and learn to improve its jumping capabilities. However, it would have served us well to compare our design ideas to the biomimetics of frog jumping earlier in the process.

If we were to continue improving our design, we believe there are several simple adjustments we could make that would vastly improve the success rate. For example, we would more clearly define the minimum spring constant, k, necessary to achieve a jump of one meter and find fewer, larger rubber bands that met that spring constant. Our group would also add a small switch the the robot, reduce weight and friction by using lighter and smoother materials, test more motor-battery configurations, and ensure the string-motor system pulled the robot straight down instead of precariously leaning towards one side. Adjusting the robot so that the string-motor system pulled the robot straight down would have also helped our creation better mimic frog and mynock behavior.

[1] A mynock is a fictional creature from the popular *Star Wars* films.

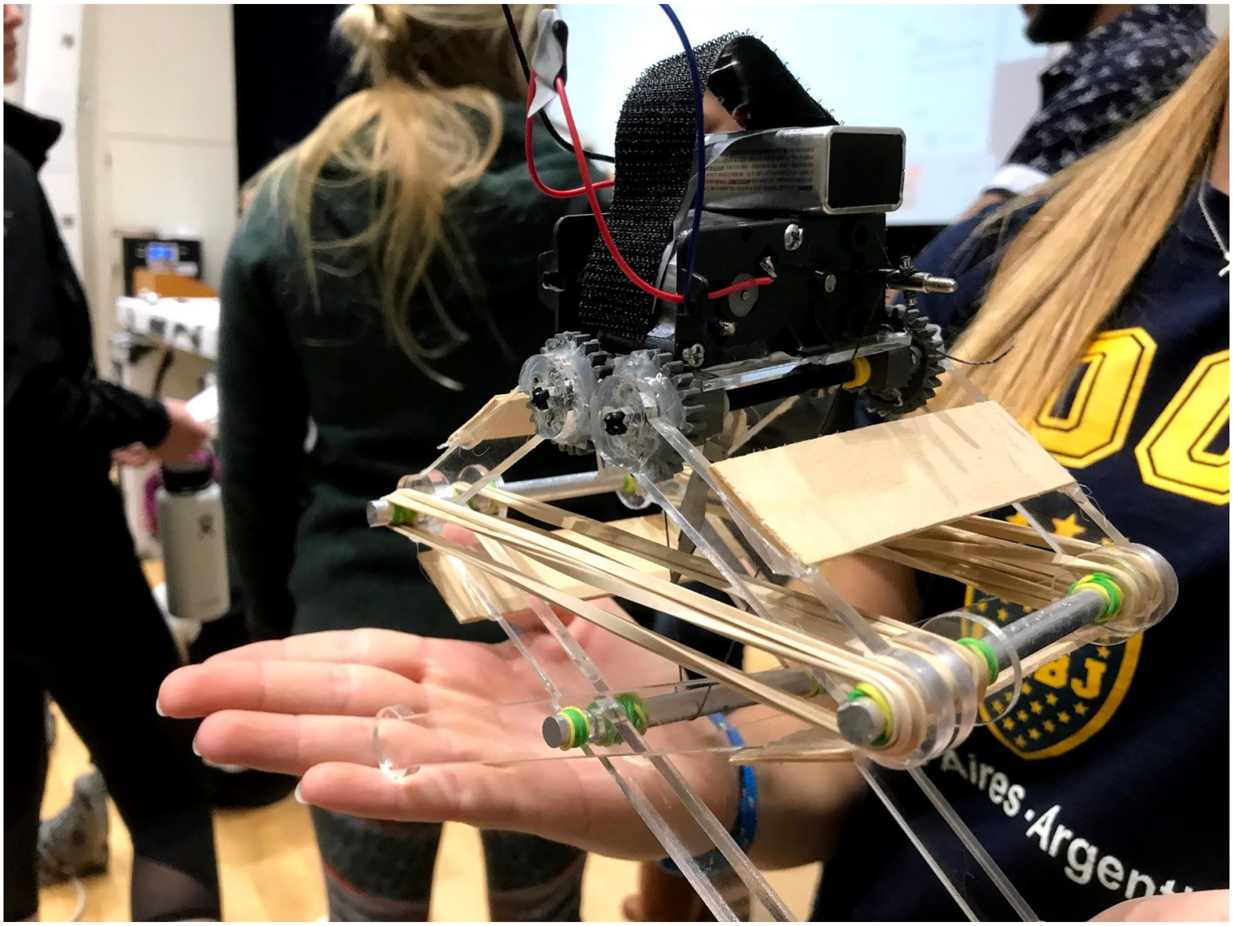


Figure 1.1: Our final jumping mynock robot.

Contents

2 Background

2.1 Overview

The goal of this project was to create an autonomous jumping mynock robot. The robots were intended to keep mynocks off of spaceships, humanely, to avoid spaceship damage. For this assignment, mynocks were described as a key part of the outer space ecosystem so it was important our solution deterred them without eliminating them. Observations of wild mynocks revealed that they are communal but territorial. They will not come within several meters of another feeding mynock. A mynock jumping onto a spaceship's hull is an indication to other mynocks that it has staked claim. Therefore, our mission was to design a robotic mynock to emulate mynock behavior, staking claims on spaceships and deterring real mynocks without actually doing any damage.

As mynocks are fictional creatures from the popular *Star Wars* films[2], the closest living creature we could emulate was a frog. Our group began by looking at research on frog motion. "Biological Jumping Mechanism Analysis and Modeling for Frog Robot" by Wang et al.[3] was helpful in getting us to think about four, five, and six-bar linkage systems. We also watched several videos, like the one in Figure 2.1.1 below, to visualize a frog's takeoff. Appendix A.2 provides a more in depth look at our research, listing several additional sources we found for inspiration.

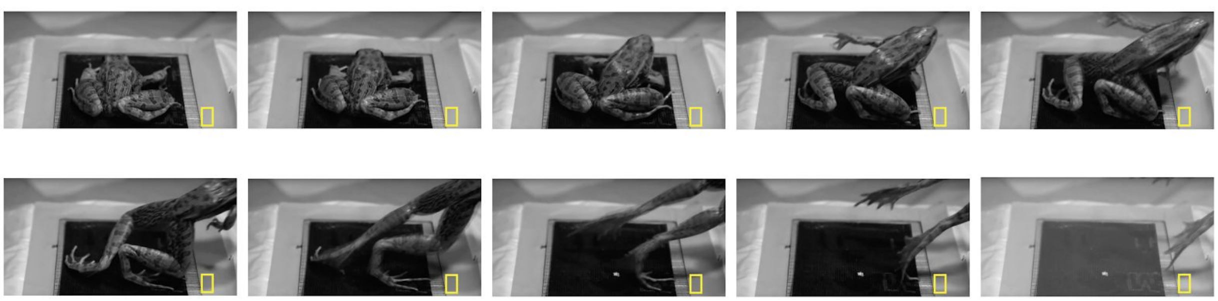


Figure 2.1.1: Screenshots of an Earth frog taking off. Mynock jumping behavior is similar but our design would need to be as vertical as possible. [source: National Geographic, 2010]

[2] "I don't know… I have a bad feeling about this." From *The Empire Strikes Back* (Lucas et al., 1980).
[3] Wang, Meng, et al. "Biological Jumping Mechanism Analysis and Modeling for Frog Robot." Elsevier, vol. 5, no. 3, Sept. 2008, pp. 181–188.

2.2 Design Requirements

Based on the assignment specifications, our team set out to create a durable and reliable model Mynock that would easily leap off the ground and attach itself to the hull of the “spaceship” one meter above. A successful design was measured against four main design criteria, the ability of our robot to:

1) Autonomously jump within five seconds of activation
2) Travel upward at least a meter
3) Stick to the hull of the faux spaceship using velcro
4) Resemble the jumping mechanics of an Earth frog (and mynock)

Other initial design constraints included the size of the robot; it couldn’t measure more than 0.30 meters wide or more than 0.10 meters tall when crouched and ready to jump. Additionally, our device had to be battery operated, meaning our battery would need to be integrated into the design. During the final demonstration, Mynocks would be placed below the “Millenium Falcon” (see Figure 2.2.1 below), and teams would be allowed to switch their mynocks on before they were expected to behave autonomously.

Figure 2.2.1: Pictured here is the testing set-up for the robotic mynocks. The underside of the upper platform is velcro and it is raised one meter above the ground.

3 Design Description

This section discusses our design decisions as we created the mechanical and biomimetic features of our mynock. Below you can see several annotated drawings of our robot. Our mynock design was centered around a few essential features including the motor, the linkages, the energy storage system, and the release mechanism. In order to get a good start on coming up with designs for our mynock we began with some simple calculations to get a sense of what the numbers on the project might look like. Appendix A.5 provides further details, but overall the early calculations gave us at least an idea of the magnitude of values we might need.

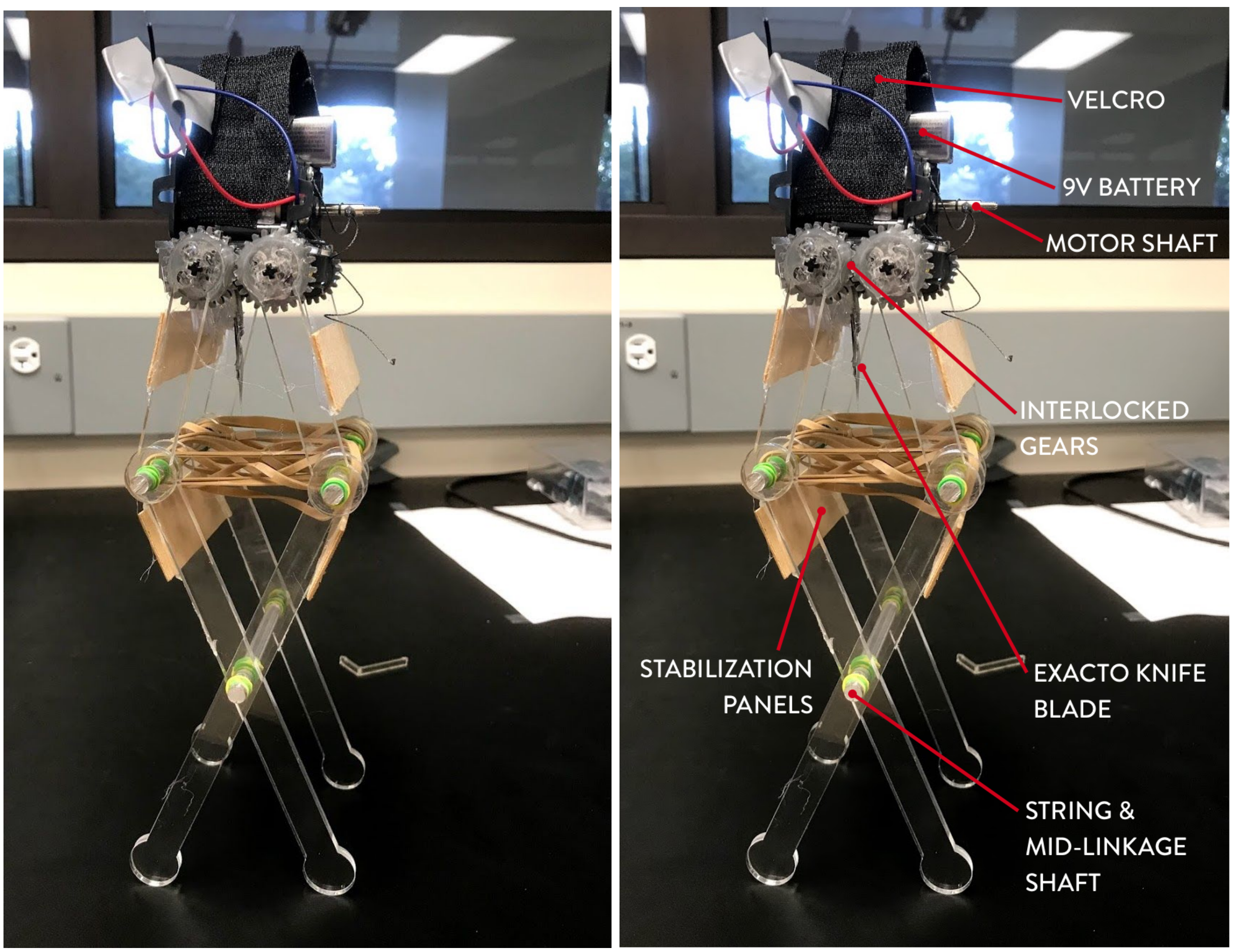


Figure 3.1: Pictured above is our final mynock and an annotated version of the design to highlight some of the key components.

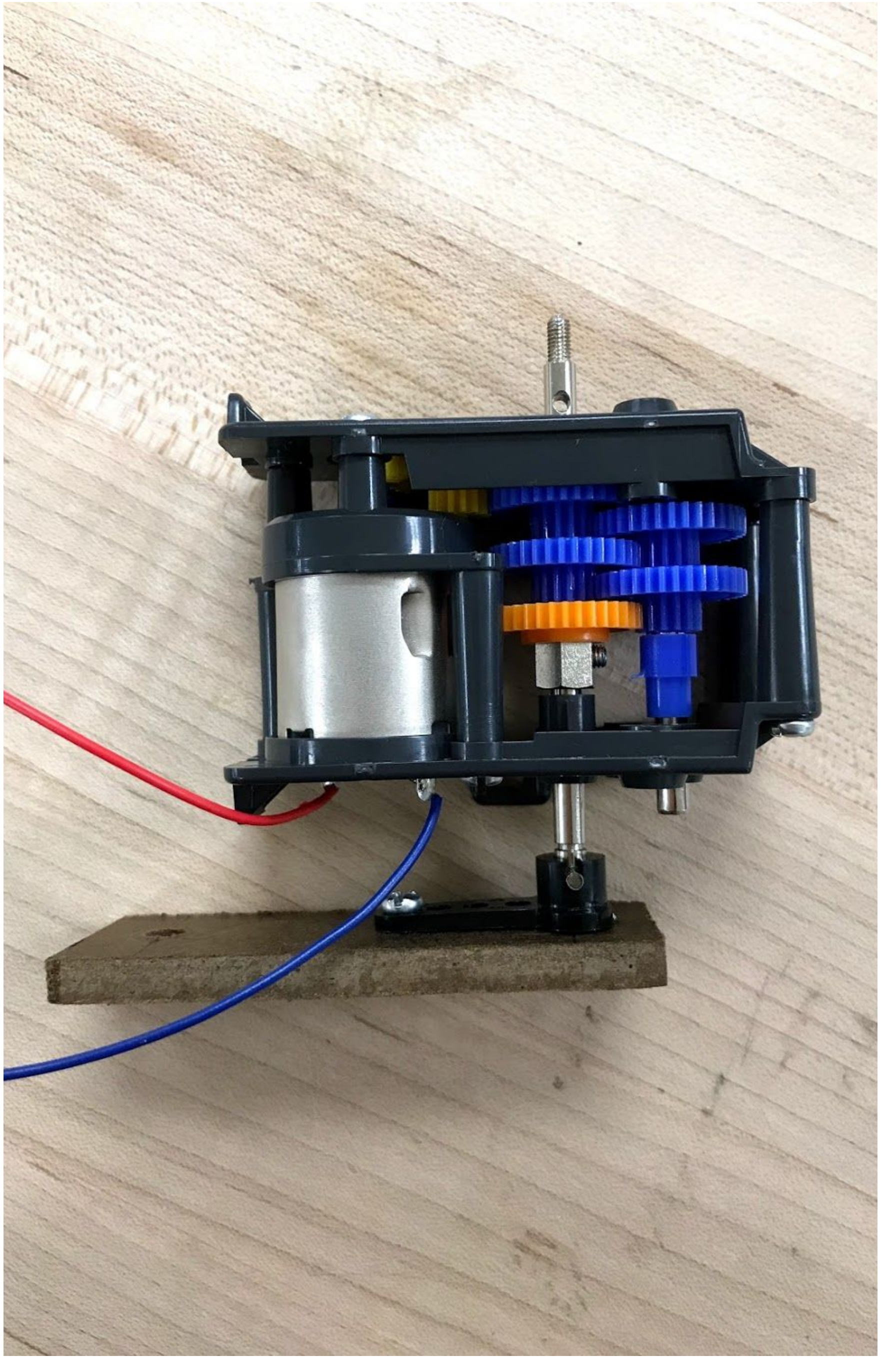


Figure 3.2: Pictured is the Tamiya 72005 6-Speed Gearbox we used on our final robot. More detailed motor specs can be found here: https://www.pololu.com/product/74/specs.

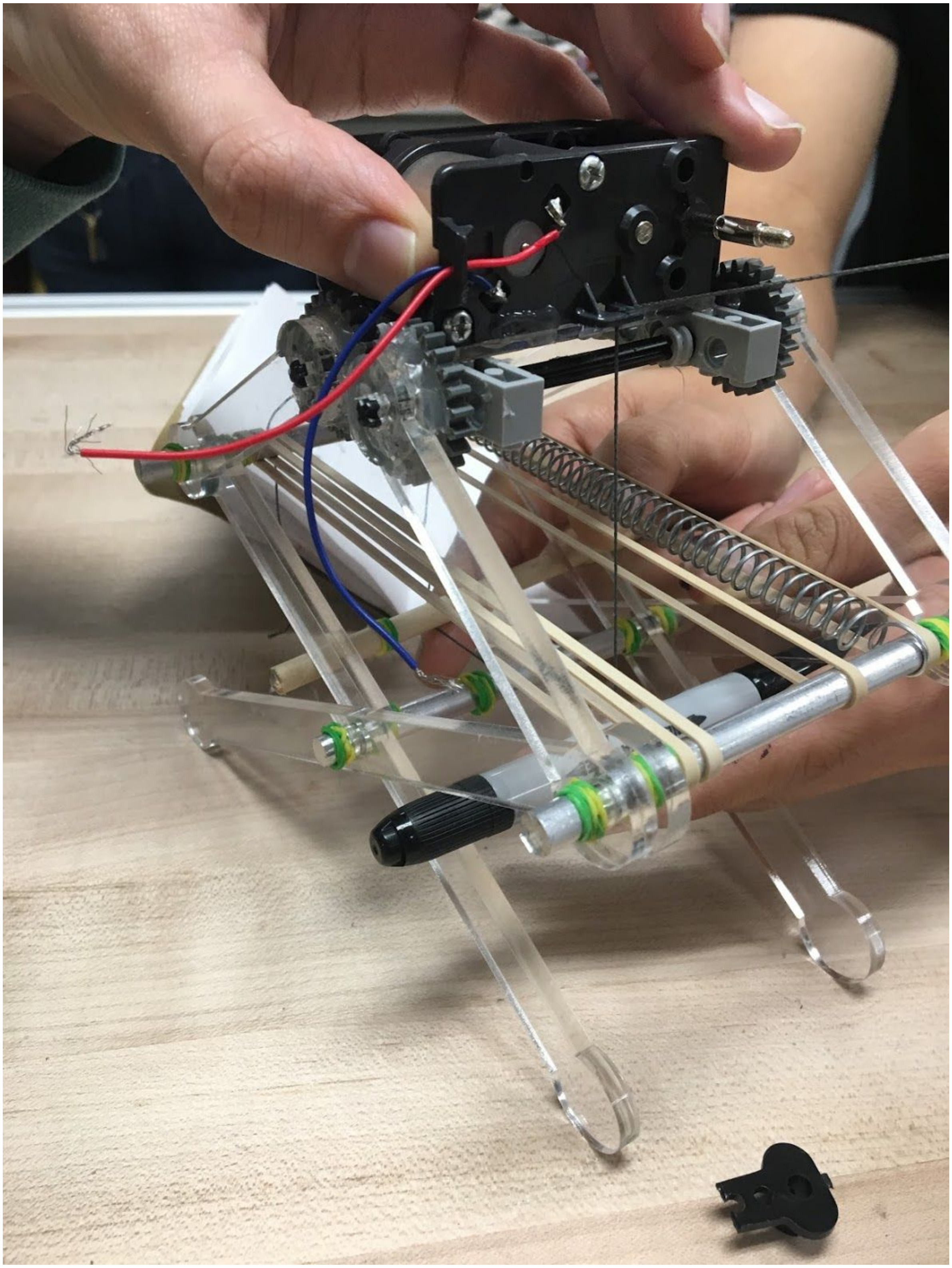


Figure 3.3: The bilateral symmetry of our robot is easily visible here in a design iteration before springs were replaced completely with additional rubber bands and before wooden stabilization panels had been added.

