Pixar's Luxo Jr. Lamp Final Report

MIE38

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Pixar pioneered computer animation in 1986 changing the future of animation by introducing 3D stills using computer technology. The animations had depth that looked more realistic than any animation made before it. Pixar would take inspiration from real objects, like a lamp from Luxo lighting, and render them completely within a computer screen. Pixar changed the animation industry and its perception of computer animation with the short film, "Luxo Jr.". For this project, the team combines research and engineering principles to create a robot replication of the animated Luxo Jr., the lamp that started and continues to represent Pixar Animations Studios' brand. The Luxo Jr. robot is designed to hop both upwards and forwards. Through related research, the team created several designs. The design that was chosen includes an actuator that uses gears to compress a pair of springs. The goal is to use the energy from the springs to propel the Luxo Jr. model up off the ground. For the chosen design, the model was scaled to replicate Pixar's Luxo Jr while incorporating our designed actuator. Additionally, ANSYS workbench was used to perform failure analysis on both the actuator and the lamp. The Luxo Jr. robot was fabricated to reflect any findings and results from the research, failure analyses, and prototyping process.

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Nomenclature

T	=	Torque
ω	=	Angular Velocity
$\Delta\theta$	=	Change in Angular Rotation
Δt	=	Change in Time
F	=	Force
r	=	Radius
k	=	Spring Constant
Δx	=	Spring Elongation
η	=	Spring Efficiency
m	=	Mass
g	=	Gravity
h	=	Height of Dual Struts
H	=	Hopping Height

I. Introduction

It can be hard to replicate an animation into reality. Even so, the outcome of transforming an animation to real-life is very rewarding. This is how Disney Parks brings their cartoons to life- using robotics to create physical animation with life-size scale models. It was also a way to modernize toys from action figures to more advanced toys, like a light up Buzz Lightyear. Animation can negate the laws of physics while appearing to follow them. Using Pixar's animation of Luxo Jr., all physics elements will be considered to bring the Luxo Jr. lamp model to life. The group will be studying hopping mechanisms to incorporate into our model. The team will be incorporating some kinetic energy as well to achieve a better hopping motion compared to other examples. The group will also study previous examples to study what can be improved from past short outcomes. That way past misconceptions are not repeated. This project will also be completed using different materials to withstand the force of the required hopping forward motion. In the end, the team will achieve a real Luxo Jr. with forward hopping motion. The motivation of this project is visualizing, developing and producing a Luxo Jr. toy or even a display model to use as an attraction piece.

A. Problem Statement

The project for the group is to create and animate the Luxo Jr. lamp from Pixar Animation Studios. The goal is to create a real-world model that will have real-world actions. This project has been assigned before but did not meet expectations of a hop forward. The expected actions are hopping and moving forward with each hop. The reason that this project may be difficult is because it is taking animation from a computer, where there are no limits to what can be done, to the real world where movement is limited by laws of physics. Pixar achieved realistic animation by including authentic movements on the lamp. The team aims to achieve these similar movements on a physical Luxo Jr model.

B. Sponsor Background

The sponsor for the Luxo Jr. lamp project is Pranav A. Bhounsule. Pranav Bhounsule currently is an Assistant Professor for the Department of Mechanical and Industrial Engineering at the University of Illinois at Chicago where he leads the Robotics and Motion Laboratory as well as teaching several courses relating to robotics and design. Bhounsule has a B.E. in Mechanical Engineering, M. Tech. in Applied Mechanics, and a Ph.D. in Mechanical Engineering. Prior to working with the University of Illinois at Chicago, Bhounsule completed postdoctoral research at Disney Research Pittsburgh. The research he conducted at Disney Research Pittsburgh was about accurate task-space tracking for humanoids with modeling errors using iterative learning control. Bhounsule is very interested in this project because he attempted this project in the past, but the group he sponsored wasn't successful and didn't achieve the desired results. Since no one has successfully completed this challenge, Bhounsule is very eager to sponsor this group to hopefully achieve success by attaining the desired results for this project. With his prior Disney experience and research experience, Bhounsule is an ideal sponsor for the project of creating a working prototype of the Pixar mascot, Luxo Jr.

C. Literature Survey

In Pixar's animation, the Luxo Jr lamp hops up and forward. Achieving that movement is the main goal of this project. It is not only important to research experiments specifically of the Luxo Jr, but it is also important to research the physics behind achieving a hop, and any attempts on creating a mechanism that is able to hop. This is very important because it will help the group to find possible methods of achieving the goal of this project.