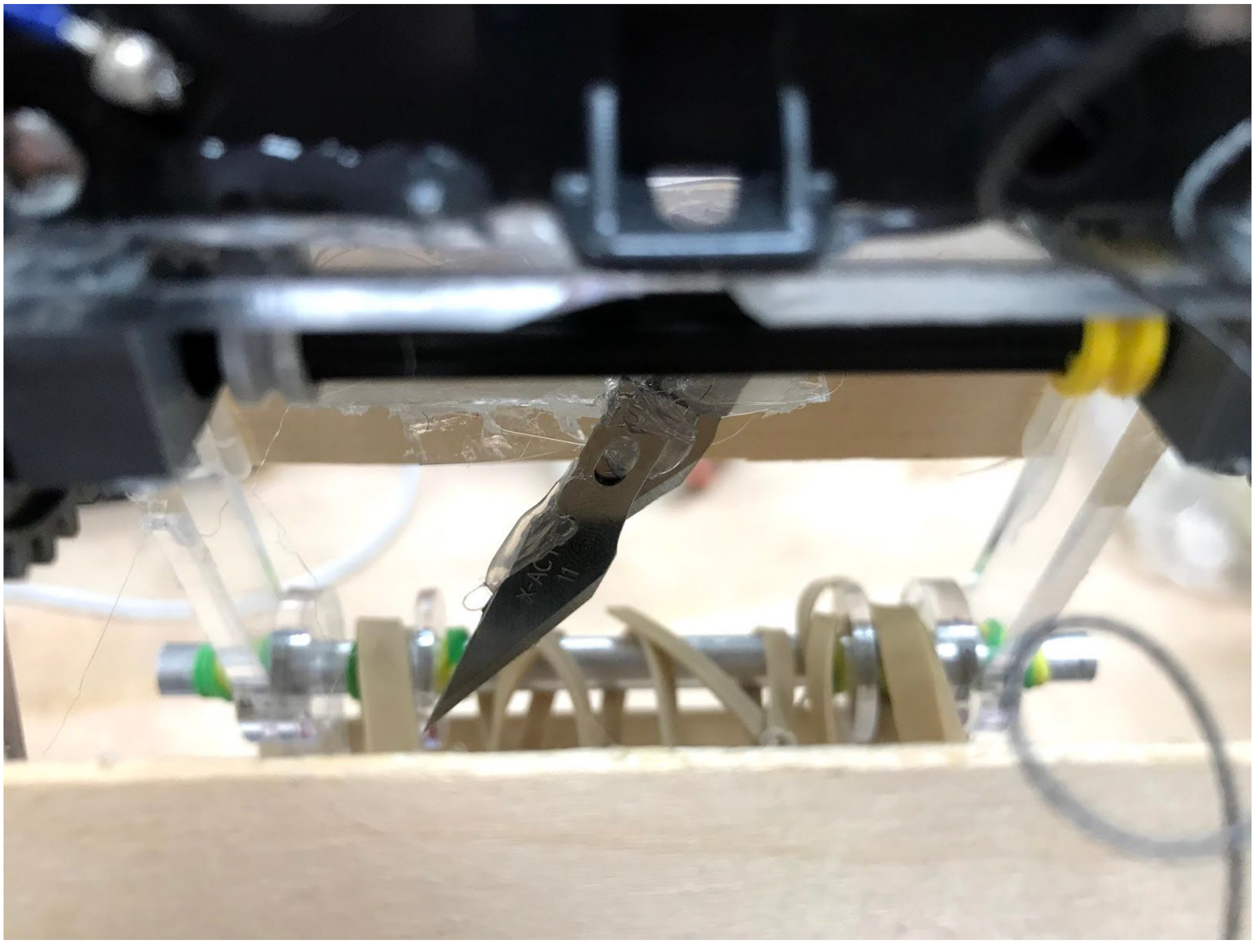


Figure 3.4: A close up view of our release mechanism - an exacto knife blade that slices through the string connected to the bottom shaft and the motor shaft. As the top of the robot lowers down, so does the blade until it eventually comes into contact with and cuts the string.

3.1 Motor Gearbox & Battery

The mynock we made used a Tamiya 72005 6-Speed Gearbox[4] for the final demonstration. The gearbox can be assembled at gear ratios of 11.6:1, 29.8:1, 76.5:1, 196.7:1, 505.9:1, and 1300.9:1. We began running at a 505.9:1 gear ratio before switching to the 1300.9:1 ratio because the clutch in our gear train was skipping and we realized we needed more torque to lower the robot. The new ratio worked much better and was able to successfully compress the robot in tandem with a 9V battery.

During testing we briefly tried a much smaller Yosoo Mini motor[5] in an attempt to reduce weight, however, we struggled to get the required amount of torque, even using two of those motors each running at 12V. We rapidly prototyped a second robot in parallel with the first that was not bilaterally

[4] More detailed motor specs can be found here: https://www.pololu.com/product/74/specs.
[5] More information on this motor can be found here: https://www.amazon.com/Yosoo-Reduction-300RPM-Gearbox-Replacement/dp/B01BBSXDGW

symmetrical, for dramatic weight reduction to see if we could get the smaller motors to perform successfully. This would have meant using fewer rubber bands for a smaller k value. Figure 3.1.1 below shows this parallel prototype, but, the small motors were still unsuccessful with the lighter mynock. The gear ratios on these motors were not adjustable so we returned to the Tamiya motor.

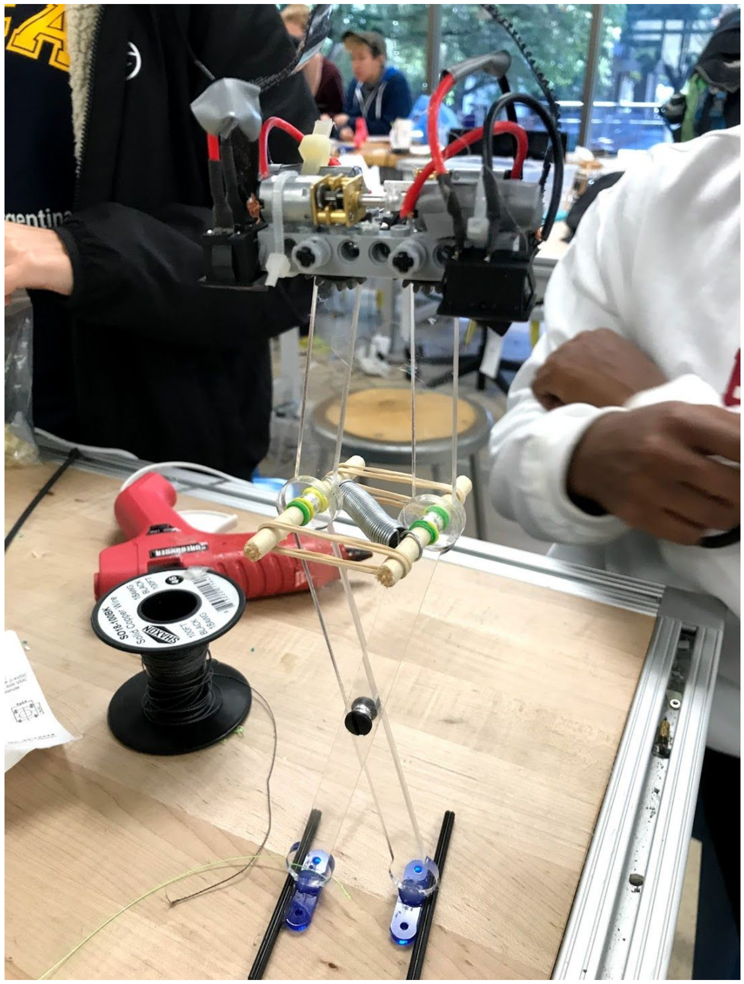


Figure 3.1.1: This prototype was an attempt to dramatically reduce weight and therefore reduce the torque necessary in order to get the smaller motors to work.

The accompanying batteries were essential in getting the motor and robot to run. We attempted to make our small 12V batteries work with both types of motors we tried. However, the amount of current the small 12V batteries allowed limited the amount of torque output and we switched to a larger 9V battery (Figure 3.1.2) with much more success. The additional torque of the 9V battery was still worth the additional weight.

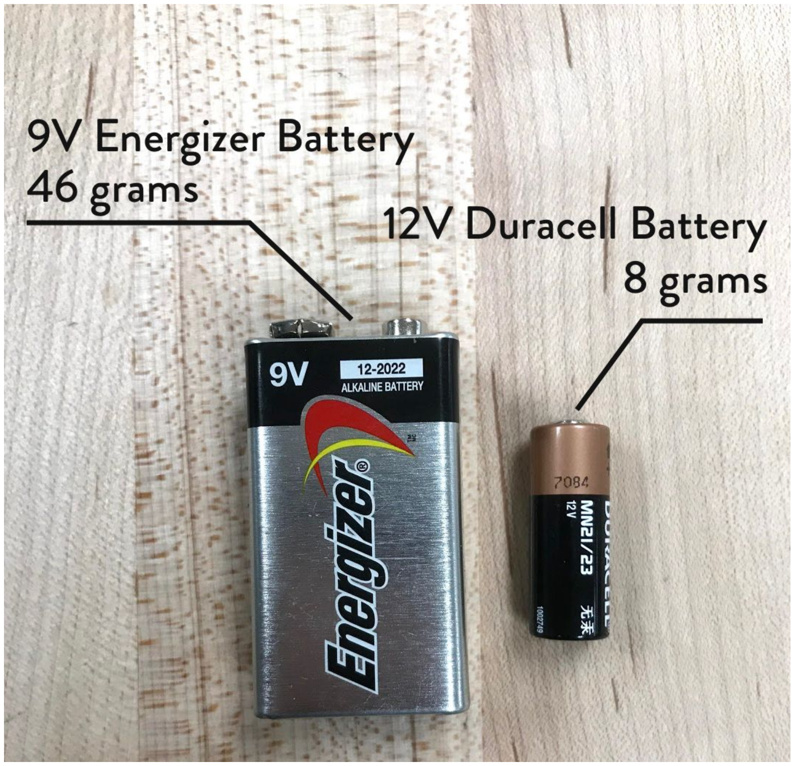


Figure 3.1.2: Comparison of two batteries considered during design.

3.2 Linkage Design

Based on the assignment constraints, our group began by modeling our frog-like jumping mechanism using a six-bar linkage that we hoped would be both simplistic and realistic, while still allowing us to meet the design requirements. We thought that a base plate on the ground would mean extra stability, an early point of concern. Desire for stability also led us to a bilateral design with six-bar linkages on each side connected by platforms. When we switched over to a five-bar linkage design we maintained this bilateral symmetry.

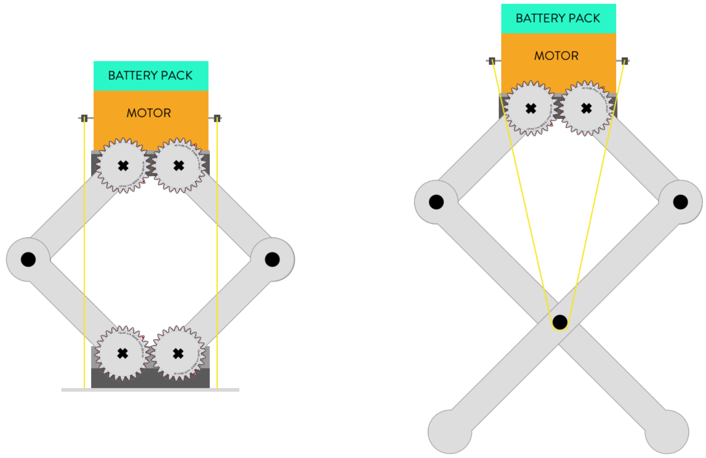


Figure 3.2.1: The left model is our initial six-bar design, while the right shows our final five-bar design. As is evident, foot weight is significantly reduced in the design on the right.

The final five-bar linkage design of our mynock maximized the height it could jump given a certain amount of power by significantly reducing the weight in the feet. As seen in Figures 3.2.1 and 3.2.2, our bottom linkages ended up being double the size of our upper linkages at 7 inches and 3.5 inches, respectively.

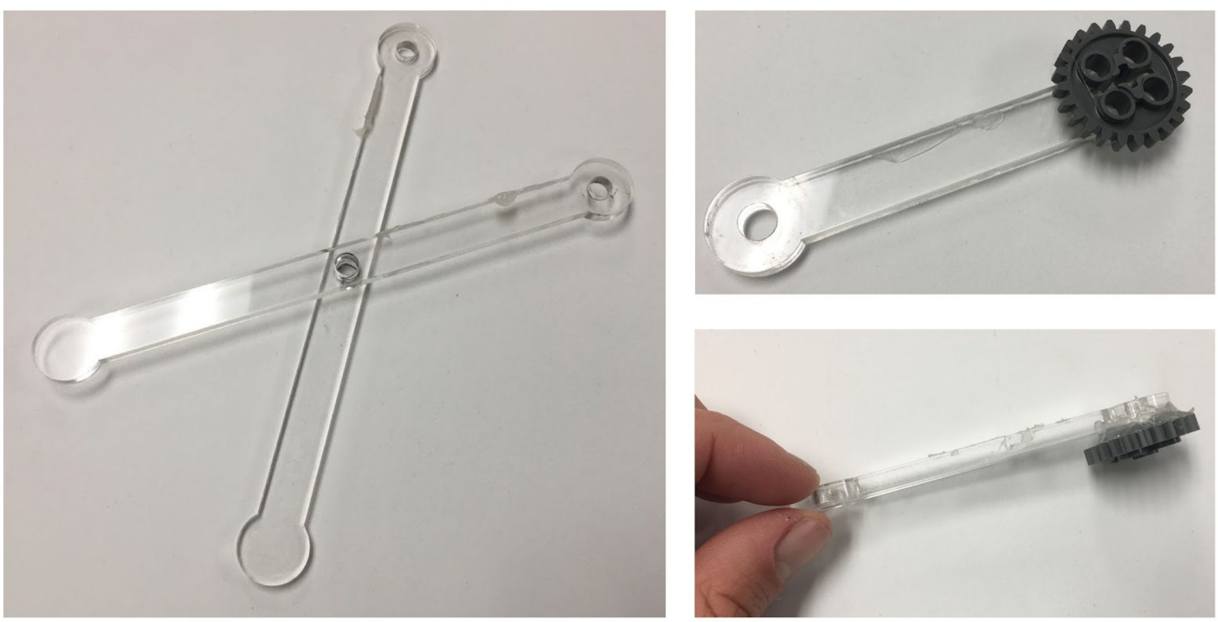


Figure 3.2.2: Pictured above are our final linkages made using laser cut acrylic.

The five-bar linkage also more closely mimicked the motion of a frog jumping. As you can see in Figures 3.2.3 and 3.2.4, the five-bar linkages map onto frog legs similarly to Wang et al.'s[6] paper as referenced in the background section.

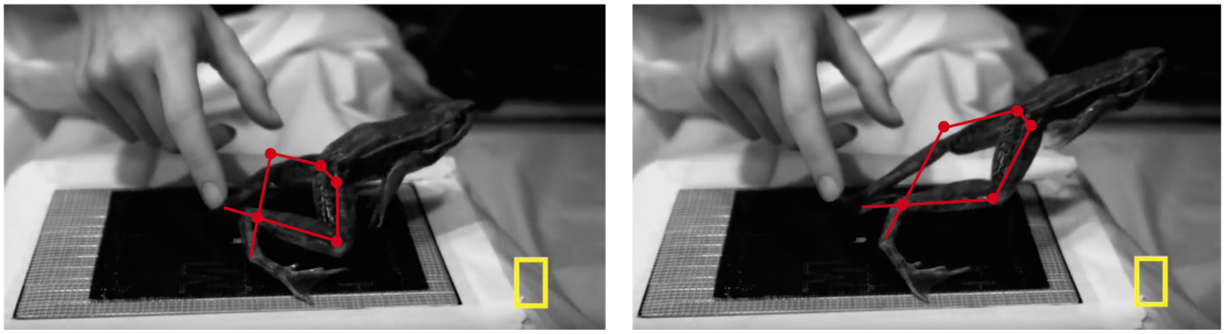


Figure 3.2.3: Linkage model of the frog (half the body).

Figure 3.2.4: Linkage design from frog motion mapped onto our mynock design.

[6] Wang, Meng, et al. "Biological Jumping Mechanism Analysis and Modeling for Frog Robot." Elsevier, vol. 5, no. 3, Sept. 2008, pp. 181–188.

Another reason we switched from a six-bar to a five-bar linkage system was our analysis of our virtual Working Model 2D prototype. Figure 3.2.5 shows the many iterations of WM2D jumpers we made and Figure 3.2.6 shows the final five-bar linkage design jumping a little over a meter during a simulation. We knew the five-bar linkage was a better design when we were able to simulate higher jumps than six-bar prototypes with comparable spring constant, k, values. You can find more on our working model prototypes in appendix A.3.

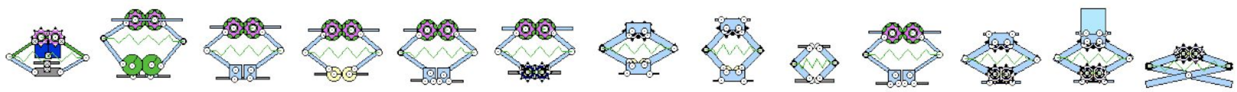


Figure 3.2.5: An overview of our WM2D design iterations. You can find more on each version in appendix A.3.

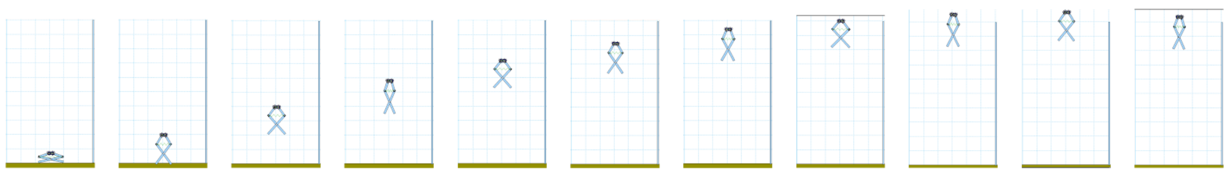


Figure 3.2.6: Working Model software test of our final design.

We chose 3/16th inch thick acrylic for our linkages. Acrylic was an ideal material because it is lightweight, durable and we were able to laser cut it using the machinery that was available to us. The thinner 1/16th inch thick acrylic we initially tested with cracked several times. 3/16th inch acrylic proved thick enough to sustain the required forces yet thin enough to avoid adding excess mass to our robot.

We toyed with the idea of laser cutting gears straight onto the linkages as seen in Figure 3.2.7, but decided that the proven meshing and strength of the lego gears was more valuable and created less friction. In order to reduce the shear stress on the glue between the linkages and the gears, we switched from laser cutting circular holes for the shaft to cutting crosses for a tight fit onto the lego shaft, demonstrated in Figure 3.2.8.

Figure 3.2.7: Gear linkage prototype.

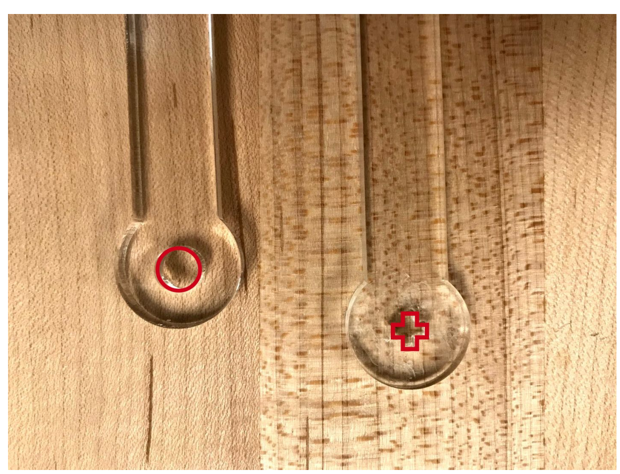


Figure 3.2.8: Switch from circular holes to crosses.

3.3 Converting Potential Energy to Kinetic Energy

Though we thought that springs would be the best option for storing potential energy at the onset of this project, we soon learned that there were several advantages to using rubber bands. Because individual rubber bands are lightweight and have relatively low k values, using them gave us flexibility to get a more exact k value. Instead of over or under shooting the one meter target, we could test for exactly the right number of rubber bands that would give us a little over a meter in height (so the robot would collide with the velcro and stick). The rubber bands also have a higher energy density compared to springs, making them the more efficient choice. The only downside to the vast number of rubber bands we used was the friction created between them and the two shafts they wrapped around. Appendix A.6 shows some initial k value calculations we did for springs we purchased.

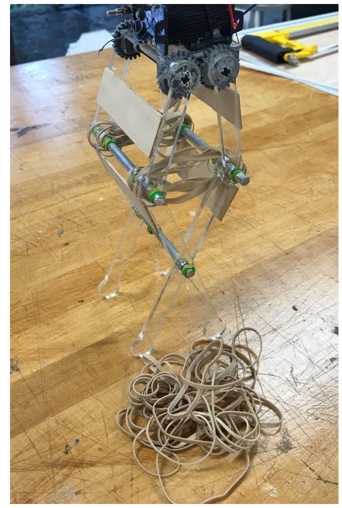


Figure 3.3.1: The rubber bands used to reach optimal height.

3.4 Release Mechanism

Although we chose to prioritize stability and height, we also tried to simultaneously brainstorm release mechanisms. Our first instinct was to place two lever arms on the on the motor output shaft, one connected to the shaft, the other loosely rotating. The loose arm would be attached to a string that was attached to the base of the robot and when the first arm spun with the shaft, the second would be carried until it was released at the top of the rotation arc. Ideally, with this setup, as the motor turned the string would be pulled up, rubber bands or springs stretched and just after the peak of rotation the robot would be free to jump (Figure 3.4.1).