Pneumatic Actuators

Through research for the Luxo Jr lamp project, multiple previous attempts for similar projects were found. This project has previously been performed by Christian L. Nall of The University of Texas at San Antonio and the sponsor Pranav Bhounsule, but did not achieve the desired results of this project. Through their research, they concluded that the use of 3D printed pneumatic actuators worked to create the desired hopping motion, but did not have the strength to hop and instead moved forward with a "tipping and sliding motion" when attached to the model of Luxo Jr.[6] This design is shown in fig. 1. This research will be helpful for this project, as a similar set up can be used and improved upon. It proves that it is important that the mechanisms used in the project are strong enough to cater to the weight of the Luxo Jr lamp model.

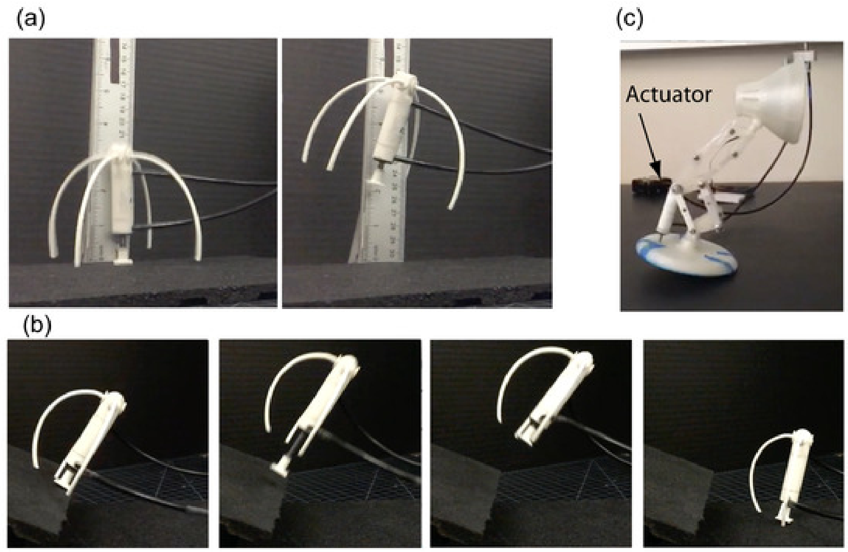

Figure 1. Nall and Bhounsule's design for the Luxo Jr lamp with a 3D printed actuator. *The figure shows how high the actuator mechanism can hop. It also shows the actuator attached to the Luxo model. [6]*

Elastic Actuators

Another similar experiment was performed by Daniel J. Paluska of the Massachusetts Institute of Technology. Through his experimentation, Paluska was able to model the Luxo Jr's hop in a realistic computer model and also able to create a physical model of the lamp but was unable to actually test if his design could achieve a hopping motion.[7] Despite never physically testing his model, Paluska's research can be very helpful in this project as he presents the physics of a jump in his thesis paper. Often, when creating a jumping bipod, the mass of the legs would be negligible and thus they could be swung in order to ease the landing. This is not the case for the Luxo Jr lamp, as its base is relatively large in comparison to the body. It is important to find the proper base position for landing in order to absorb and dissipate the body's kinetic energy. This can be seen in fig.2. This plays a key role in one of the project's design criteria of not toppling over when landing.

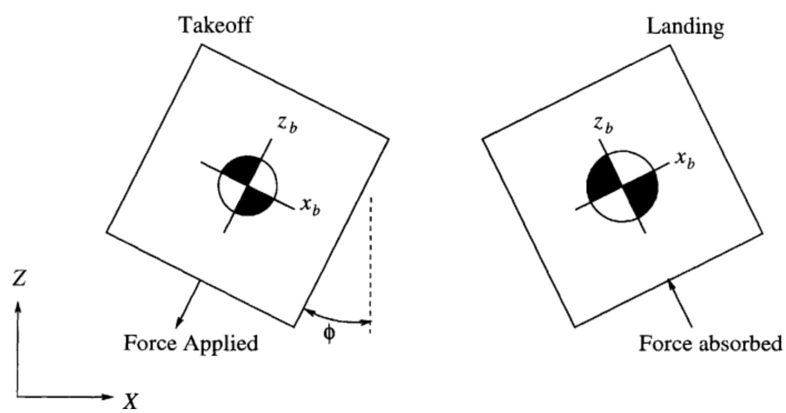

Figure 2. The symmetry of a jump. *This figure shows the importance of reorientation midair [7]*

6 (Nall and Bhounsule 72)
7 (Paluska)

Disney Research Studios also attempted to create a hopping mechanism.[8] Batts, Kim, and Yamane created a "Linear Elastic Actuator in Parallel" (AKA LEAP) to achieve a hopping motion and were successful. Looking at this research will be helpful for the Luxo Jr project as it shows a setup that can be used and expanded on to achieve the project's goals. This design can be seen in fig. 3. Batts, Kim, and Yamane used either one or two springs of multiple different stiffnesses in their experimentation in order to find which stiffness achieved the greatest jump height. The result that they found is that the height achieved was highest with a single spring with a stiffness of 800n/m. These results can be seen in fig. 4. This research can greatly help with the group's project as it shows possible spring strengths to use and also designs to achieve the hop needed.