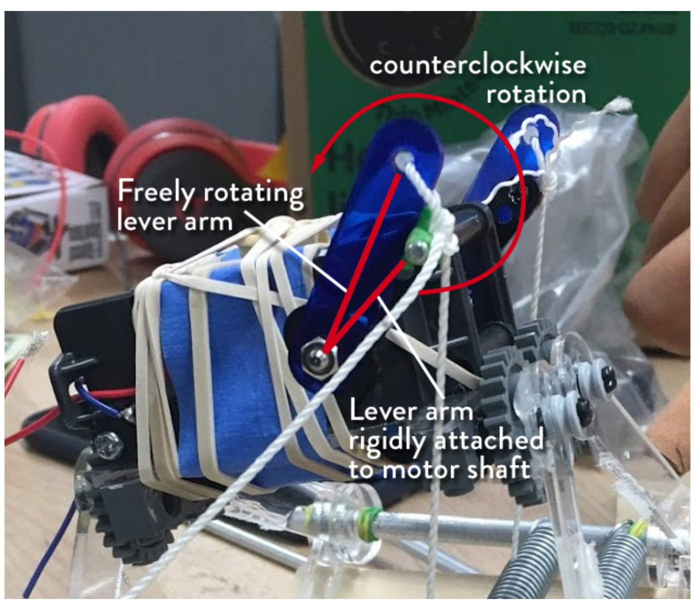


Figure 3.4.1: Lever mechanism using follow lever arm as release.

However, in order for our rubber bands or springs to be loaded as much as possible, which would lead to the highest possible jump, the crank piece needed to be able to pull the string approximately eight centimeters. Although creating such a crank might have been possible, not only would it have added weight, but it would also force the motor to load the springs with a drastically increased amount of torque. When prototyping with a three centimeter lever arm, the clutch within the gear train began skipping.

We decided that we needed a new method for loading and releasing our springs. After brainstorming, we settled on a cutting mechanism. As the robot lowered down and the springs stretched, a blade would cut through the string once the robot was fully crouched, releasing the stored energy. Figure 3.4.1 above shows the blade inside our jumper and Figure 3.4.2 shows the blade just before it cuts the string.

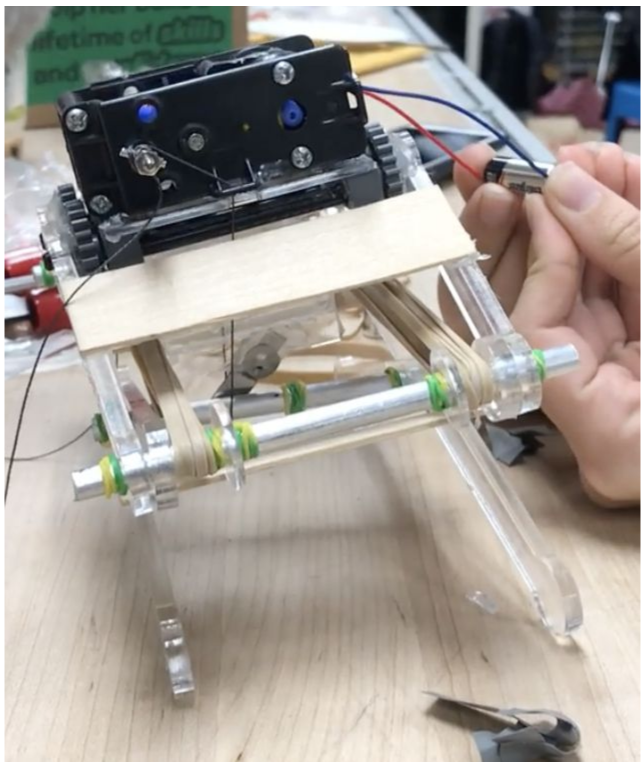


Figure 3.4.2: Our cutting mechanism moments before it sliced through the string and allowed the jumper to launch.

To do this, we attached one long piece of string to each side of the motor output shaft and wrapped it under the lower shaft holding the long linkages together. As the motor ran, the string would wrap around the output shaft on both sides, winding itself up and pulling the body of the robot down. To cut the string we used a glued X-acto knife blade on the underside of the platform at the top of the robot. The blade was strategically placed such that it wouldn't cut the string until the robot was as fully crouched (see prototype 17 in appendix A.1). This release mechanism worked very well and was consistent throughout testing.

3.5 Free Body Diagrams

We used free body diagrams (Appendix A.4) to determine the relationships between the string force, the rubber band force, and the position of our jumper while crouching. We knew the general geometry of our jumper (Figure 3.5.1), thus were able to relate the total height of our linkages to the angle theta between linkages, as well as the length of the rubber bands to the angle theta. From free body diagrams of the joints, we related the force in the rubber bands and the string. A summary of the variables used is below (Table 3.5.1.)

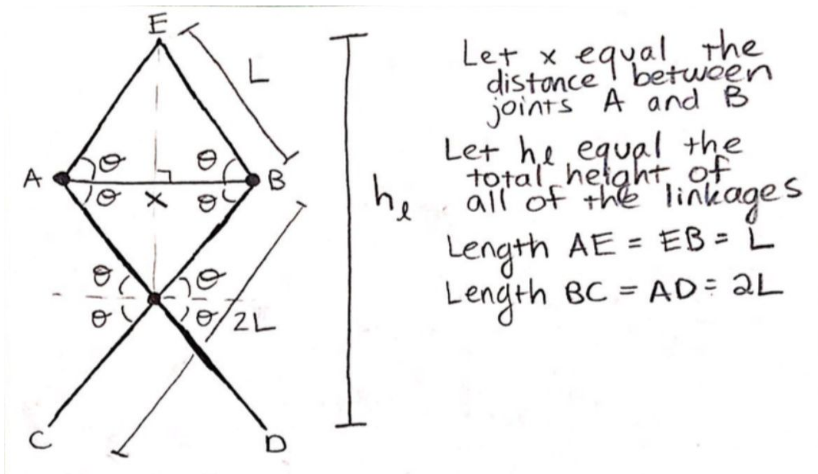


Figure 3.5.1: Geometry of our Mynock

Variable	L	θ	h_l	x
Represents	Length of the shorter linkage	Angle between the rubber bands and the link	Total height of all of the linkages	The current length of the rubber bands

Variable	Δx	k	F_{St}	F_{Bands}
Represents	The change in length of the rubber bands	The spring constant of all the rubber bands	The force of the string pulling the robot down	The force of the rubber bands

Table 3.5.1: Summary of Variables used in Free Body Diagrams and Geometric Analysis

Our geometric analysis allowed us to relate each of the geometric variables we were interested in through the following equations:

$$x = 2 * L * cos(\theta) \quad (1)$$

$$h_l = (3/2) * x * tan(\theta) \quad (2)$$

This geometric analysis confirmed that our jumper would remain within the design requirements: a total height of less than 10 cm (as calculated by adding h_l and the height of the motor box), and a total width (as approximated by calculating the value of x as compared to θ above) of less than 30 cm. To better visualize the relationships between each of the variables, we used Matlab to plot the above equations (Appendix A.4).

From our free body diagram analysis (Appendix A.4) we were able to compare the forces required at different values of theta and x, through the equations below:

$$F_{bands} = F_{St}/tan(\theta) \quad (3)$$
$$F_{St} = k * \Delta x * tan(\theta) \quad (4)$$

Matlab aided us in plotting these equations to determine at what point in the process of crouching the maximum force was required. We found that the maximum force in the string was required partway through the lowering process, at an angle of about 0.65 radians, after which the force decreased as the mynock gained mechanical advantage (Figure 3.5.2). The maximum force in the rubber bands occurred, as expected, at the smallest angle between the linkages, confirming that our robot has its maximum potential energy at its fully crouched position (Figure 3.5.3). Thus, we knew that we needed our motor to provide the highest amount of torque partway through crouching. We were more confident in using an overdriven motor after determining this, because as the temperature of the motor increased towards the end the crouching process, the overall torque required of the motor would decrease.

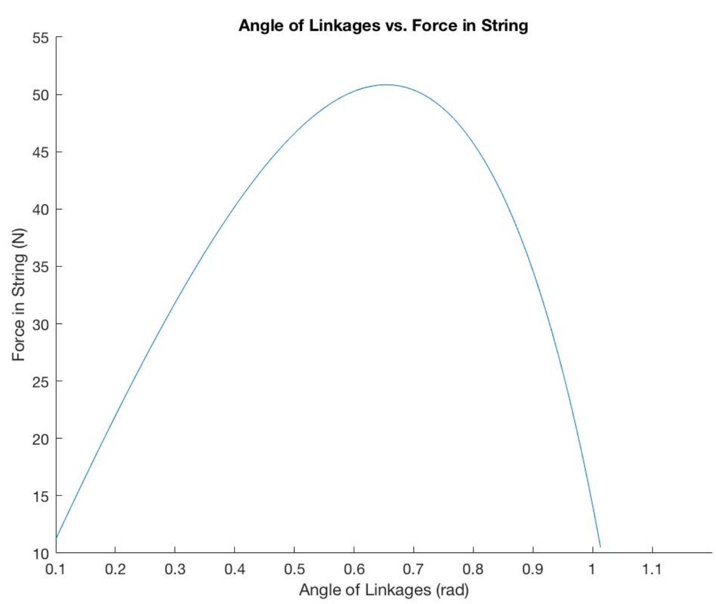


Figure 3.5.2: Graph of the angle of the linkages vs. the force in the string for our jumper. When lowering itself, the robot started at an angle of about 60 degrees, or 1.04 radians, then decreased that angle to less than 30 degrees, or 0.5 radians. Thus the motor had to have sufficient power to reach the maximum force, 52 N, on this graph at a linkage angle of about 0.65 radians.

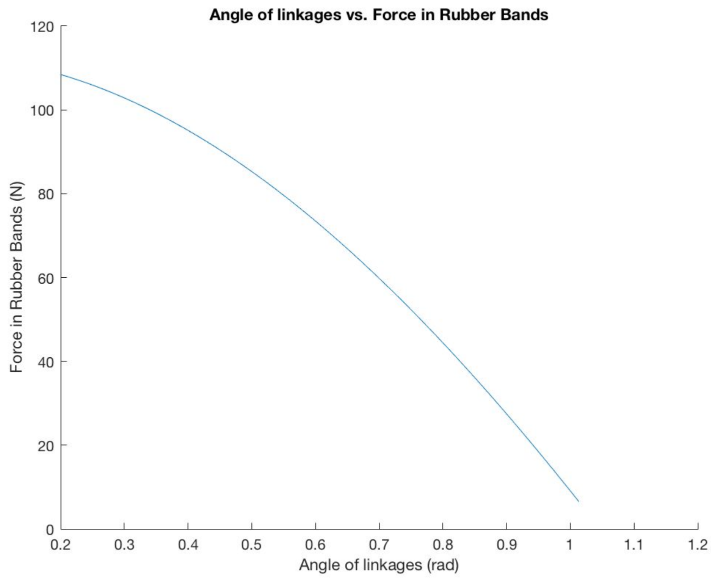


Figure 3.5.3: Graph of the angle of the linkages vs. the force in the rubber bands. The highest force in the rubber bands occurs at the smallest angle of theta.

3.6 Final Touches

After deciding on and implementing all the major design decisions that aided our robot in meeting the main design requirements, there were a few final design changes we made to improve stability and consistency.

The first thing we did was add stabilization four panels that lay across opposing linkages (Figure 3.6.1) so when one side began to bend, the other side was more likely to move in a synchronized manner. We also tried to even out the weight distribution of our robot so that it would result in a more directly vertical jump. To do this, we worked to reposition the battery, the only component whose specific location was flexible. We concluded that the battery should be placed on top of the gearbox towards the side with the output shaft because our robot tended to pull more towards the other side.

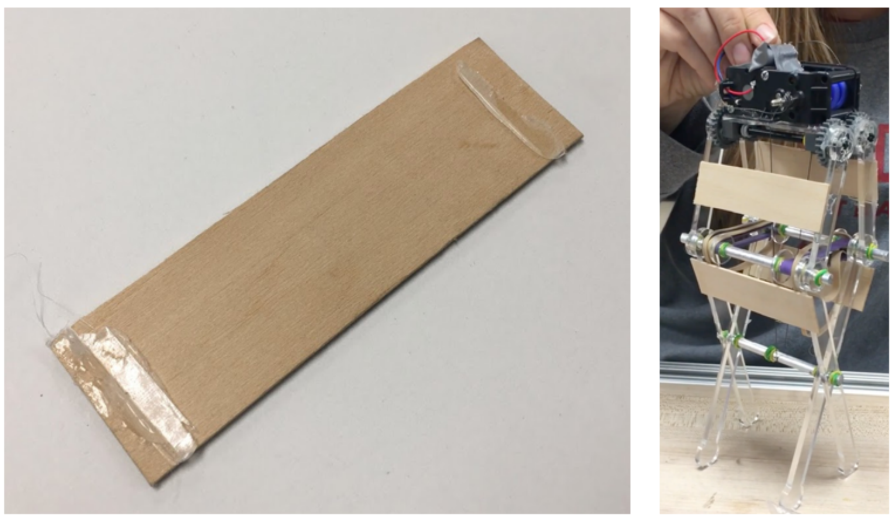


Figure 3.6.1: Stabilization panels used to reduce unwanted twisting and rotation.

Another final touch we made to our robot came after we decided on using rubber bands as our energy store-and-release mechanism. With the rubber bands taking up the same space our string and X-acto blade occupied, we needed to ensure that the two wouldn't interfere with each other. To avoid this problem we used washers (held in place by mini rubber bands) attached to the shafts to keep the rubber bands outside the path of the string and X-acto blade. We also added velcro to our jumper. Since velcro was the sticking mechanism for attaching to the hull of the platform, we had to secure it well to our robot. Using the strong adhesive on the back of the velcro strips, we wrapped the velcro around our motor and battery platform. We increased the surface area of the velcro by using multiple pieces to ensure more sticking power and to compensate for a crooked jump if one were to occur.

4 Analysis of Performance

4.1 Motor Characterization and Efficiency

To calculate our motor efficiency, we ran multiple tests. We expected two sources of efficiency loss in the motor's conversion of electrical power to mechanical power. The first source came from the fact that the motor had some internal resistance. The second source was the motor shaft which experienced forces in opposition to its motion. The following equations, derived from Kirchoff's law and the Lorentz force model to the motor circuit, allowed us to characterize our motor:

$$V - iR - k\omega = 0 \qquad (1)$$
$$Ki - Tf = Tl \qquad (2)$$

Where V = voltage, i = current, k = the electromagnetic constant, Tf = friction torque, Tl = output load torque, and ω = angular velocity in radians/second.

To find the variables R, k, and Tf (assuming these will stay constant), we ran stall and no-load experiments on the motor. For our stall measurements, the angular velocity, ω, was zero so we could find the motor resistance using equation (1). We ran the motor at 9 volts while holding the motor shaft so that it could not spin. We then recorded the current coming in through the power supply. We observed a motor resistance, R, of about 2.65 Ohms.

For the no-load measurements, the output torque, Tl, is zero. The motor was able to rotate freely. Using equation (1) with V, inl and ωnl measured, and R obtained from the stall test, we could solve for k. We tested at 9 volts, recording the respective current from the power supply, and measured the ω with a tachometer. We were able to calculate a k value of 0.00234 Nm/Amp. From equation (2), we know that tl is zero and therefore Tf is equal to k*i. From the experimental values, we got a Tf value of 0.00089 Nm.

Once we had measured all the necessary values at 9 volts, we could produce plots of efficiency as a function of current at 9 volts Our robot was running at 0.75 Amps while loading as shown on the plot in Figure 4.1.1. Our motor efficiency at 0.75 Amps was approximately 38%.

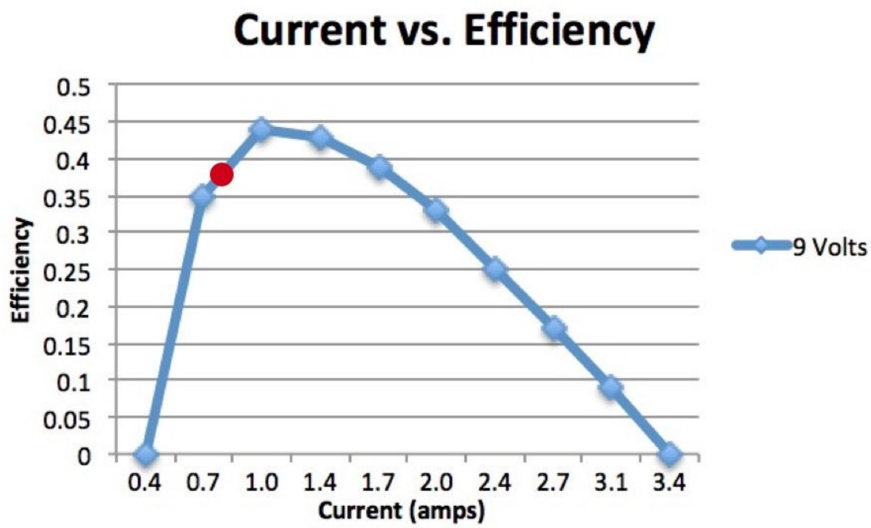


Figure 4.1.1: On this Current vs. Efficiency graph, the red dot shows where our motor was operating.

Given that our motor was running at 9 volts and 0.75 Amps, the torque in can be found with the equation (3) with our found k and Tf values from our experiments.

Tin = k*i-Tf   (3)

With this equation, we found that our torque in to the motor was about 0.000867 Nm. Since we chose our gear ratio to be 1300.9:1, that brings our output torque to 1.127 Nm. Given this output torque, we calculated the efficiency of our gear train (section 4.2).

4.2 Gear Train Efficiency

We determined our combined gear train and motor efficiency by testing the maximum mass that our motor and gear train could lift over a pulley of known radius at 9 V and 0.75 Amps. We used that voltage and current because our robot ran at those values while stretching the rubber bands, thus they allowed us to approximate the combined efficiency of our motor and gear train while the robot crouched into jumping position.

We compared the actual torque output of the geartrain to the expected ideal torque output, 1.127 Nm, given by our analysis in section 4.1 above. We found that our motor and gear train were 15.4% efficient. In section 4.1, we found that our motor efficiency was 38%, so to determine the efficiency loss in the gear train alone, we divided the motor and transmission efficiency by the motor efficiency and found a gear train efficiency of 41%. However, our measured motor and gear train efficiencies may have been less than our jumper was actually running at on test day, because our motor was damaged from repeatedly running at 9 V when it was designed to run at a max voltage of about 3.5.

4.3 Spring Constant, k, Analysis

The spring constant of the rubber bands was another important value to find in order to estimate losses. Using a known mass to stretch all the rubber bands used in our final mynock (Figure 4.3.1), we were able to obtain a rough estimate of the spring constant using equation (1).

$$F = k * \Delta x \qquad (1)$$

One big assumption we made in order to use this equation and our test setup was that for small applied forces, the stretching action of rubber bands follows Hooke's Law.[7] Although the forces on the rubber bands probably fell outside of the linear region of the force vs. change in length curve, we assumed a linear relationship to get an estimation of k. The estimated k value we found was 1482 N/m.

Figure 4.3.1: Setup to test for the spring constant, k, of our rubber bands.

[7] http://c21.phas.ubc.ca/sites/default/files/rubber_band_write_up.pdf

4.4 Force Plate Testing and Analysis

We used a force plate to determine the initial acceleration and velocity of our robot while jumping. We created a “hat” out of foam core to fit over the force plate because our robot, when fully crouched, was longer than the actual plate. We thus had to account for the weight of the “hat” in all of our force plate analysis. Our results are shown in Figure 4.4.1 below.

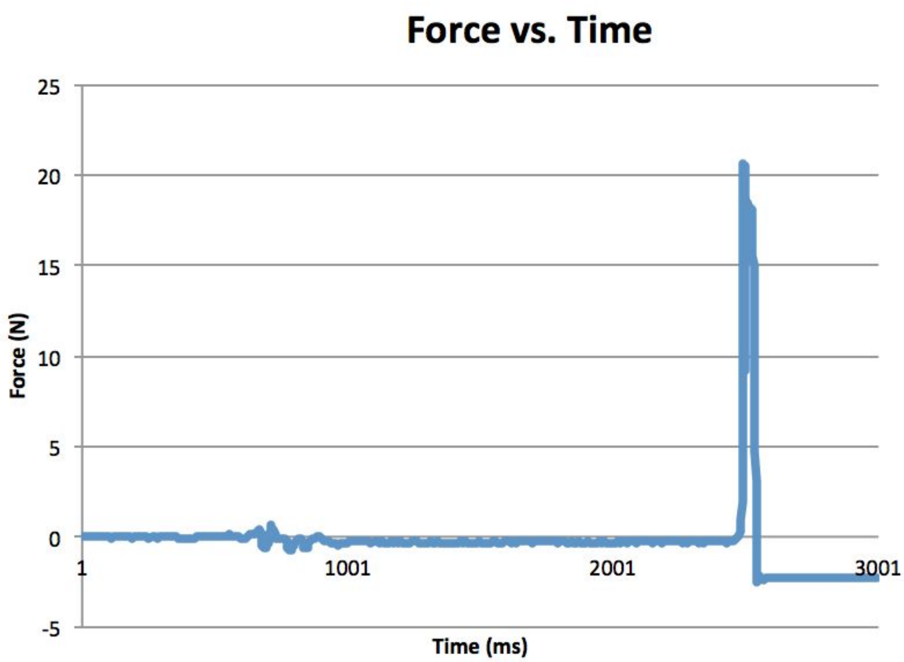


Figure 4.4.1: Results from Force Plate testing: a Force vs. Time graph of our robot jumping. The jump is seen at around 2500 ms, when the force peaks to 21.0 N.