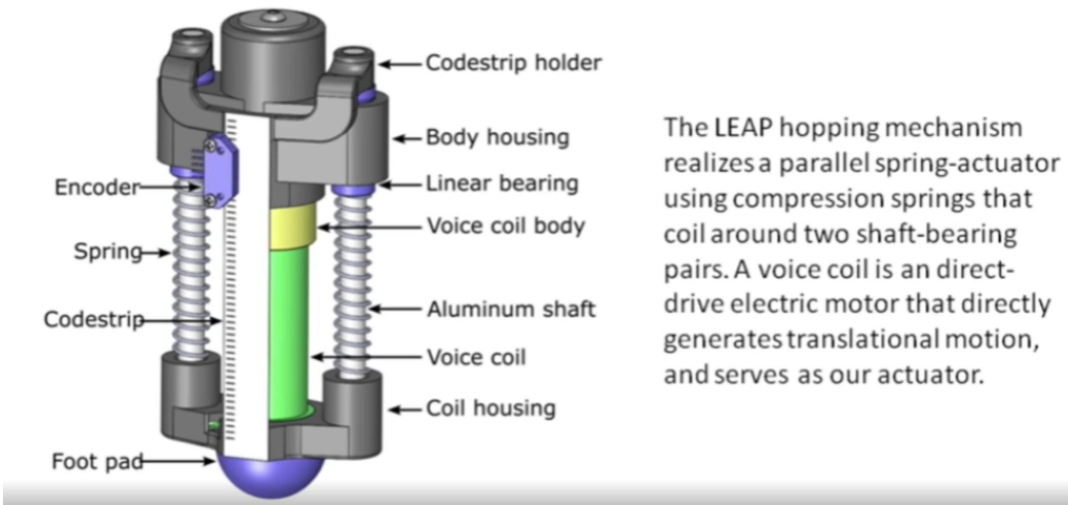

Figure 3. LEAP. *This figure shows the setup of the Linear Elastic Actuator in Parallel. [8]*

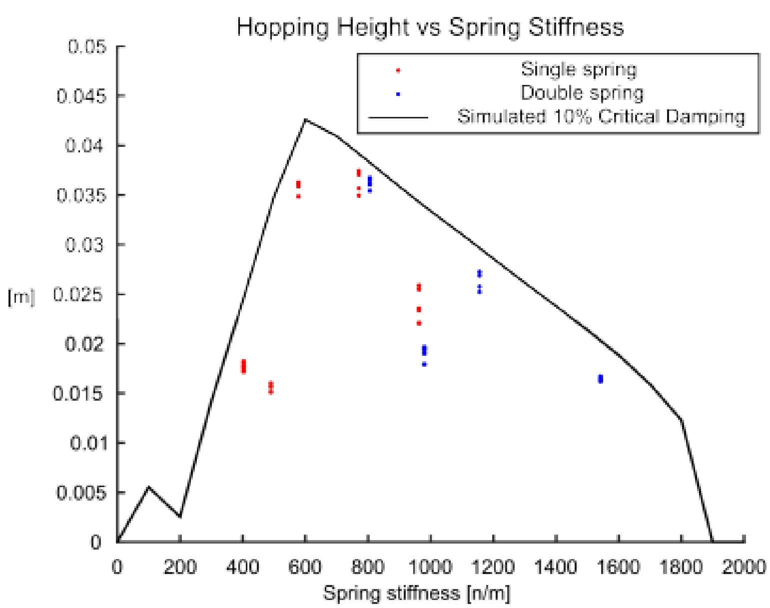

Figure 4. LEAP's height vs spring graph. *This graph shows the height achieved with springs and sets of two springs of various stiffnesses. It shows that the highest height was achieved with a single spring with a stiffness of 800 n/m. Single springs are shown with a red dot, while double springs are represented by a blue dot. This graph*

[8] (Batts, Kim, and Yamane)

also shows the simulated damping of the experiment. [8]

Servo Mounts

A fourth project was performed by Dheera Venkatraman, using an IMU sensor, servo parts, and a raspberry pi.[9] In his experiment, Venkatraman was able to achieve very minimal movement. This can be helpful to look at to see what can work and what does not work, such as the servo parts not being strong enough to achieve upward displacement. Venkatraman's design is shown in fig.5.

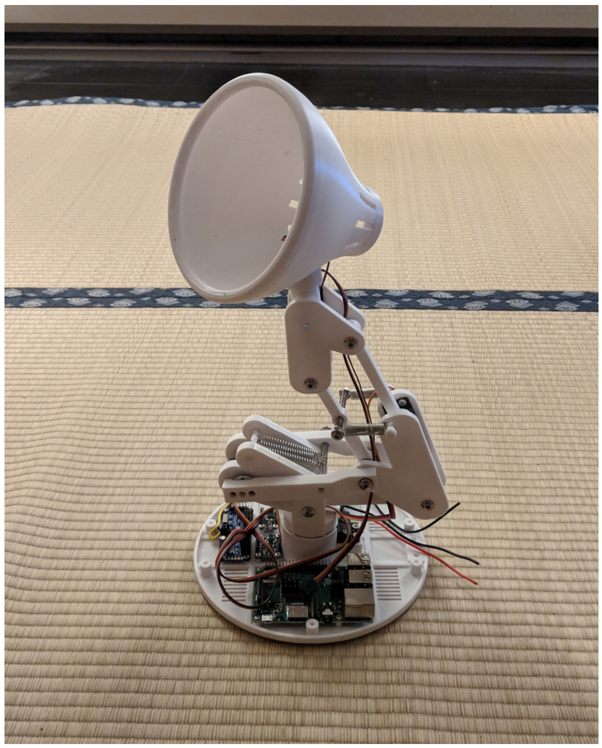

Figure 5. Venkatraman's Luxo Jr. *This figure shows how Venkatraman set up his hopping mechanism within his model of Luxo Jr. [9]*

Non-Luxo Designs

When designing life-like movements in robotics such as jumping, it can be helpful to first study a living creature. In Ruan et al's study on designing a robotic leg, they analyzed the jumping mechanisms of flea beetles.[10] They studied the beetles through high-speed video and 3D model recreation to determine how the bug manages to jump. They discovered that a structure in the beetle's femur, referred to as an elastic plate, enables the bug to jump in an explosive catapult while protecting other structures within the body. This study provides evidence to the importance of internal springs when attempting to make a device that can jump. Their research also provides a comprehensive look into the movements leading up to the jump that will provide the energy needed to get off the ground. The jump begins with muscle contraction, contraction continues until the elastic plate is caught, then the plate is released, causing an explosion of energy. This explosion causes liftoff. Finally, while in the air the muscles relax. This process is shown in fig. 6. This analysis may prove very beneficial for the Luxo Jr lamp project as this process could be replicated with the lamp.

[9] (Venkatraman)
[10] (Ruan, et al)