We first used the force plate data to calculate our maximum acceleration during the jump from the ground using F=m*a. We found our maximum acceleration to be 75 m/s^2, a value consistent with the magnitude found in our working model simulated robot of around 150 m/s^2. Using Excel, we focused on the relevant portion of our Force vs. Time graph (Figure 4.4.2 below) to more closely examine the jump. A well-designed jumping robot would have a long, smooth acceleration phase. Our initial acceleration (16 to 22 ms in Figure 4.4.2) was smooth, but after that became rougher, and our acceleration occurred over about 27 ms.

We also used Excel to estimate the initial upwards velocity. We calculated the integral of (Force/Mass)*dt for the jump by averaging the area beneath two points across the entirety of the jump phase and summing the areas. This gave us an initial upwards velocity estimate of 5.75 m/s.

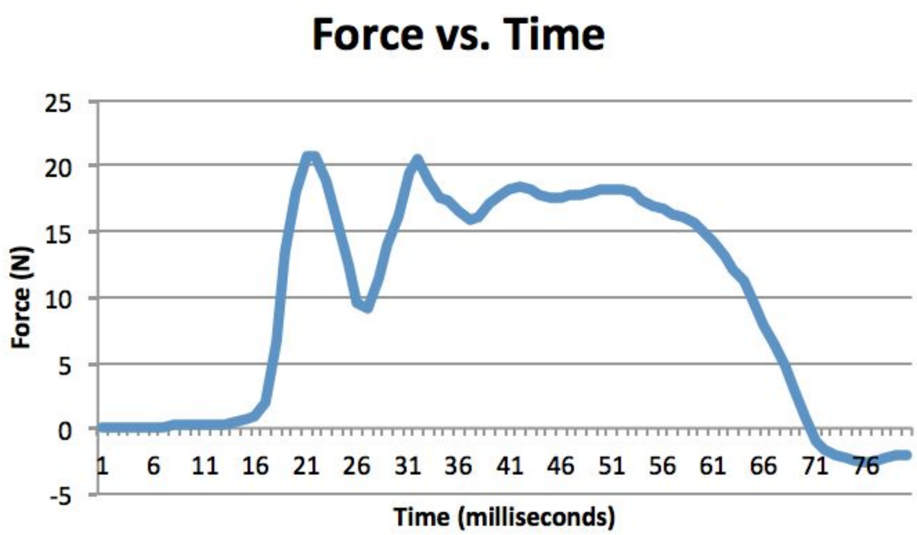


Figure 4.4.2: Results from Force Plate testing: a Force vs. Time graph of our robot jumping. This graph shows a close up of the section during which the jump itself occurred.

We then used our initial velocity value to estimate our energy losses. With no losses, we would expect that:

$$0.5 * k * (L_{max}{}^2 - L_{min}{}^2) = 0.5 * m * v^2 = m * g * h \quad (1)$$

In other words, Spring Energy = Kinetic Energy = Potential Energy. From our initial velocity, we can calculate the kinetic energy when the robot first jumps as 4.6 Joules, which compares to our robot's potential energy at 1.0 meter of 2.7 Joules. (Appendix A.8). This gives us an energy efficiency of 59% during the airborne phase. Losses during that phase would include the force of air drag as well as losses from rotational motion or leftover kinetic energy leftover in our robot.

We can also estimate our losses within our robot by relating the spring and kinetic energy above. Our calculated initial velocity gives us an initial kinetic energy of 4.6 Joules, which when equated with spring energy, with our robot's dimensions, should require a spring constant of 602 N/m (Appendix A.8). However, our calculated spring constant of the rubber bands (Section 4.3) was actually 1482 N/m, which creates a spring energy value of 11.3 Joules. Thus, our energy efficiency within the robot was about 41%. We likely lost a lot of energy through friction in the joints, amongst the rubber bands and as the string rubbed against platform & shaft. With additional time, we could have attempted to reduce that friction by using fewer, larger rubber bands and using different materials in our linkage joints (e.g. not using rubber bands as shaft collars). More on this can be found in section 5, future directions.

4.5 Drivetrain Gear Strength Estimate

We performed Lewis stress analysis on our Tamiya 6-Speed Gearbox gears to ensure that the acrylic drivetrain gears would not fail. Lewis stress, which is the bending stress on the gear teeth when treated as cantilevered beams, is expressed as:

$$\sigma_{Lewis} = \frac{F_{tan} P_d}{b J_{Lewis}} K_m K_o K_v$$

Where Ftan is the tangential force, Pd is the pitch (teeth per inch of diameter), b is the face width, and JLewis is the Lewis geometry factor. The Lewis stress accounts for gear-specific factors like rigidity of mountings, uniformity of power supply, and how fast the gear is rotating. These variables are represented by constants Km, Ko, Kv, respectively. The torque on the gears and the forces between the gear teeth are at a maximum at the point that the motor is at stall. Therefore, we wanted to compare the Lewis stress at stall to the ultimate tensile strength of acrylic to see if our gears would ever fail. The ultimate tensile strength of acrylic is approximately 10 ksi.[8]

$$\sigma_{yield} = 10.0 \text{ ksi}$$
$$\sigma_{Lewis} < \sigma_{yield}$$

We found our maximum stress to be below 10 ksi as we thought we would, given that our gears did not break while running.

4.6 Gameday Performance

Our mynock took several attempts to successfully jump one meter and latch onto the hull of the spaceship. However, we were within 10 cm of jumping a full meter in all our tests leading up to our successful trial. We believe that perhaps with the repeated stretching of our rubber bands, they may have lost some elasticity, so while they produced enough potential energy to jump one meter reliably before test day, after many cycles of stretching and relaxing their spring constant decreased and they did not provide us with as much potential energy on test day. We solved this problem by adding rubber bands to our robot to increase the potential energy after our first attempts failed. On our final test, we had added sufficient rubber bands and our mynock leaped high enough to latch onto the spaceship.

[8] MatWeb. "Tensile Property Testing of Plastics." MatWeb: Material Property Data. N.p., n.d. Web. http://www.matweb.com/reference/tensilestrength.aspx

5 Future Directions

While our current design was able to complete the mission, with more time and an unlimited budget, our team could have made several improvements to our jumper.

First, to improve consistency, our team could have more accurately defined the spring constant necessary for our mynock to jump the full meter. This may have helped us find the right rubber bands sooner and allowed us to replace many tangled bands with a few, stronger ones. Using fewer but stronger bands might also reduce friction while maintaining the same power storage and decreasing the weight and clutter.

Other methods of friction reduction in our robot would allow us to increase the efficiency of the entire system and decrease the amount of power necessary. For example, we could implement a pulley system instead of having our string drag directly on the edges of our motor platform and the lower metal dowel. Additionally, lubrication on all the joints and a better way of securing the linkages on the shafts than using small rubber bands are a few concrete adjustments we could make.

Another way to improve reliability would have been adding a switch. This would have given us a connected power system with consistent power input on every run and we would not need to carefully align wires each time.

Reducing our mass would have also allowed our robot to jump higher. To reduce the mass we could experiment with other durable, but lighter materials, as well as remove some of the hot glue we used in construction. Decreasing the overall size of our mynock would help with the mass problem and the power requirements concern.

As we built our final mynock, we considered rearranging the placement of our motor or our string so that it was in the center of the robot. In our current design, our motor output shaft isn't directly centered, so when it pulls the body of the robot down, it leads to a slightly crooked jumping form. Either using a pulley system to center the string or changing the motor orientation would better our robot's directional performance.

Finally, perhaps given more time it would be worth systematically experimenting with various motors and batteries until we found a combination that gave us the amount of power we needed with reduced weight.

6 Conclusion

Our final Mynock jumper was successful in jumping a meter and sticking on to the spaceship with an autonomous release mechanism. It took more than five seconds to load itself due to the weight of the model and the spring constant necessary to lift it. However, when we preloaded the spring, we were able to complete the jump in under five seconds. Although it took longer than we would have liked, it was a relatively successful project that ran consistently and smoothly once we increased the spring constant by adding rubber bands. We are proud of our final mynock and learned a lot through analyzing our design

One of the biggest problems we faced while building our robot was fighting the balance between our robot's weight and getting the necessary power output from a larger motor. We needed to have enough springs to jump a meter but the more we increased the spring constant, the harder it was for the motor to wind up, especially with the small 12V batteries. We struggled to find a lightweight motor that was strong enough to wind up our Mynock and in the end we settled on our original motor, adding an extra 70 grams to our robot.

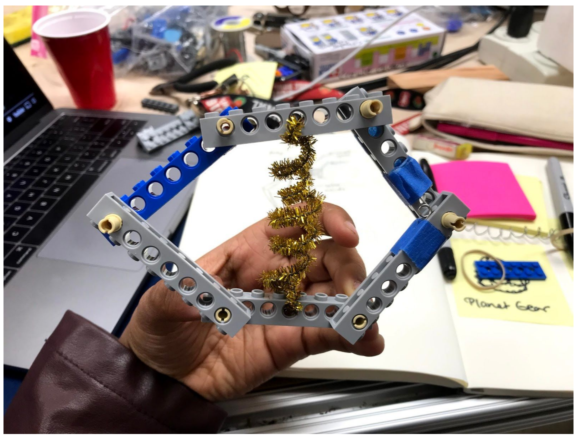
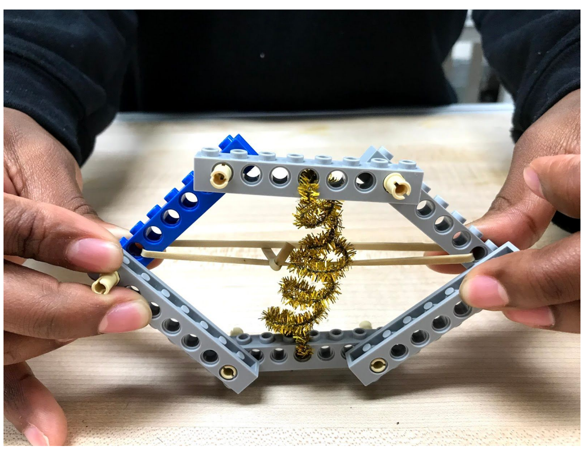
Fortunately, we were able to find a way to increase the spring constant enough to account for the extra weight while still working within the power output of the larger motor. We are proud that our robot was able to complete the mission and deter wild mynocks from destroying the spaceships.

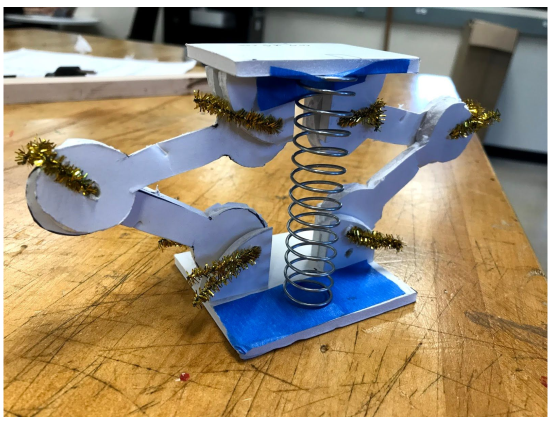
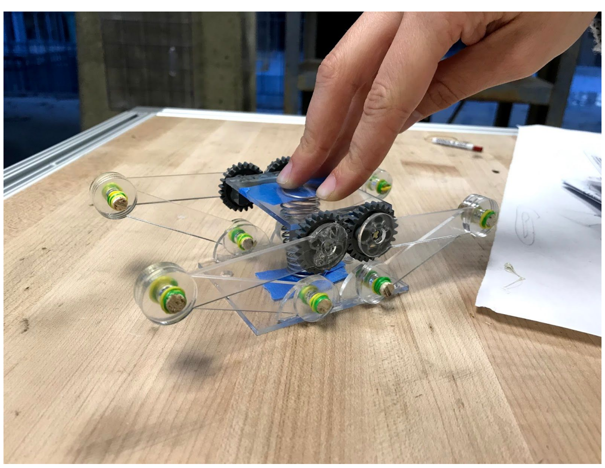
Figure 6.1: Mission accomplished

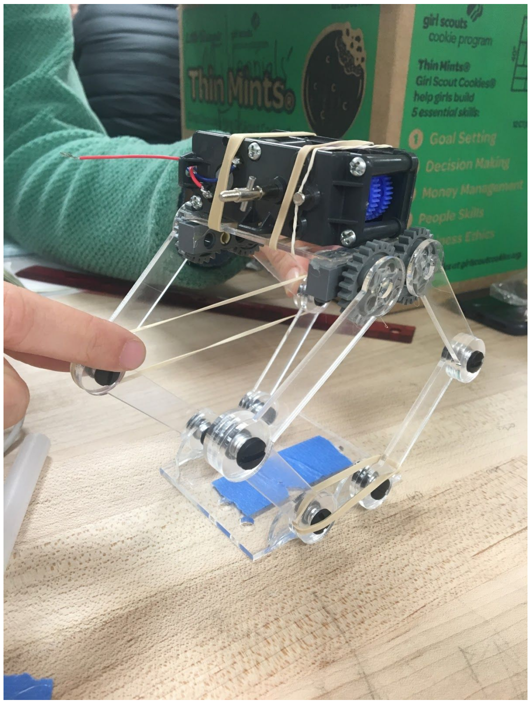
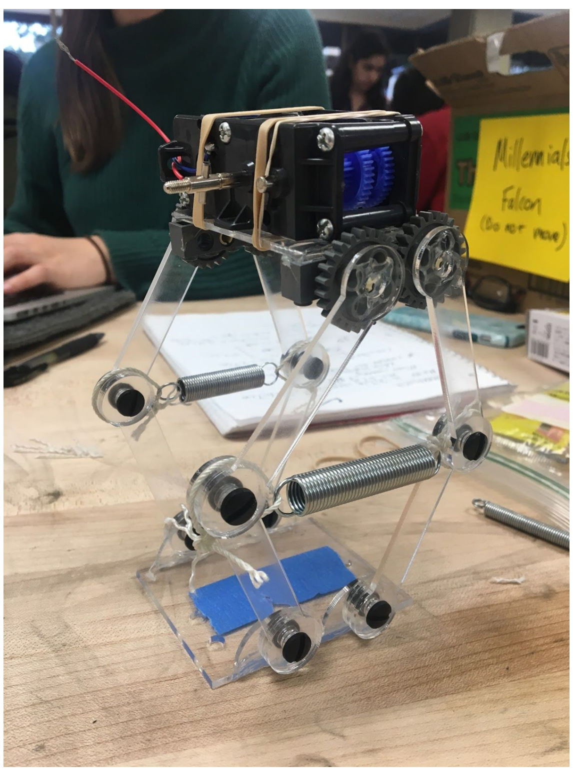
A Appendices

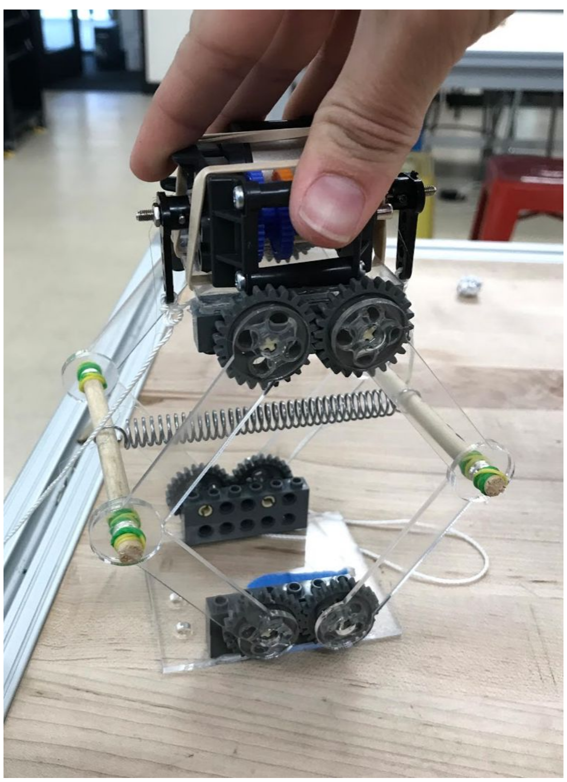
For a complete look at our project you can view all our process photos in our Google Photos folder, using this link: https://photos.app.goo.gl/YVnt6HUz0ZSg2e2s1.

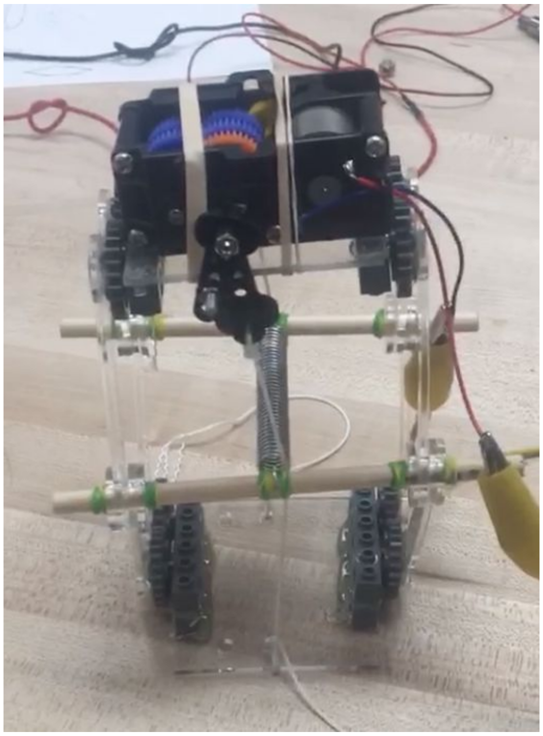
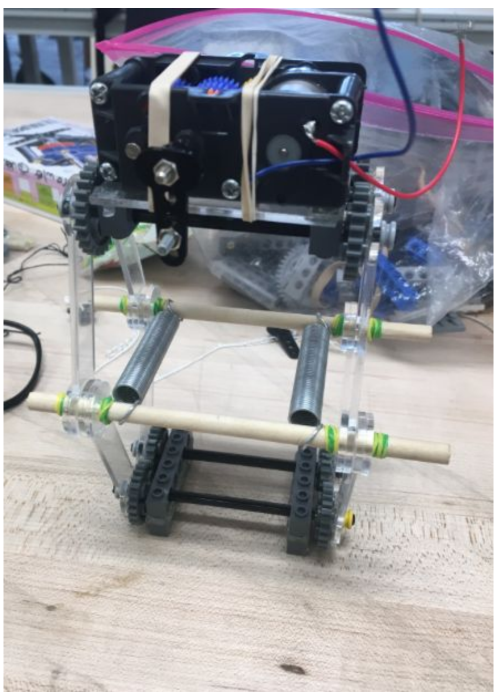
A.1 Prototype Modeling

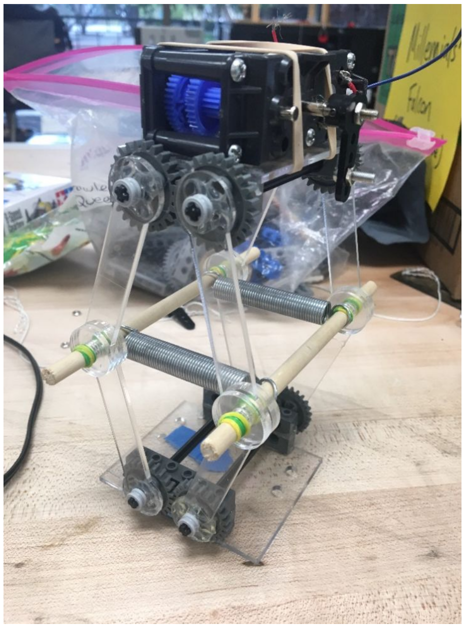
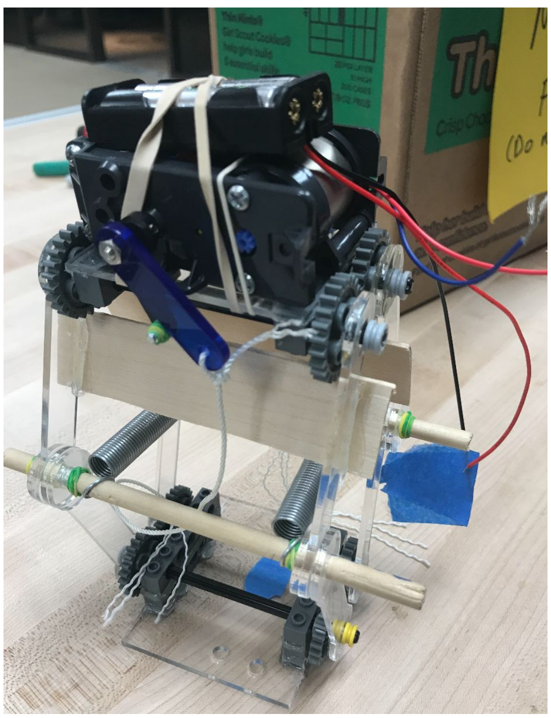
Model	Features
	**Prototype 1** - We created a basic 6-bar linkage jumping prototype based off some of the robots we found in our research using a pipe cleaner to mimic a compression spring and part of a safety pin to mimic a torsion spring. **Insights:** This prototype was not very "springy" and did not jump very high. We would need stronger torsion springs to make this prototype work but it gave us a good general idea of what the shape and linkages could look like.
	**Prototype 2** - We switched to using rubber bands instead of the improvised torsion spring from Prototype 1. **Insights:** This prototype has too many degrees of freedom (three). It can jump about 8 cm (at best) but more often than not it failed to jump straight up.