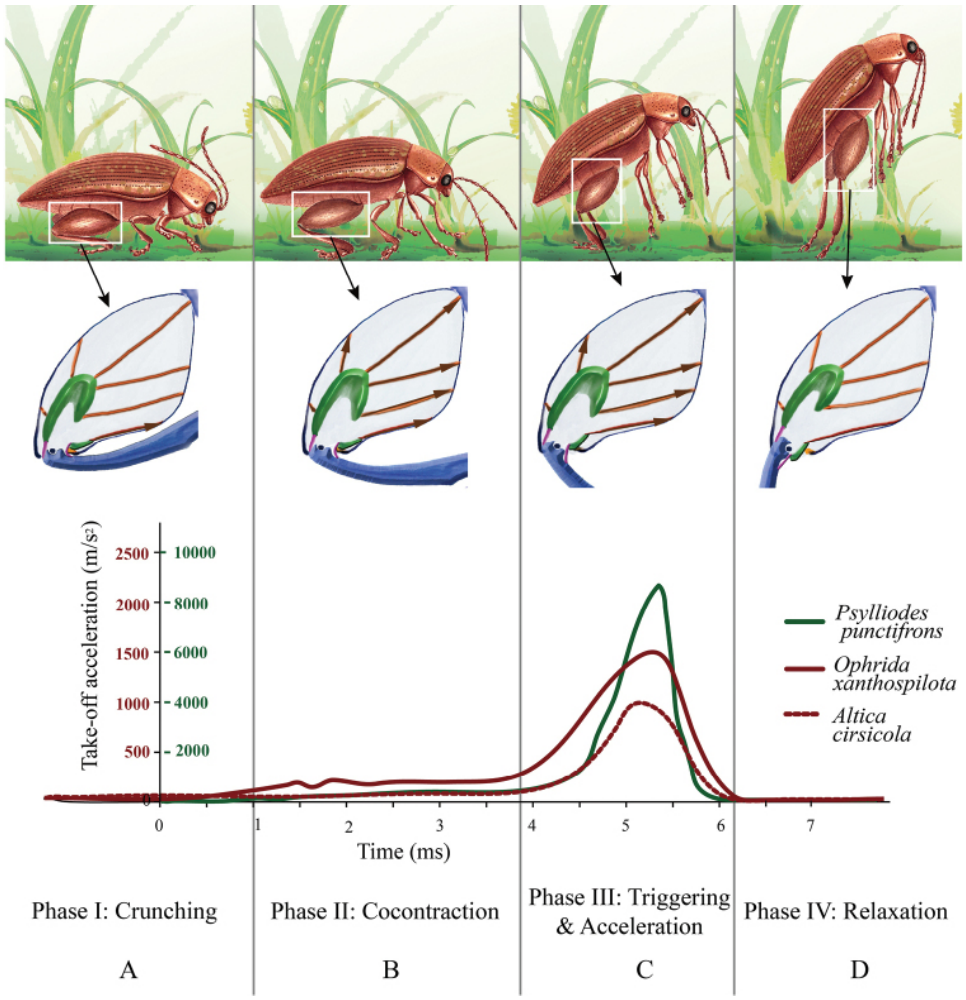

Figure 6. The process of a flea beatle's jump. *A shows the muscle contraction. B, the contraction that catches the elastic plate. C, the release of the plate that allows the beatle to take off. Finally D shows the in-air muscle relaxation. [10]*

Another real life creature that has been studied in relation to creating a robot with the ability to jump is the galago. [11] In the research article of Haldane, Plecnick, Yim, and Fearing, it is shown that actuator strength is very important when attempting to achieve vertical distance in a jump. It is also important for the robot to have control in its stance to achieve a safe and reliable landing. When constructing their jumping robot, the researchers used a series-elastic actuator. Because of this, the robot is able to use power-modulating behaviors. Their robot was monopedal with multiple joints, as the Luxo Jr model will be, so this is a particularly helpful example to research. With their design, the researchers were able to achieve a similar jump height to that of the galago. Their design can be seen in Fig. 7.

[11] (Haldane, Plecnick, Yim, and Fearing)

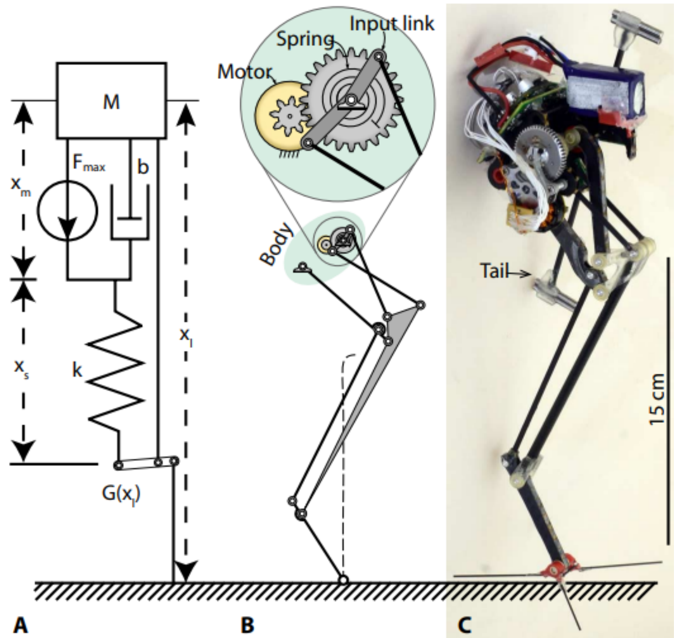

Figure 7. Design of Jumping robot with a series elastic actuator. *This figure shows the design of the actuator in part A, the linkage schematic in B, and the physical model (Salto) in C. [11]*

All of these examples will be helpful to study in the development of a functional Luxo Jr. A frequent recurrence when designing a jumping robot is the use of a series elastic actuator, which has worked in multiple designs. A summary of the previous literature can be seen in table 1.

Creator	Method	Results
Nall and Bhounsule	Pneumatic actuator	The design was able to jump until attached to the luxo model. Once attachedto the model, it onle achieved sliding and dragging motions rather than jumping
Paluska	series elastic actuators	When the design was computer simulated it was able to jump. The author was unable to test the physical design due to time constraints
Batts, Kim, and Yamane	parallel elastic actuator	This design was able to jump nearly 0.04 m
Venkatraman	servo mounts	This design was only able to achieve dragging and sliding motions and was not able to leave the ground.

Table 1. A summary of Luxo Jr. Attempts. *This table summarizes the methods and results of the attempts at repicating Luxo Jr. mentioned throughout the literature review.*

D. Design Criteria

The robot should look like Luxo Jr. There are designs of the lamp on the web that may be downloaded and 3D printed. The robot should move forward by jumping/hopping. The base of the robot must be completely off the ground with zero contact between the base of the lamp and the ground after jumping. The robot should be in a different position from its starting point after each jumping/hopping motion. The robot should not topple/fall when jumping. This can be achieved by having a wide base and low center of mass. There is no constraint on type of actuation (e.g., electric motors, pneumatics, spring, clutches, or others are allowed). However, if using a passive actuation like a spring, it would need to have a motor to compress the spring. The robot can be pre-programmed to move; no need for sophisticated control using sensors. Joystick control is optional. The robot may have all or some parts tethered or untethered. A tethered system has its batteries and/or motors off-board which makes the design light weight.

E. Codes and Standards (Not required)

II. Technical Content

F. Assumptions

Gravity will be taken into account. Friction between the base of the lamp and the ground will be taken into consideration. The lamp will be considered as a rigid body. The lamp will consist of a linear spring system.

G. Metrics

The Luxo Jr. lamp should hop forward as seen in animation. The forward displacement of the lamp will be measured in millimeters. The hop of the lamp should be a minimum distance of 5 millimeters; however, the stretch goal is for the lamp to hop twice its base length, roughly 36 centimeters. The lamp should also jump into the air, displacing the model over the ground as it is hopping forward from its point of origin. The height of the lamp jumping off the ground will be measured in millimeters. The base of the lamp should achieve a minimum height of 5 millimeters off the ground when jumping. The weight of the lamp will also be taken into account which will be measured in grams. The weight of the lamp is important because if the lamp is lightweight, it is more likely for the lamp to jump higher in the air. Most of the weight of the lamp should be towards the bottom of the lamp to give the lamp a low center of mass, which increases the chance of the lamp not toppling/falling over after jumping. The force of the actuators that will launch the lamp into the air will be taken into consideration and will be measured in Newtons. The force of actuation is important because it is the mechanism that will allow the lamp to jump and hop forward and the higher the force is of the actuator, the higher the lamp will jump.