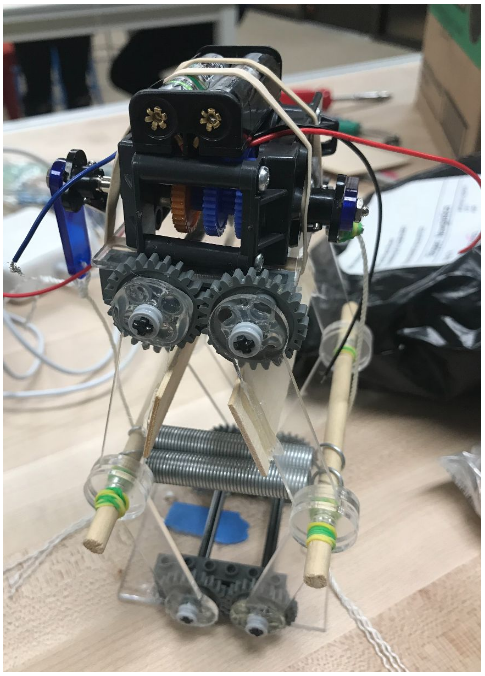
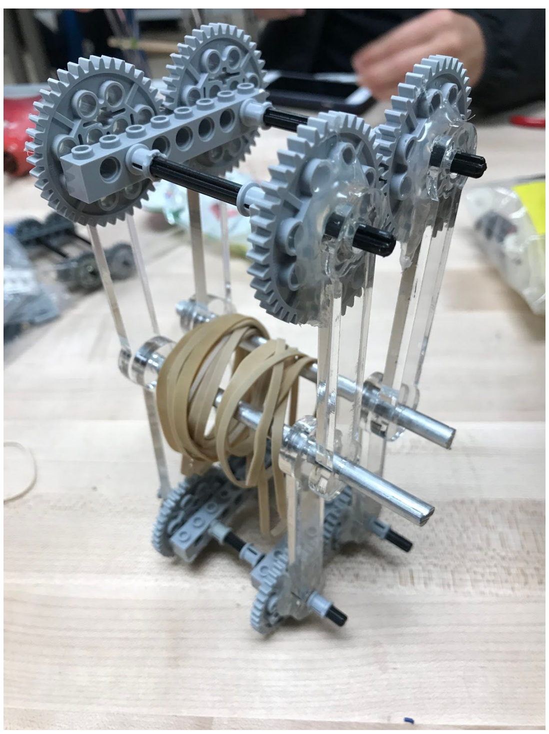
	**Prototype 3** - We built a new prototype made out of foamcore and put together with hot glue. Pipe cleaner was used for temporary joints and rubber bands were the first method of spring energy we tested. **Insights:** This prototype was helpful in that dimensions were much closer to those we were actually considering. While still not particularly springy, it helped us think about how our linkages would connect and potential spacing or the elements.
	**Prototype 4** - For the second iteration of the foamcore model, the rubber bands were substituted for a spring purchased from ACE hardware. **Insights:** The spring was incredibly helpful in getting our group to think about how far down we need our upper platform to go in order to have enough spring energy for the one meter jump. This prototype sprang up about 5 or 6 centimeters.
	**Prototype 5** - Using laser cut pieces of acrylic, prototype five was assembled. We used a ¼” thick wooden rod for the joints and small rubber bands as stoppers on each end. The lego gears were to help the two linkages move at the same angle and we placed a spring in the middle as the jumping mechanism. **Insights:** The lego gears were very helpful in keeping the linkages closer to the same angle, but we also discussed doing the same on the bottom linkage ends. This prototype had a much cleaner jump than any previous prototypes but went only about 2 cm high.

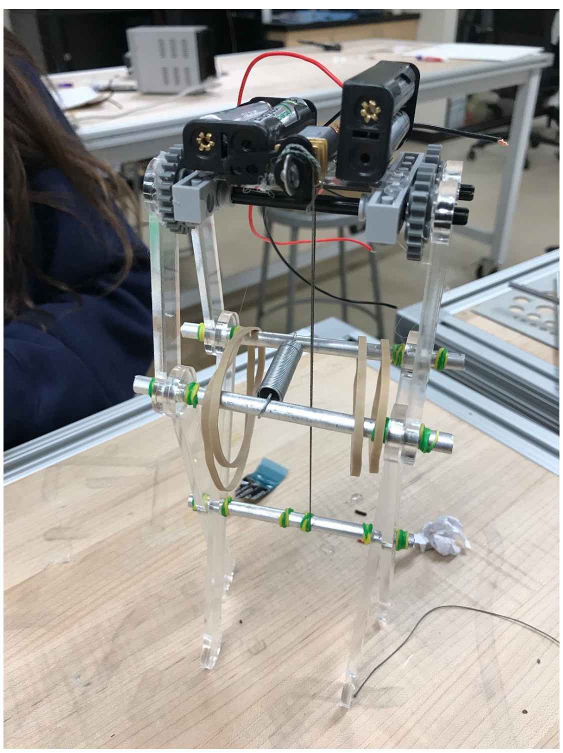
	**<u>Prototype 6</u> -** In prototype 6 the joints were replaced with pin joints, and rubber bands were tested as a possible jumping mechanism for both "legs". **<u>Insights:</u>** The pins worked well in holding the mechanism together and we started to think more seriously about the best way to attach rubber bands or a tension spring to the system.
	**<u>Prototype 7</u> -** Attached springs to the center leg joints for use as a force for jumping. **<u>Insights:</u>** Tension springs seem to be an appropriate way to generate the energy needed to get out bot to jump.

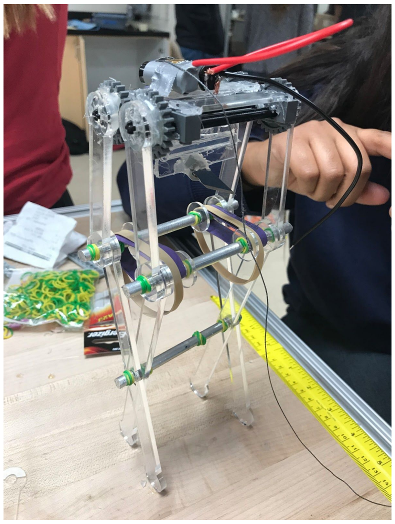
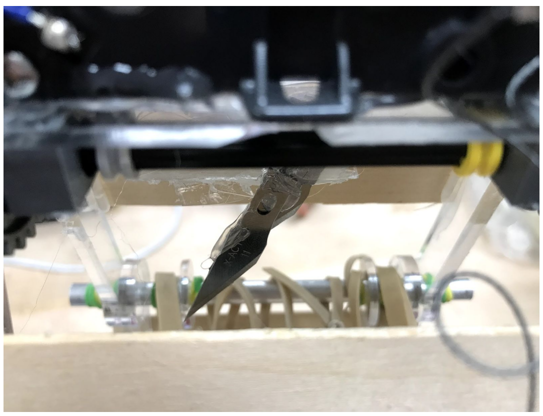
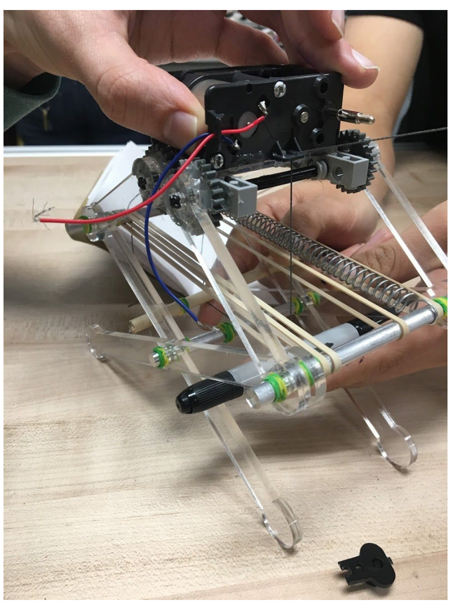
	**Prototype 8** - Implemented two crank mechanisms that will wind up and stretch out springs to build energy for our jump. **Insights:** Initially, we used a single crank directly powered by the motor, but the mechanism proved to be very uneven. However, using two cranks evenly distributed the pulling force being used to load the spring.
	**Prototype 9** - Added dowels to connect the opposing legs to provide more stability and decrease the stress on the center bending joints. We also created a gear connection at the base of the bot so that the lowest joints move in sync, removing a degree of freedom and creating more stability. **Insights:** Now when loading the spring, the legs stay an equal distance apart. However, when using this method, the strings attached to the cranks get in the way of the dowels and vice versa.

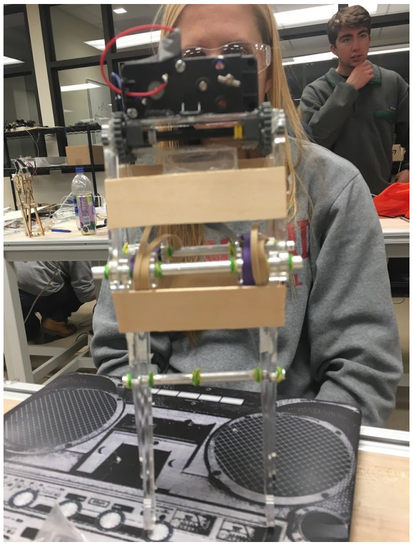
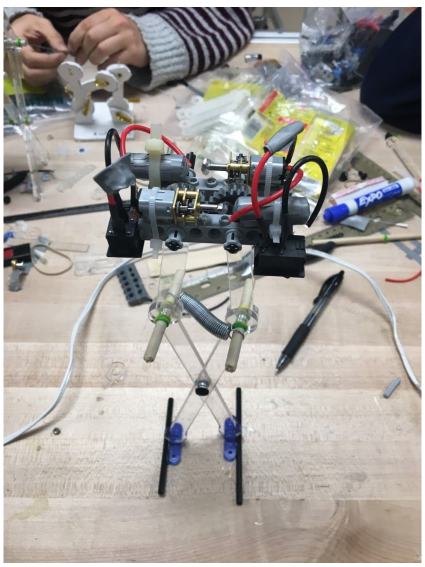
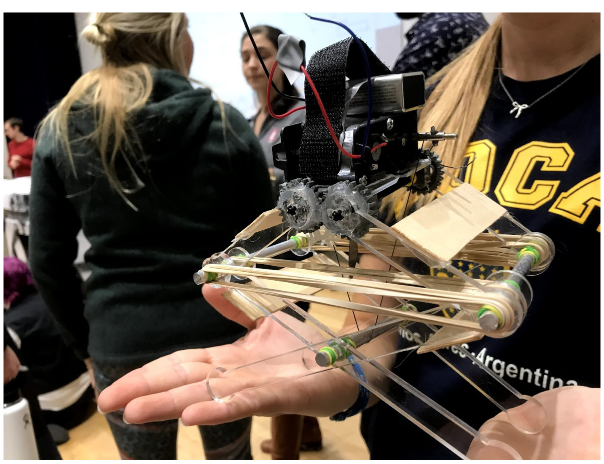
	**<u>Prototype 9</u>** - Implemented our own one-way clutch mechanism to allow the crank to pull on the strings and load the springs while the motor is winding. This way, when the crank reaches its highest point, it’s able to release quickly allowing the springs to recoil and force the bot to jump. We also moved the sting to the inside of the dowels so that the dowels are getting in the way of strings. **<u>Insights:</u>** Since the cranks are not centered, when the strings are pulled, the cause a greater force on one side of the bot than the other. This causes the bot to tip over when the cranks are winding up. Additionally, the string gets wrapped around the crank-clutch mechanism as opposed to moving freely.
	**<u>Prototype 10</u>** - We added an additional spring to increase the stability of our bot. We also connected the pairs of opposing gears so that they will rotate at the same velocity, decreasing the likelihood that our bot will experience the lopsided strain that caused it to tip over initially. **<u>Insights:</u>** When a downward force is applied to only one side of the bot, the difference in spring loading is decreased.

	**<u>Prototype 11</u>** - The legos used by the bottom gear mechanism were glued together and then glued to the bottom platform so that they wouldn't come apart during take off. **<u>Insights:</u>** When the jumping ability is tested, the stability is very consistent, but the bot still does not jump a full meter.
	**<u>Prototype 12</u>** - We lengthened the cranks so that they would pull the body of the bot lower, allowing the springs to store more energy. We also glued flat boards to the undersides of the upper-legs to add more stability and synchronicity to the jumping motion. **<u>Insights:</u>** The cranks still aren't long enough to pull the body close enough to the ground to allow for maximum jumping height. Additionally, when run with a power source, the maximum allowable torque load that our motor can handle is close to be met.

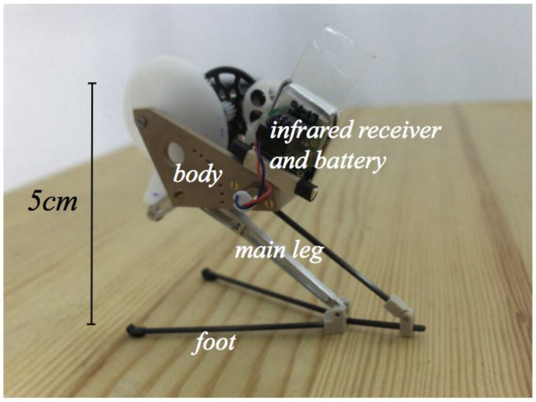
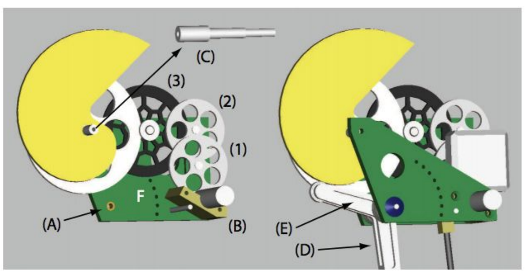
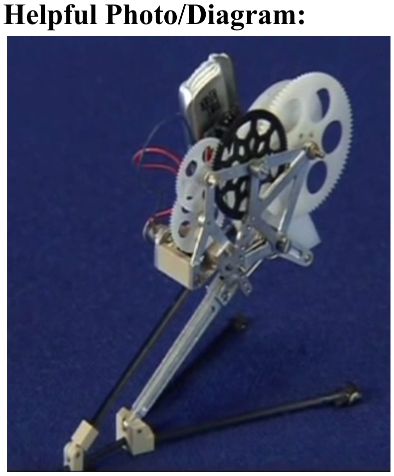
	**<u>Prototype 13</u>** - We changed our gear ratio from 505.9:1 to 1300.9:1 **<u>Insights:</u>** Motor doesn't have enough torque to pull body of the bot down and stretch the springs. Additionally, the linkages tend to break close to the bending joint.
	**<u>Prototype 14</u>** - We switched out loading mechanism to rubber bands so that our motor won't encounter a high torque load until after it's been working for a while. We also lengthened all the linkages to allow the the rubber bands to stretch farther; therefore, building more energy. Additionally, we used ¼-inch acrylic for our linkages, hoping that they would be less prone to snapping. **<u>Insights:</u>** This bot weighs more and still doesn't reach a meter high until we add more rubber bands than out motor can handle. A crack began to appear in one of the linkages, proving that the thicker acrylic didn't solve our stress problem. We realized we needed to find a way to make the feet much lighter

	**Prototype 15** - We switched out linkages so that the bottom linkages are twice as long and cross at their midway point. This also helped with decreasing the weight of the feet. **Insights:** This model is much lighter than recent models. It also doesn't require nearly as much force to get it to jump a meter high. The wooden dowels attaching the opposing sides of the model are snapping at the point where the spring is applying force.
	**Prototype 16** - We switched the spring shafts to metal. We also, added another battery pack after seeing that 2.4 volts wasn't enough power to create the torque we needed. **Insights:** We still need more power. Our little motor isn't strong enough on its own to load the robot.

 	**<u>Prototype 17</u>** - We implemented a release mechanism for our loaded sting by attaching an x-acto knife blade to the underside of out robot's body. Additionally, we removed our spring and replaced it with only rubber bands. **<u>Insights:</u>** This model jumps a full meter manually, however, the motors still aren't able to activate our loading mechanism on their own.
	**<u>Prototype 18</u>** - After trying two little motors, we realized that they were not strong enough. Even though there was a large increase in the weight, we decided to go back to our first motor which was more powerful. **<u>Insights:</u>** This motor was able to bring it down but it took a really long time and it burned through three 12V batteries by the time the release mechanism was initiated.

	**Prototype 19** - We added thin wooden plates to stabilize the jumper even further **Insights:** This helped to make the model more sturdy but the model still took too much voltage and time to lower and release.
	**Prototype 20** - We decided to start from scratch again, trying to get our model to be as light as possible, allowing us to use the smaller motors (instead of the big one we were given) and less springs to make our robot jump higher with less voltage. **Insights:** This model worked great but was hard to stabilize since it only had two legs and the motors began to run a little slow. This was probably due to the fact that the 12V batteries were getting burned out or not providing enough current to the motor. If we added more rubberbands, the motors were not strong enough to lower it.
	**Prototype 21** - We went back a design and worked on trying to get the motor to run faster by using 9 volt batteries that had much more current. This worked really well and our model was able to lower much faster. **Insights:** Although it lowered much faster, it was much heavier with the big 9 volt battery and therefore we had to add a bunch more rubber bands to make it reach the meter height. We also added a velcro strap over the top of it so it could stick to the bottom of the ship.

A.2 Sources Documentation

Helpful Photo/Diagram:	Source Title: A miniature 7g jumping robot
 Fig. 1. 7g jumping mechanism prototype capable of overcoming obstacle of up to 1.4m height.  Fig. 6. CAD model of the gearbox. (A) brass bearing to reduce friction, (B) distance piece to align the two body plates, (C) cam axis, (D) slot in main leg for the cam, (E) main leg and, (F) series of holes for spring setting. (1),(2) 0.2mm POM gears and (3) 0.3mm POM gear	**Source Type:** Article/Paper **Link:** http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4543236&tag=1 **Citation:** Kovac, Mirko, et al. "A Miniature 7g Jumping Robot." *2008 IEEE International Conference on Robotics and Automation* , 2008, pp. 373–378., doi:10.1109/ROBOT.2008.4543236. **What we learned:** This bot uses a four bar linkage system and elastic elements to jump more effectively than all other comparison bots named in the paper. It also leverages an incredibly small weight in order to jump 27 obstacles times its size. "Since there is no actuator capable of producing that much power at a weight of only a few grams, we decided to design a mechanisms which can be charged slowly, store the energy in a spring and release it on demand using a click mechanism. This mechanical principle is used by several small jumping animals, such as frogs [6], locusts [7], springtails [16], click beatles [4] and fleas [8]."
Helpful Photo/Diagram: 	**Source Title:** 7 Gram Jumping Robot moving in Rough Terrain **Source Type:** Video **Link:** https://www.youtube.com/watch?v=0SPrrn07m2Q **What we learned:** This bot is the same as the one mentioned in the article above. This video allowed us to view the mechanics of the jumping motion in action. With this video, we were really able to understand how the gears actuated the release mechanism that allowed the bot to both store and release it's power so that it could jump.

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Helpful Photo/Diagram:

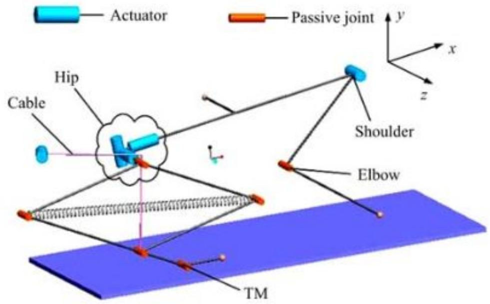

Fig. 11 The mechanical model of frog (half of the body), and the *x*-*y*-*z* axis orientation is the same with Fig. 1.

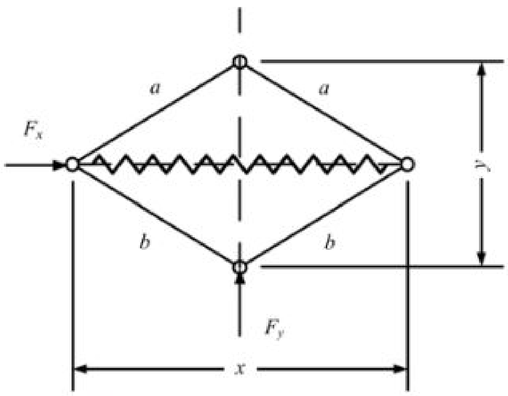

Fig. 9 4-bar spring/linkage mechanism.

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Source Title: Biological Jumping Mechanism Analysis and Modeling for Frog Robot

Source Type: Article

Link:
https://www.sciencedirect.com/science/article/pii/S1672652908600232

Citation: Wang, Meng, et al. "Biological Jumping Mechanism Analysis and Modeling for Frog Robot." *Journal of Bionic Engineering*, vol. 5, no. 3, 2008, pp. 181–188., doi:10.1016/s1672-6529(08)60023-2.

What we learned:
A frog's legs have three degrees of freedom, which is something we'd like to limit as we create our jumping bot. A frog uses its forelimbs as a source of support in addition to assisting with jumping. Additionally, a frog's leg can be modeled using a four-bar linkage that keeps the range of the joint angles within realistic parameters.

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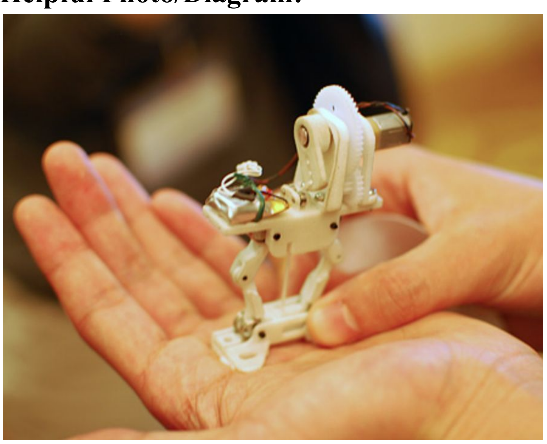
Helpful Photo/Diagram:



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Source Title: Brilliant Little Jumping Robot Only Needs One Motor

Source Type: Article

Citation: Ackerman, Evan. "Brilliant Little Jumping Robot Only Needs One Motor." *IEEE Spectrum*, 6 June 2011, spectrum.ieee.org/automaton/robotics/diy/brilliant-little-jumping-robot-only-needs-one-motor.

Link:
https://spectrum.ieee.org/automaton/robotics/diy/brilliant-little-jumping-robot-only-needs-one-motor

Video Link:
https://www.youtube.com/watch?v=XxHRqZGQM38

What we learned:
"The actual jumping mechanism was directly inspired by the legs of a frog… Everything is driven by one tiny

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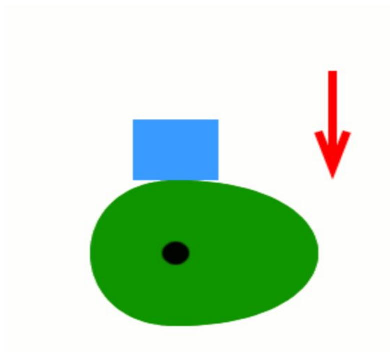
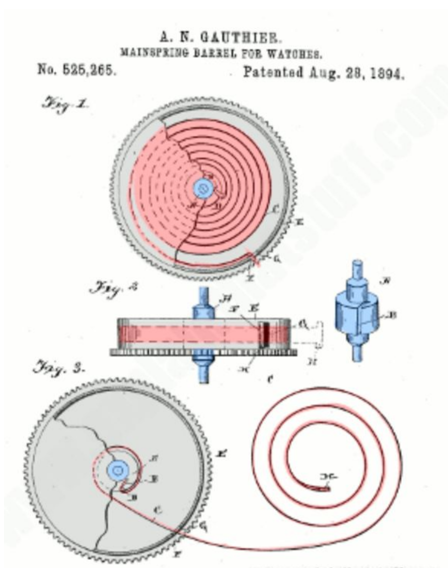
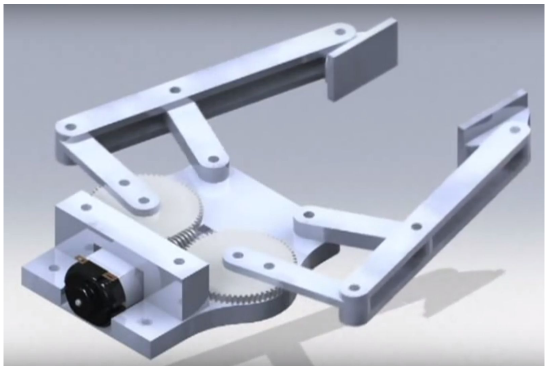
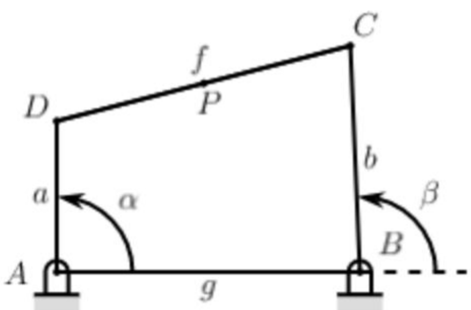
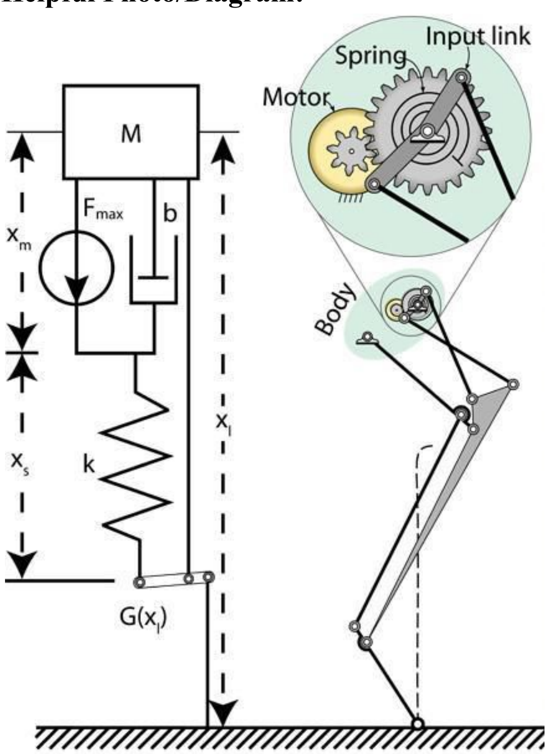
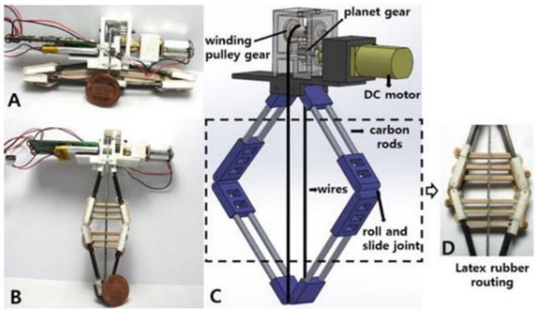
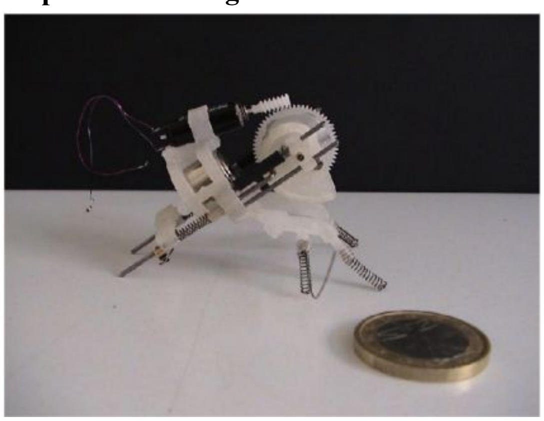
	pager motor, and here's how it works: To jump, the pager motor engages a gear which pulls the robot's body down towards its legs, slowly charging four torsional springs. The gearing and springs help keep the power requirements low without sacrificing jumping energy. When the springs are fully charged up, the gear trips a little lever, and the legs are released.”
Helpful Photo/Diagram:   	**Source Title:** Clockwork (windup) mechanisms **Source Type:** Article **Link:** http://www.explainthatstuff.com/how-clockwork-works.html **What we learned:** Mainspring springs can be helpful when trying to add and store energy; however, tightening the springs can take a lot of work. Cams and Cranks are good for creating back-and-forth motions similar to the motion of a leg when walking, and can assist in creating energy when using springs.
Helpful Photo/Diagram:	**Source Title:** 4 Bar Linkage End Effector, Robot Gripper Animation **Source Type:** Video **Link:** https://www.youtube.com/watch?v=HMQ4u9UlPSQ **What we learned:** The use of gears helps create a frog-like jumping

	motion with the incorporation of a worm gear. By removing the worm gear and having the spur gears interact directly, we can reduce friction while still making the individual legs act in unison.
Helpful Photo/Diagram: 	**Source Title:** Four-Bar Linkages **Source Type:** online application **Link:** http://dynref.engr.illinois.edu/aml.html **What we learned:** Four-bar linkages can be used for many mechanical purposes, including to: convert rotational motion to reciprocating motion, convert reciprocating motion to rotational motion, constrain motion and magnify force.
Helpful Photo/Diagram: 	**Source Title:** SALTO the Agile Jumping Robot **Source Type:** Article **Link:** http://www.deviceplus.com/inspire/salto-the-agile-jumping-robot/ **What we learned:** Crouching is a good way to build energy. "Vertical jumping agility (meters/second) = h/(t_stance + tapogee), where h = jump height; t_stance = total stance time from the onset of actuation; and tapogee = flight time from when the jumper leaves the ground until it reaches the highest point of a jump (when the vertical velocity is zero)."

Helpful Photo/Diagram:  	**Source Title:** JumpRoACH Is a Robotic Bug That Leaps and Flips Just Like an Insect **Source Type:** Article **Link:** https://spectrum.ieee.org/automaton/robotics/robotics-hardware/jumproach-robotic-bug **Video:** https://www.youtube.com/watch?time_continue=21&v=kekOiptWL6U **What we learned:** Planetary gear allows motor to reverse itself to allow for jumping after desired amount of winding is reached. Rubber bands act as good spring-like mechanisms for jumping.
Helpful Photo/Diagram: 	**Source Title:** Design and Development of the Long-Jumping "Grillo" Mini Robot **Source Type:** Article **Link:** http://ieeexplore.ieee.org/document/4209135/ **What we learned:** "Inspired by frog locomotion, a tiny motor load the springs connected to the hind limbs. At take-off, an escapement mechanism releases the loaded springs." A cam could be a good option for a release mechanism.
Helpful Photo/Diagram:	**Source Title:** MultiMo-Bat: A biologically inspired integrated jumping–gliding robot **Source Type:** Article **Link:** http://journals.sagepub.com/doi/pdf/10.1177/0278364914541301 **What we learned:** Four-bar linkages are reliable when mimicking the knee joint and for enacting the energy storage phase of the jump needed to get the bot off the ground.

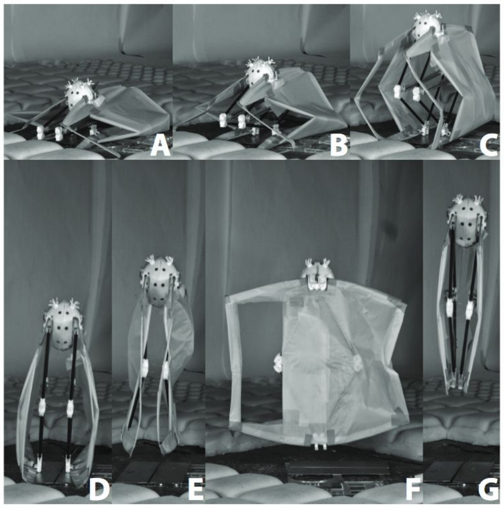


Fig. 3. Video snapshots of the lift-off behavior of the MultiMo-Bat prototype which illustrates the wing membrane tensioning and the effects of the out-of-plane torques produced by the air-foils. (A) Initial jumping position with the membranes collapsed. (B) The four-bar legs begin to extend, powering the jump. (C) The membranes are reaching full extension. (D) The MultiMo-Bat just before it leaves the ground showing the airfoils inflated by the escaping air mass between them. (E–F) Front- and side-views of the robot at the point of maximum out-off-plane deformation. (G) The wings quickly stabilize at about a body length above the ground and remain beside the body until the robot nears the apex of the coast phase.

A.3 Working Model Testing

During this project, the Working Model 2D (WM2D) software helped us gain a better understanding of how our jumper might perform in ideal conditions. The software was only capable of modeling 2D jumpers so we had to simplify our design in order to create a model, but the software still helped us gain insight into what different weight ratios would do and what spring constants would be effective. Below you can see each iteration of WM2D jumpers we made to model the mynock we had built. As our design went back and forth with different features, so too did our WM2D designs.

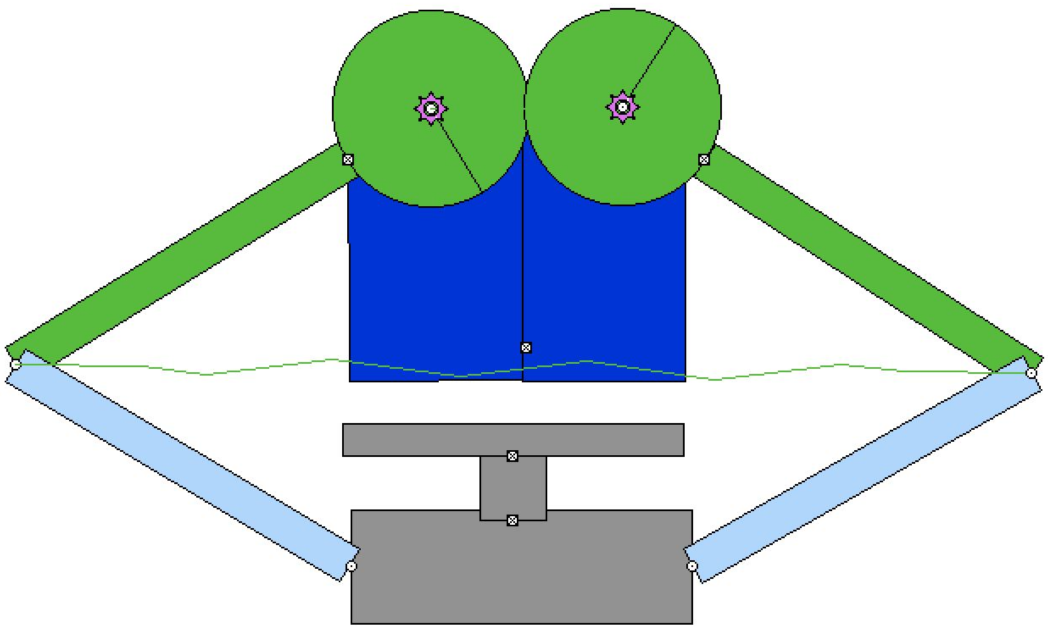


Figure A.3.1: This was the first WM2D jumper given to the class as a demonstration by the class teaching team.

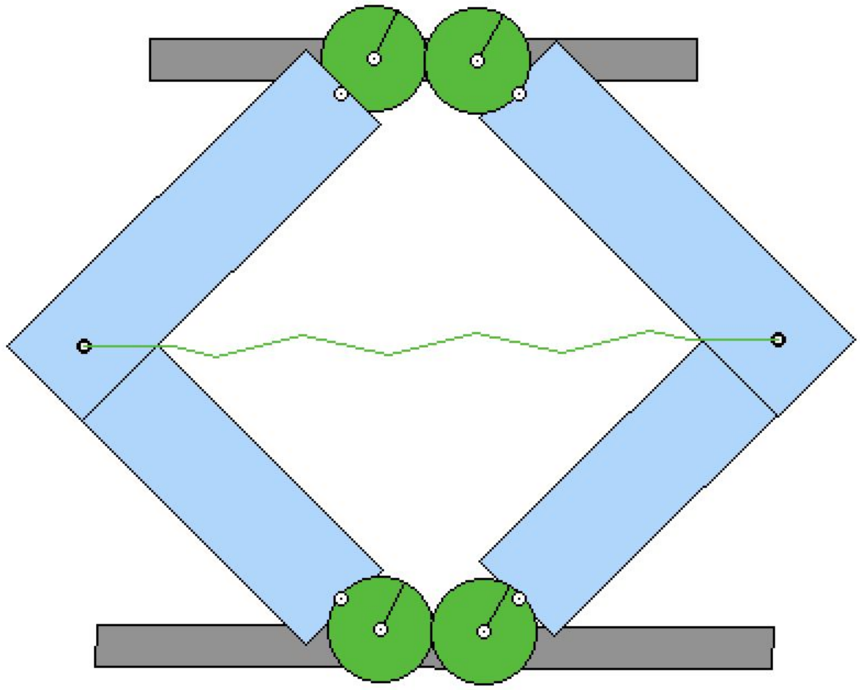


Figure A.3.2: Our very first try at making a WM2D model.

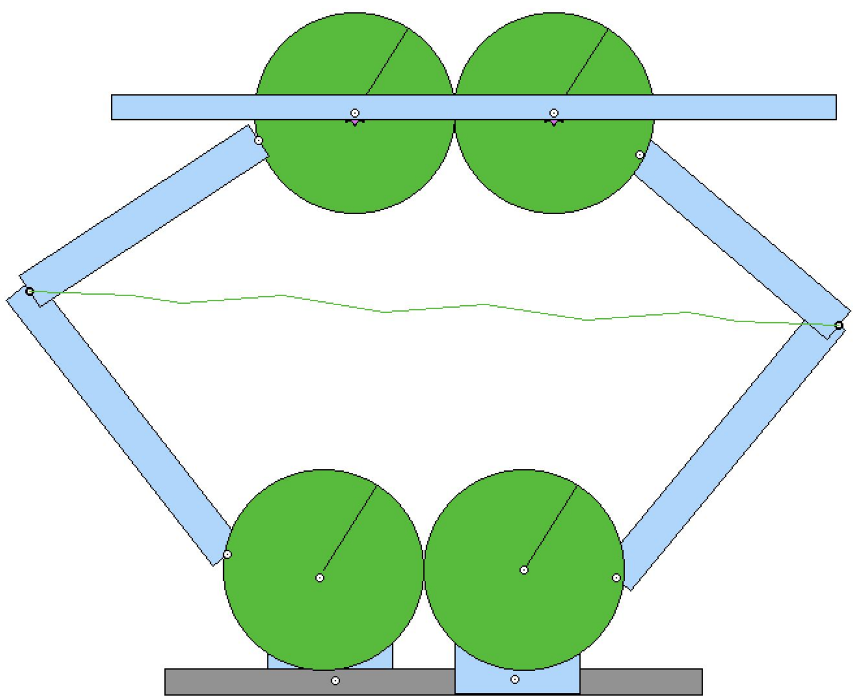


Figure A.3.3: Though modeled by connecting circles at the bottom, this WM2D mockup does not have gear connections on the bottom, increasing the degrees of freedom.

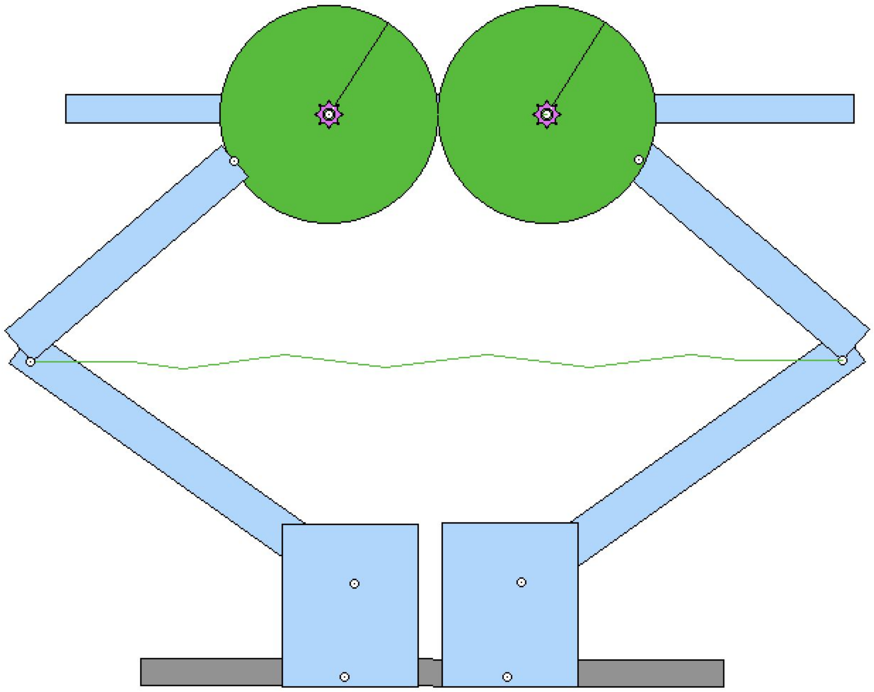


Figure A.3.4: This model increased stability slightly but still had an additional degree of freedom that affected its movement and trajectory.