H. Proposed Solutions (Not required)

I. Selected Design

Design 1

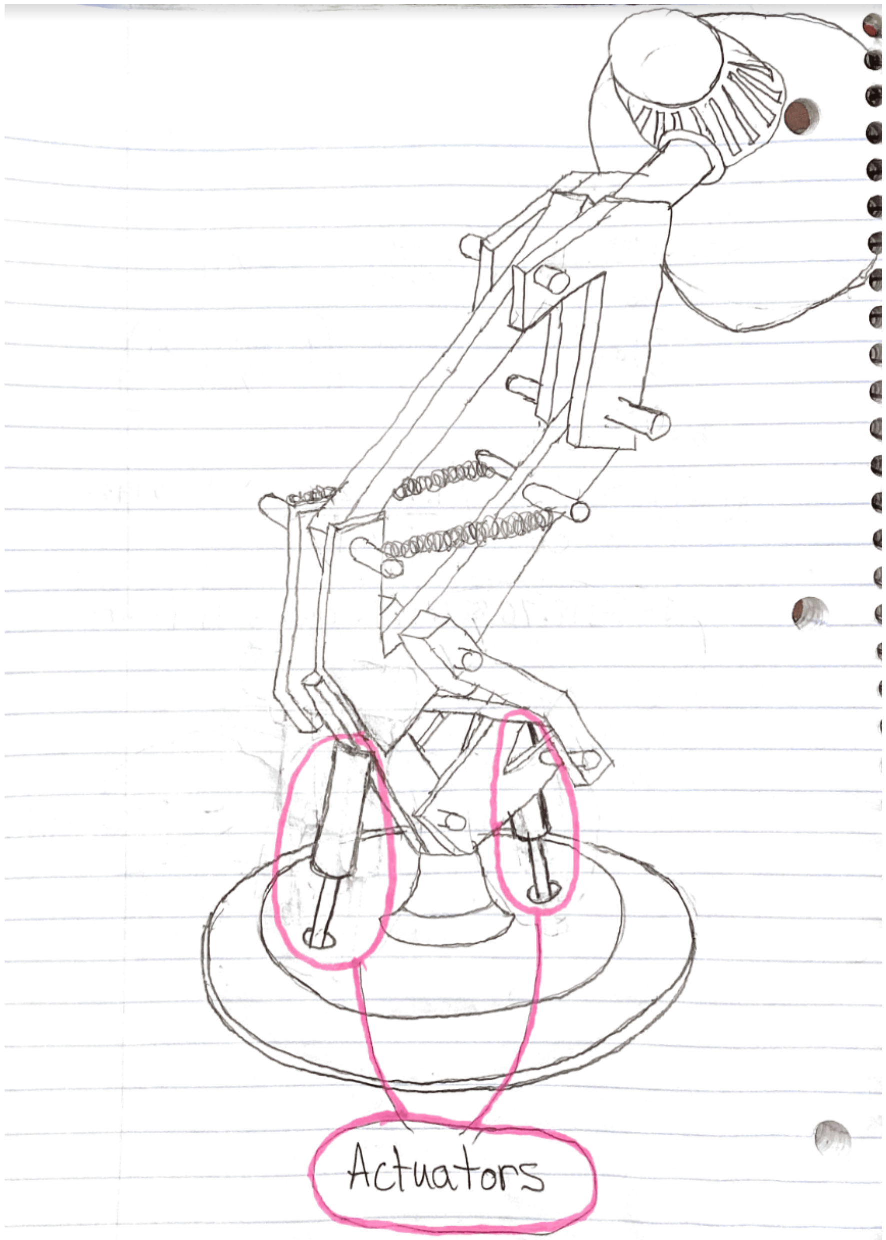

Figure 8. Luxo Jr. lamp design 1. *This figure shows the first design option for the Luxo Jr. Lamp.*

Design 1 of the Luxo Jr. lamp consists of two pneumatic actuators. The first actuator is attached on the back, bottom half of the lamp going through the back of the lamp's base. The second actuator is attached on the front, bottom half of the lamp, which goes through the front of the lamp's base. To get the lamp to launch into the air, the actuator on the back of the lamp would first launch into the ground, creating the force needed to launch the back end of the lamp. Then as soon as the back end of the lamp's base starts lifting off the ground, the actuator in the front of the lamp would launch into the ground, forcing the front end of the lamp's base into the air. This action of the back actuator activating first and then shortly after the front actuator activating would also cause the lamp to gain some forward displacement. That is because when the back of the lamp lifts off the ground first, the lamp will be at an angle tilting forward because the front end of the base of the lamp is still touching the ground. As soon as the front actuator is activated, the front end of the lamp's base will lift off the ground at an angle, since the lamp will already be tilting forward due to the back actuator, which will cause forward displacement. A possible issue that could arise from this design is getting the timing right between the two actuators activating because the timing in between the two actuators activating has to be perfect for each jump the lamp makes in order to gain a forward displacement and for the lamp to be stable when landing. Another problem with this design that could arise is the actuators not delivering a force strong enough to get the base of the lamp off the ground and airborne.

Design 2

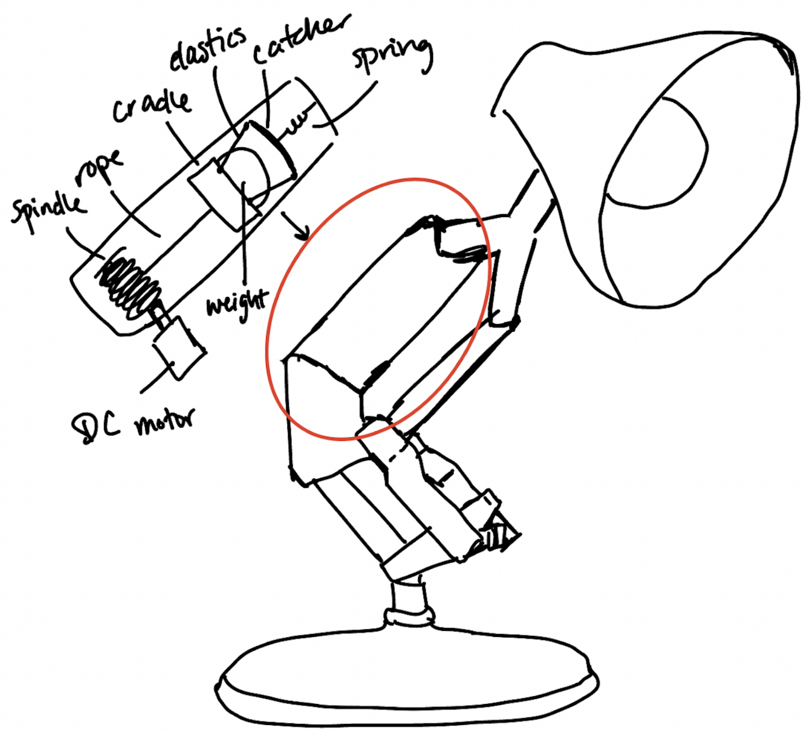

Figure 9. Luxo Jr. lamp design 2. *This figure shows the second design option for the Luxo Jr. Lamp.*

This second design moves by launching a weight within the frame of the Luxo Jr. Lamp. As seen in the above figure, the "backbone" of Luxo Jr. widened to fit the following equipment: spindle, rope, cradle, weight, elastics, catcher, and spring. The goal is to launch the weight towards the head of the lamp, so that the collision of the ball and the catcher causes the lamp to move both upward and forward. The ball would sit in the cradle that is being held up by elastics. The DC motor would rotate the spindle tightening the rope and pulling the cradle and ball down. As the cradle is pulled down, it pulls on the elastics, creating tension. When the rope is released, the elastics will pull the cradle and ball up towards the head of the lamp. The ball, being a free moving object not connected to anything, will come in contact with a catcher. The catcher is a barrier to stop the ball and push on the spring behind it. Once the ball hits the catcher, the ball will fall back down into the cradle. The cycle would then repeat for the next jump.