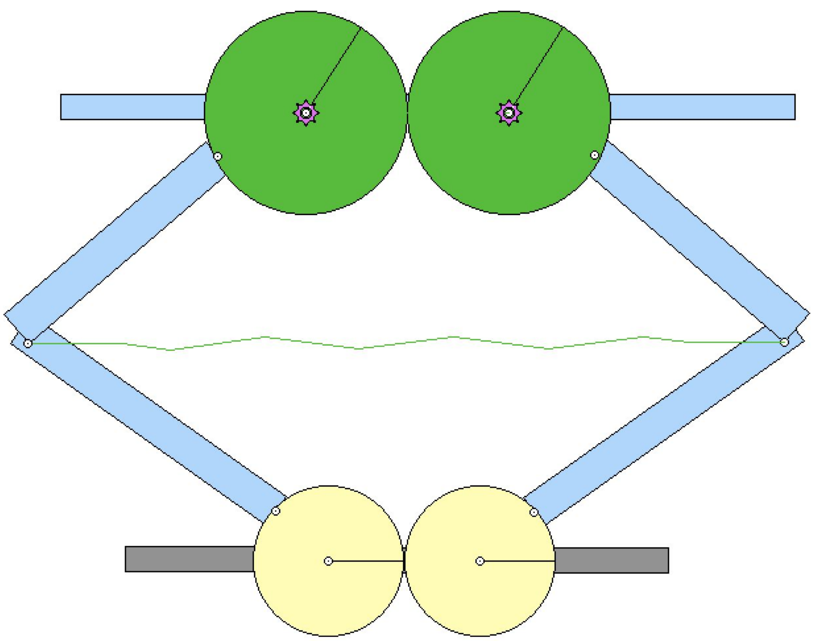


Figure A.3.5: Though difficult to see in this model, we began modeling the linkage-to-gear connections more accurately by extending the thin blue rectangles on the bottom so they had two points of connection with the lower pale yellow circles, the center and the outer rim.

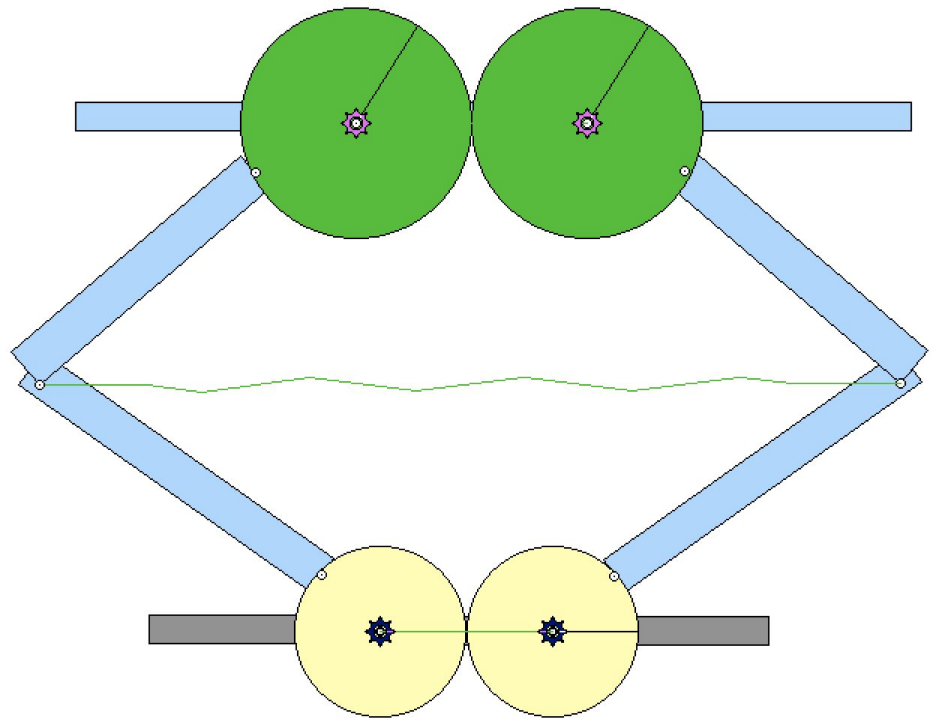
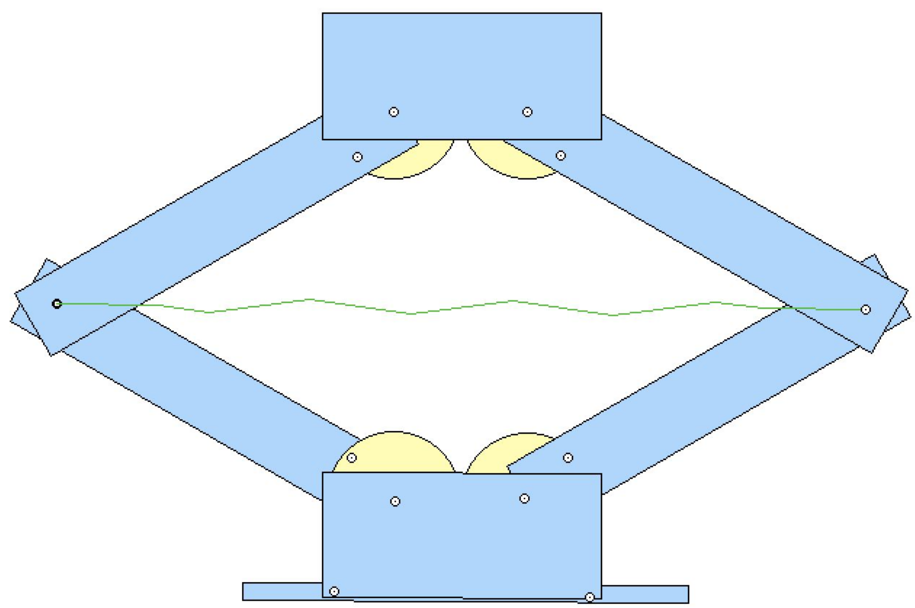


Figure A.3.6: Finally, we used gears to stabilize both the top and bottom linkages.



A.3.7: By adding pieces to represent the legos we were using, this model gave us a better idea of our jumpers' possible movements and though not visible, the circles in this mockup are connected as gears.

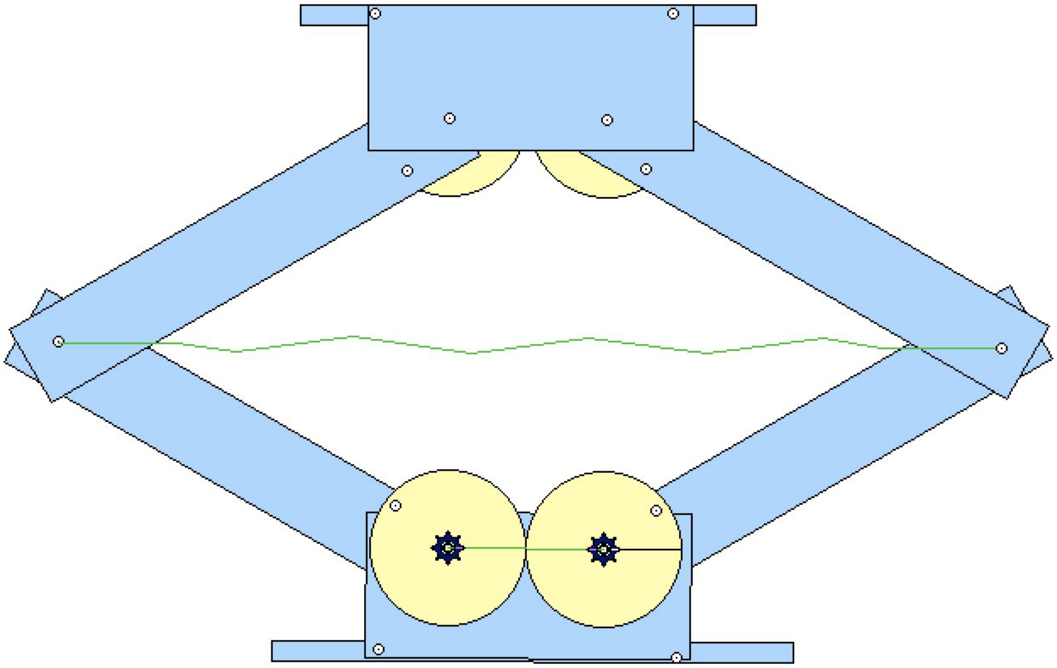


Figure A.3.8: One of the most accurate models we made, this version of our jumper was scaled to the actual mynock we had built at the time.

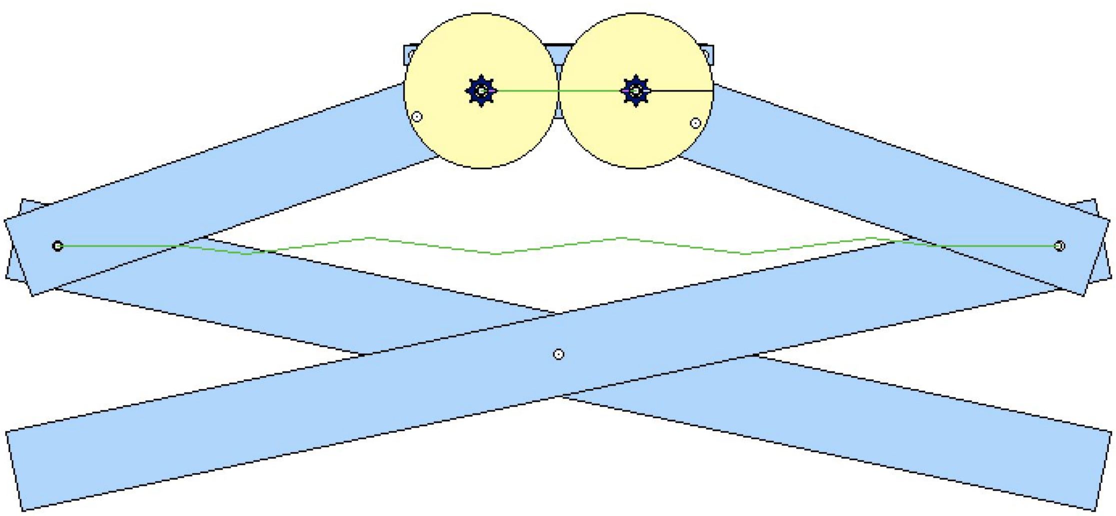


Figure A.3.9: After switching designs, this is our final WM2D prototype. The linkages are scaled accurately, the weight of each piece was calculated to be as similar as possible to our 3D design and the spring constant was representative of the one we found in our analysis.

A.4 Free Body Diagram Analysis

Variable	L	Theta	h_l	x
Represents	Length of the shorter linkage	Angle between the rubber bands and the link	Total height of all of the linkages	The current length of the rubber bands

Variable	Δx	k	F_{St}	F_{Bands}
Represents	The change in length of the rubber bands	The spring constant of all the rubber bands	The force of the string pulling the robot down	The force of the rubber bands

Table A.4.1: Summary of Variables used in Free Body Diagrams

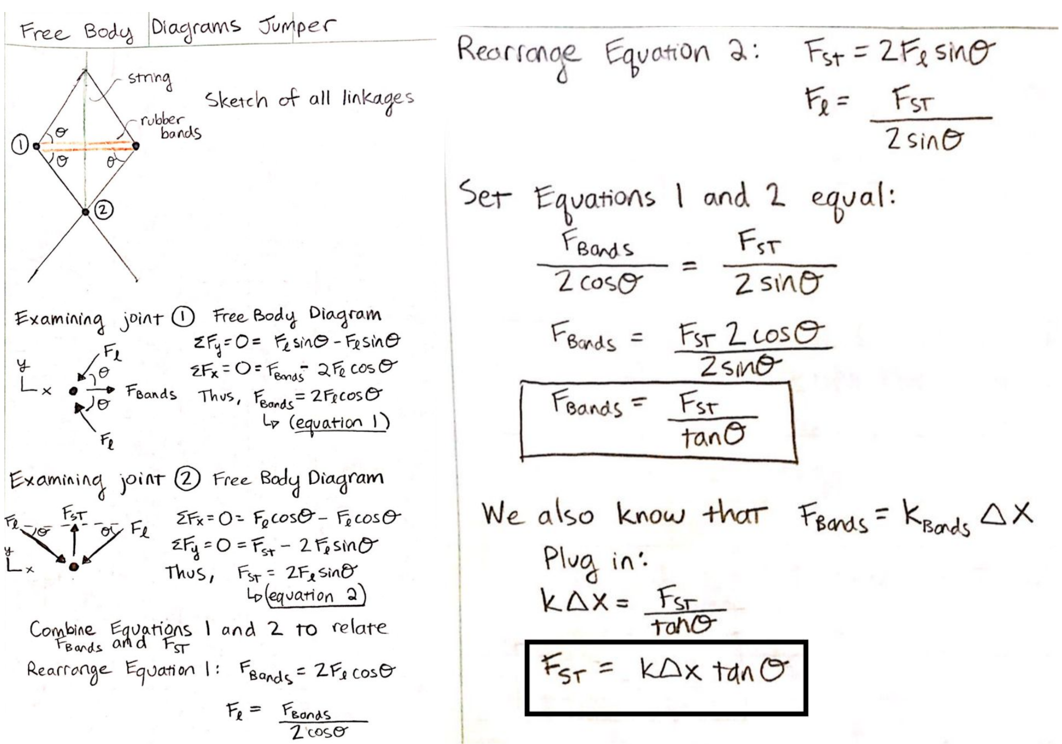
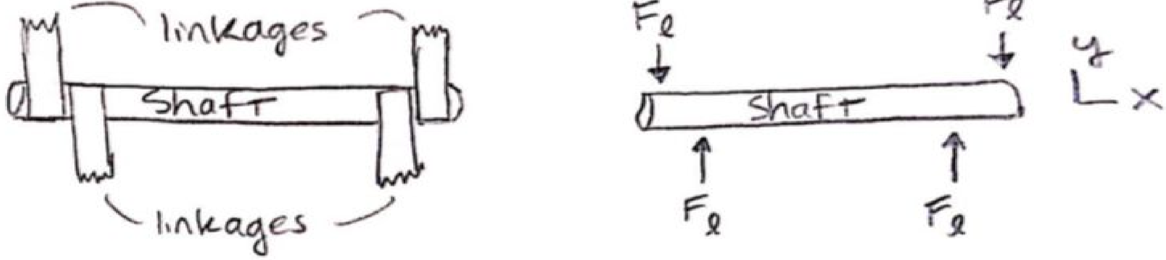


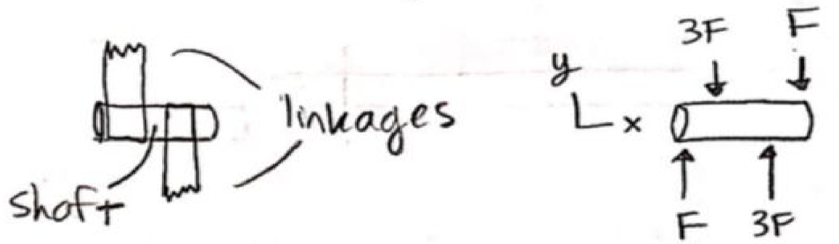
Figure A.4.1: Our initial analysis of the required forces on our robot. This analysis ultimately relates the required force in the string attached to the motor to the force generated by the rubber bands, and shows the string force depends on the angle between the linkages.

Examining shafts: Free Body Diagram



Our simply supported shaft design, as shown above, decreases the magnitude of the required forces as compared to a cantilevered design, as diagrammed below:

Cantilevered Shaft Example (NOT our final design):



Thus, by using a simply supported shaft design, we decreased the forces exerted on our shaft, and, in turn, our friction loss in the shaft joints.

Figure A.4.2: Our analysis to aid in shaft design. We determined that the magnitude of the forces, and in turn the overall friction, would be less in a simply supported beam design as compared to a cantilevered beam design.

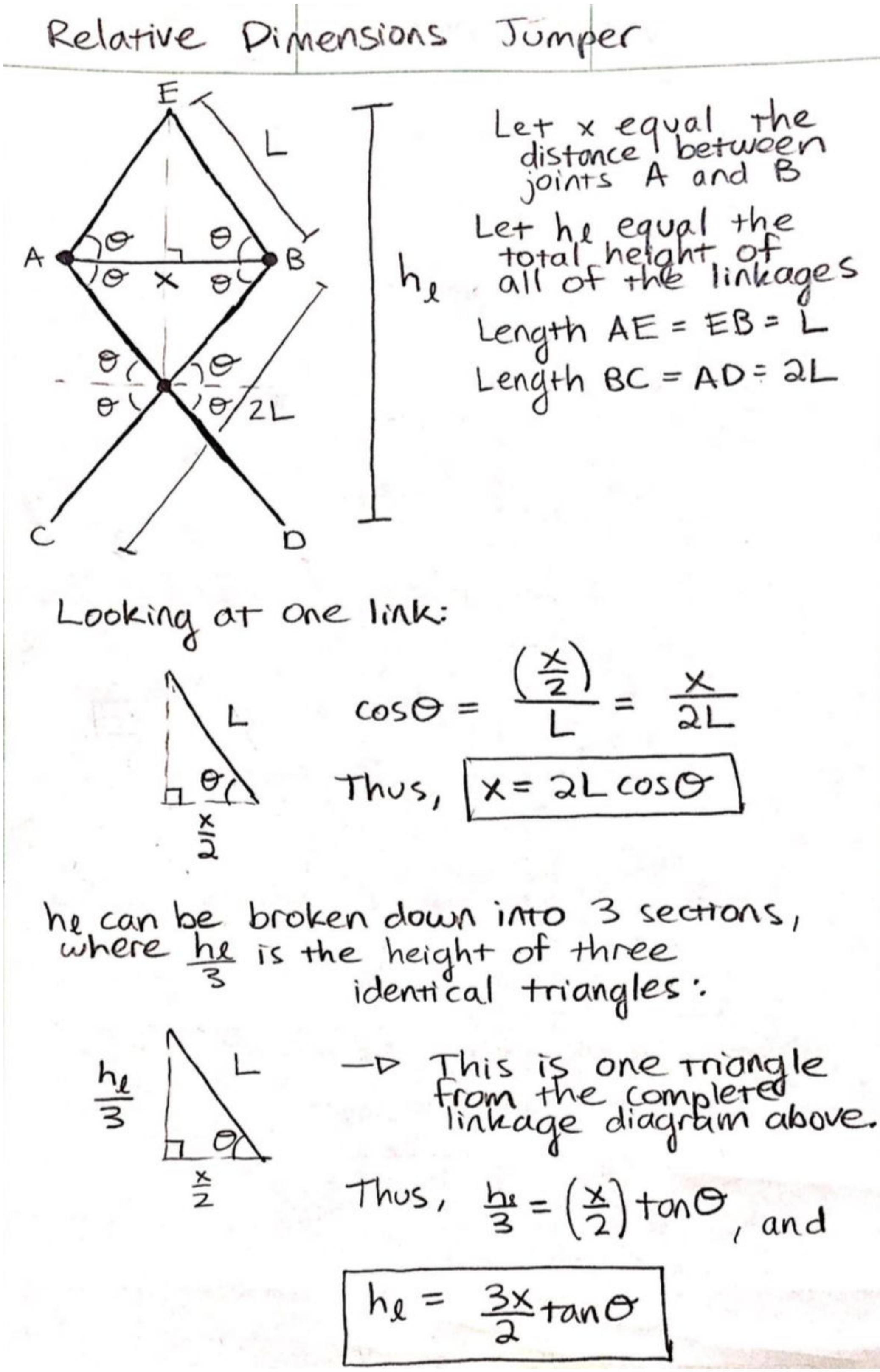


Figure A.4.3: Our geometric analysis to relate the angle between linkages, the distance the rubber bands are stretching, and the total height of the linkages.

```matlab
clear all
close all

%Establish constants
L = 0.0762; %length from joint to joint in m
k = 1482; % measured spring constant of rubber bands in N/m

theta = linspace(0.1, pi/2); %create a vector of values for theta
ranging
%from zero to 90 degrees

%Calculate the length of the rubber bands as compared to the
angle
%between the linkages
x = 2.*L.*cos(theta);

%Calculate the height of the entire linkage
h_link = (3/2).*x.*tan(theta);

%Create plots
plot(theta, x)
hold on
title('Angle of Linkage vs. Length of Rubber Bands')
xlabel('Angle of linkage (rad)')
ylabel('Length of rubber bands (m)')

figure()
plot(x, h_link)
title('Length of Rubber Bands vs. Height of linkages')
xlabel('Length of rubber bands (m)')
ylabel('Height of linkages (m)')

figure()
plot(theta, h_link)
title('Angle of Linkages vs. Height of Linkages')
xlabel('Angle of linkages (rad)')
ylabel('Height of linkages (m)')

%To determine delta x, set a start value for theta, vary the
%end value of theta and calculate delta x from the difference
%of the x values with the two angles
theta_initial = pi/3; %set initial value of theta
theta_actual = linspace(0, pi/3.1);
delta_x = -2.*L.*cos(theta_initial)+2.*L.*cos(theta_actual);

%Calculate the string and rubber band forces
Fst = k.*delta_x.*tan(theta_actual);
F_rubberbands = Fst./tan(theta_actual);

%Create plots for String and Rubber Band Forces
figure()
hold on
plot(delta_x, Fst)
title('Change in Rubber Band Length vs. Force in String')
xlabel('Delta x, change in rubber band length (m)')
ylabel('Force in string (N)')
xlim([0 0.07])

figure()
hold on
plot(theta_actual, Fst)
title('Angle of linkages vs. Force in String')
xlabel('Angle of linkages (rad)')
ylabel('Force in String (N)')
xlim([0.1 1.2])

figure()
hold on
plot(theta_actual, F_rubberbands)
title('Angle of linkages vs. Force in Rubber Bands')
xlabel('Angle of linkages (rad)')
ylabel('Force in Rubber Bands (N)')
xlim([0.2 1.2])

figure()
hold on
plot(delta_x, F_rubberbands)
title('Delta x vs. Force in Rubber Bands')
xlabel('Delta x (m)')
ylabel('Force in Rubber Bands (N)')
xlim([0 0.07])
```

Figure A.4.4: Matlab code to generate plots of the equations found from our free body diagrams

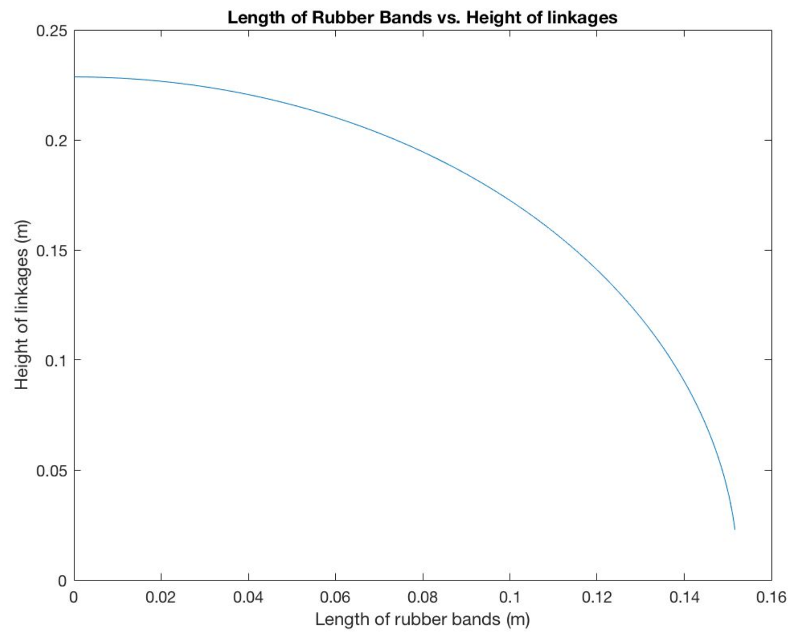


Figure A.4.5: Graph of Length of Rubber Bands vs. Height of Linkages

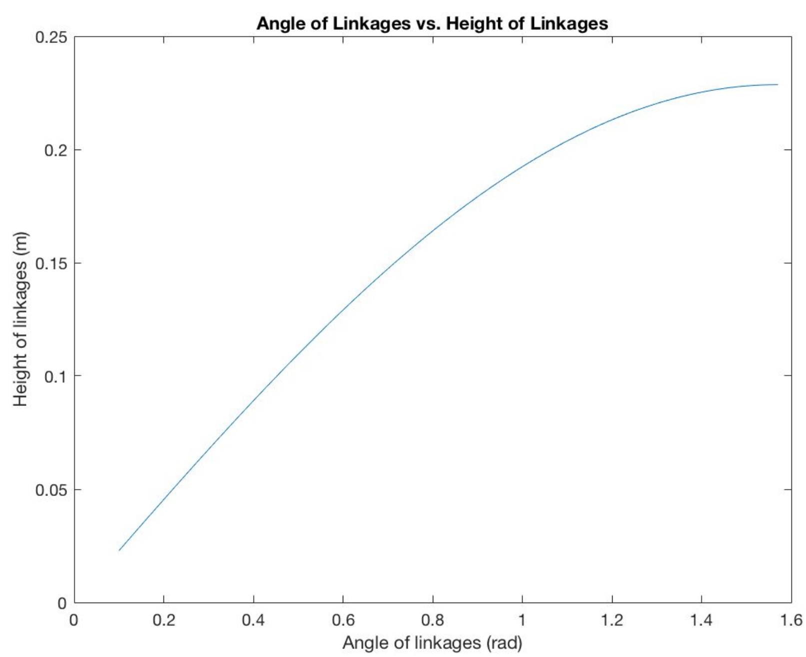


Figure A.4.6: Graph of the Angle of the Linkages vs. the Height of the Linkages

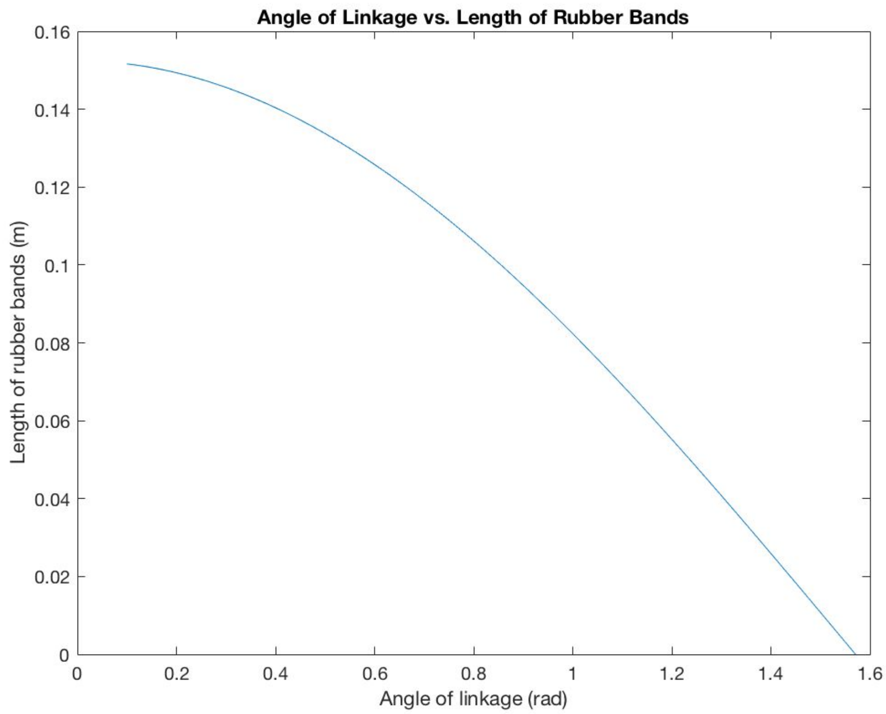


Figure A.4.7: Graph of the Angle of the Linkages vs. the Length of the Rubber Bands

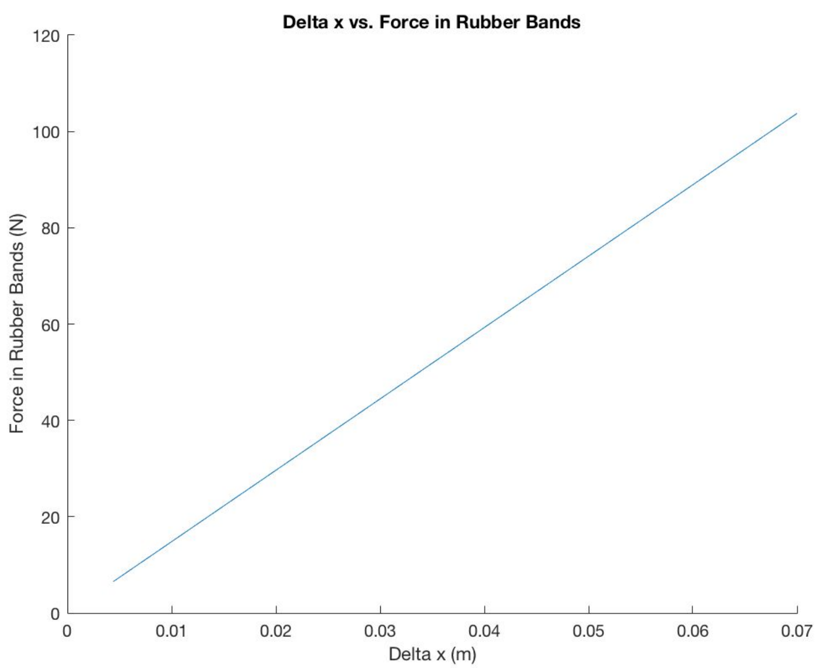


Figure A.4.8: Graph of the Change in Length of the Rubber Bands vs. the Force in the Rubber Bands. The slope of this graph is our spring constant, k.

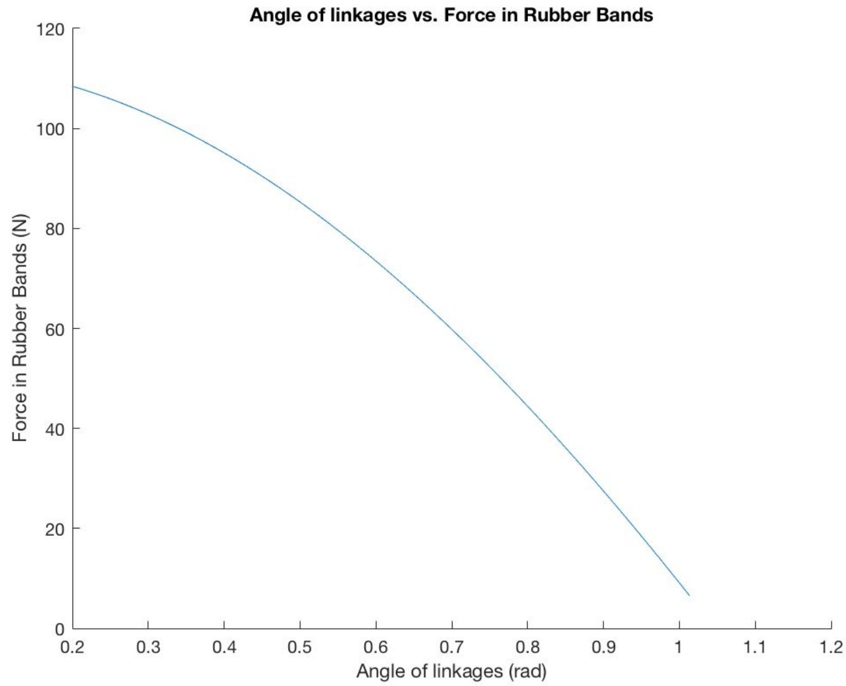


Figure A.4.9: Graph of the Angle of the Linkages vs. the Force in the Rubber Bands

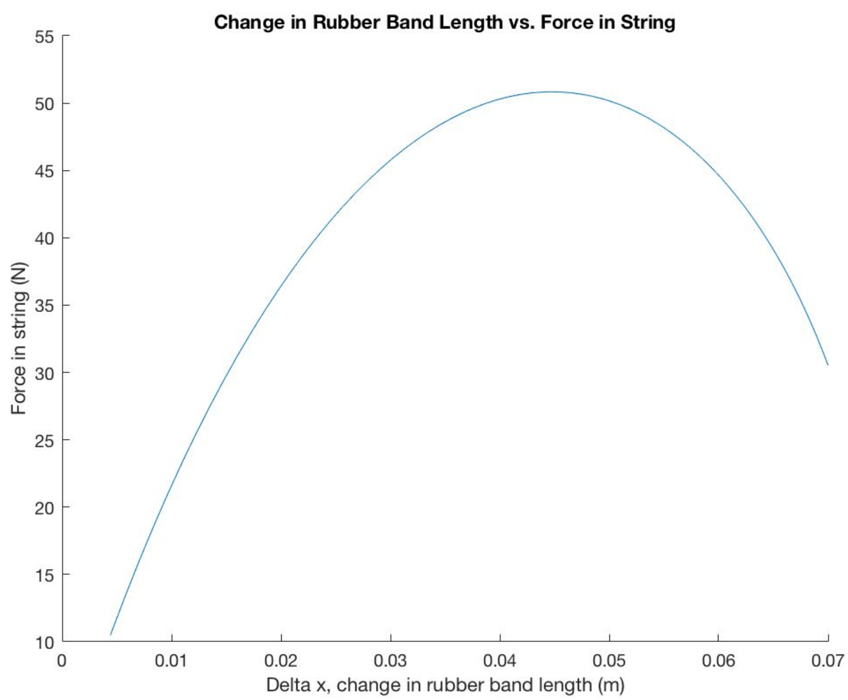


Figure A.4.10: Graph of the Change in Length of the Rubber Bands vs. the Force in the String

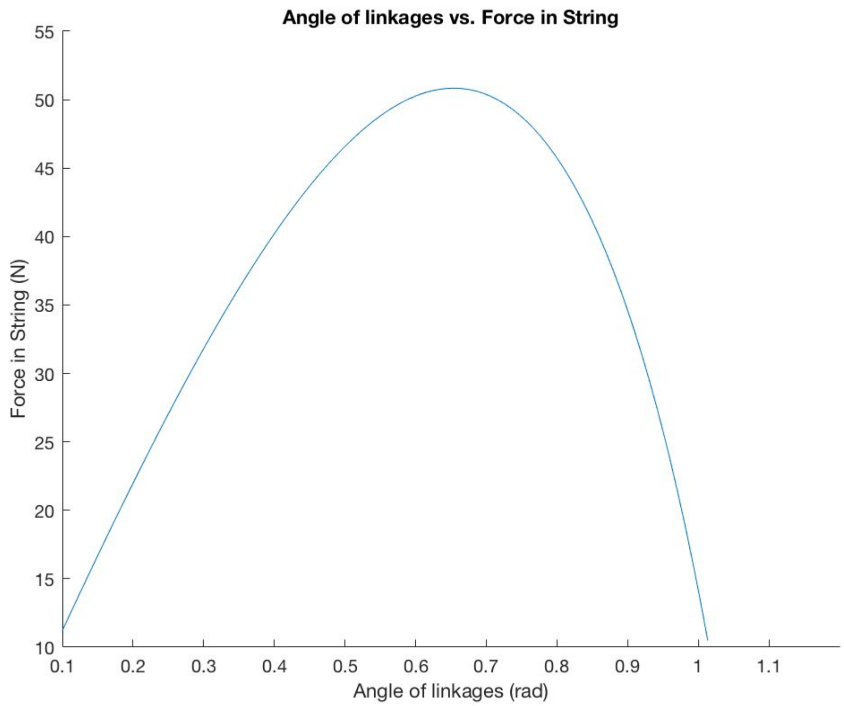


Figure A.4.11: Graph of the Angle of the Linkages vs. the Force in the String

A.5 Initial Calculations

Listed here are some initial calculations we did to get a very rough estimate of the numbers forces and power required of our jumper.

Calculations are assuming m = 100 g and V = 1.5 V

Power
Power out = m*g*h. With m = 100 g = 0.100 kg ,
P = 0.10 kg * 9.8 (m/s^2) * 1.0 m = **0.98 Joules**
Power in = V * I * t = 1.5 volts * 0.3 amps * 4 seconds = **1.8 Joules**

Initial Velocity
KE (kinetic energy at beginning) = $0.5 * m * v^2 = m * g * h$ = Potential energy at end
Thus, $v = \sqrt{2gh}$
v = $\sqrt{2 * 9.8\ (m/s^2) * 1.0\ m}$ = **4.43 m/s** (assuming no drag)

Force needed to push off the ground
Find acceleration needed: need +9.81 m/s^2 (to counteract the acceleration due to gravity)
F = m*a
F = 0.100 kg * 9.81 m/s^2 = **0.98 N**

Spring constant/elastic energy needed
F = k*x where k = spring constant and x = change in length of spring (Hooke's Law)
If x = 3 cm = 0.03 m, then
K = F/x = 0.98 N / 0.03 m = **32.7 N/m = 0.327 N/cm = 0.0327 N/mm**

Torque required calculations:
$T = F x R$
The force required can be calculated from the force required to stretch the springs, F = k*x (assuming no losses). Above, we found F = 0.98 N. The radius of the shaft around which the string winds is 2 mm = 0.002 m.
$T = F x R = 0.98\ N * 0.002\ m = 0.00196\ N * m$

Matlab Code For initial Energy Calculations:

```
clear all
close all

%Enter constants
m = 0.278; %mass in kg
g = 9.8; %acceleration in m/s^2
h = 1.0; %height in meters
rho = 1.23; %density of air in kg/m^3
Cd = 1.0; %coefficient of drag (flat plate is 1.17, cube is 0.8)
Ay = 0.004452; %area of top surface in m^2 (5.3 x 8.4 cm)
v0 = 1.8; %initial velocity in m/s from working model
v_calc = 4.43 %initial velocity required using PE
a_max = 50; %max acceleration from working model %in m/s^2
theta = 10 %angle between bottom linkages in degrees

%Spring constant calculations
mass_on_spring = 1.209 %kg
delta_x_spring = 0.008 % amount we stretched the string in m
k_spring = (mass_on_spring*9.18)/delta_x_spring

%Calculations
Faero = 0.5*rho*Cd*Ay*v0^2
PE = m*g*h
KE_initial = 0.5*m*v0^2
F_ground = m*a_max
Spring_E = 0.5*k_spring*(delta_x_spring)^2
F_spring = k_spring*delta_x_spring %Force from spring in N
F_string = F_spring/tand(theta)

 %Calculate required motor torque and max F_spring
F_stringmax = (k_spring*delta_x_spring)/tand(90)
```

Matlab Results:

```
v_calc =

    4.4300

theta =

    10

mass_on_spring =

    1.2090

delta_x_spring =

    0.0080

k_spring =

   1.3873e+03

Faero =

    0.0089

PE =

    2.7244

KE_initial =

    0.4504

F_ground =

   13.9000

Spring_E =

    0.0444

F_spring =

   11.0986

F_string =

   62.9434

F_stringmax =

     0
```

A.6 Finding K Values

F = Kx
Known mass = 748g

SPRING #1:
Start: 3.4 cm
End: 5.5 cm
(.748kg)(9.81) = K (.055m-.034m)
K = 349.423

SPRING #2:
Start: 5 cm
End: 5.2 cm
(.748)(9.81) = k (.052 - .050)
K = 3668.9

SPRING #3:
Known mass = 1877g
Start: 7.75 cm
End: 11.3 cm
(1.877kg)(9.81) = k (.113-.0775)
K = 519

RUBBER BANDS
Rubber Band mass = 1209g
Start: 9.1 cm
End: 9.9 cm
(1.209kg)(9.81) = K (.099m-.091m)
K = 1482

A.7 Gear Train Efficiency Calculations

Radius of pulley system: 0 .022 m

$Texpected \ = \ 1.127 \ N * m$

$Toutput \ = F * r \ = \ (0.800 \ kg) * (9.81 \ m/s^2) \ * \ 0.022 \ m \ = 0.173 \ N * m$

$Efficiency: \ 0.173 \ N * m \ / \ 1.127 \ N * m \ = \ 15.4 \ \% \ (includes\ both\ motor\ and\ gear\ train\ efficiency)$

Motor and transmission efficiency = Motor efficiency * Gear train efficiency
Gear train efficiency = Motor and transmission efficiency / Motor efficiency
Gear train efficiency = 15.4% / 38% = 41%

A.8 Force Plate Calculations

Force = mass * acceleration; we know F_max = 21.0 N,

Subtract the weight of the "hat" on the force plate: F_actual = 21.0N - 0.016 kg * 9.81 m/s^2

F_actual = 20.8 N

Acceleration = force/mass = 20.8 N / 0.278 kg = 74.8 m/s^2

We used Excel to estimate the initial upwards velocity. We calculated the integral of (Force/Mass)*dt for the jump by averaging the area beneath two points across the entirety of the jump phase and summing the areas. This gave us an initial upwards velocity estimate of 5.75 m/s

Power = Force*velocity, which gives a max power of:

Power = 20.8 N * 5.75 m/s = 119.6 Watts

From the initial velocity estimate, we can calculate the initial kinetic energy:

KE = $0.5 * m * v^2$ = 0.5 * 0.278 kg * (5.75 m/s)^2 = 4.6 Joules

We calculated Potential Energy using the Matlab code, as follows:

PE = m*g*h = 0.278 (kg) *9.81 (m/s^2)*1.0 (m) = 2.7 Joules

Energy Efficiency = 2.7 Joules / 4.6 Joules = 59%

Spring Energy Calculations:

$0.5 * k * (L_{max}^2 - L_{min}^2)$ = KE at take-off = 4.6 Joules.

Our L_{max} is approximately 15 cm., and our L_{min} is approximately 8.5 cm. Solving for k:

K = KE/ $(0.5 * (L_{max}^2 - L_{min}^2))$ = 4.6 Joules/(0.5*((0.15 (m)) ^{2} - (0.085 (m)) ^{2}) = 602 N/m

Our actual measured spring constant (Section 4.3) was k = 1482 N/m

Our actual spring constant gives a spring energy value of:

Spring Energy = $0.5 * k * (L_{max}^2 - L_{min}^2)$ = 0.5*1482 (N/m)*((0.15 (m)) ^{2} - (0.085 (m)) ^{2}) = 11.3 Joules

Thus, our energy loss efficiency within in the robot was:

4.6 Joules/ 11.3 Joules = 41%