The preliminary math calculations were completed using kinematics. Since the lamp does not begin moving until the ball collides with the barrier, the initial velocity only accounts for the movement of the ball as the lamp stays stationary.

$KE\ (initial)\ =\ \frac{1}{2}m_{ball}v^{2}_{o\ ball}$

$KE\ (final)\ =\frac{1}{2}(m_{ball}+m_{lamp})v^{2}$

If velocity is 0.5m/s and the angle of the arm is +45 degrees, find v_x and v_y:

$v_x = 0.5\ cos(45)$ and $v_y = 0.5\ sin(45)$

Knowing v_x and v_y gives insight as to how far the lamp would theoretically move per second.

To determine how fast the ball would need to move for the lamp to reach the aforementioned velocity, the velocity of the ball would have to be:

$$v_{o\ ball} = v\sqrt{\frac{m_{ball}+m_{lamp}}{m_{ball}}}$$

While this design would cause the jumping of Luxo Jr. to look realistic as the head of the lamp would lead the jump, this design raises several concerns. First is the use of rope within the Luxo Jr frame, if the rope were to tangle or snap, then it would be increasingly difficult to fix. A second problem could arise with the motor that would wind the rope around the spindle. When it stops winding and releases the tension on the rope, it would not be able to fully release the rope/give the rope enough slag, which would interfere with the speed in which the ball would hit the barrier. Lastly, to house the mechanism, Luxo Jr.'s frame would be modified and the "backbone" of Luxo Jr. would be larger than that depicted by Pixar, which would begin to stray away from the replica appearance of Luxo Jr.

Design 3

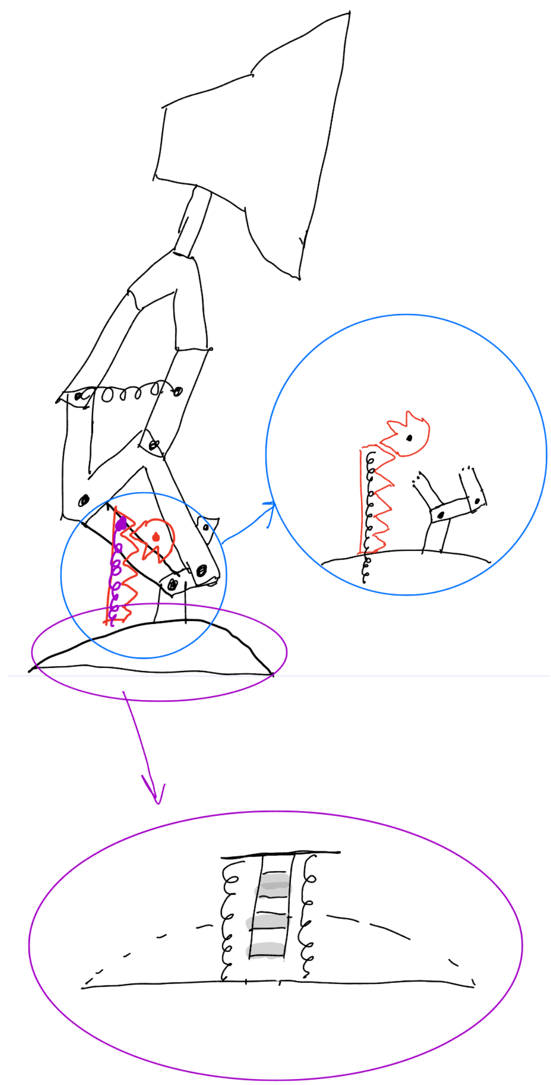

Figure 10. Luxo Jr. lamp design 3. *This figure shows the third design option for the Luxo Jr. Lamp.*

A rack and pinion system will be used to compress springs to store kinetic energy as seen in figure 12. The rack will have gear teeth and will be driven by a gear on a motor. The gear will have teeth and a blank section without teeth. The gear part with teeth will compress the springs that will be storing the kinetic force from a pair of springs as given by the equation of force equal to the k constant times delta x of how much compression. The rack assembly will press down on the springs for around 0.0254 meters. That kinetic energy will then be released when the gear runs out of teeth and the rack will direct the force into an impact force consequently resulting in an upwards and forward direction. This will be accomplished by setting the mechanism at an up and forward angle. The design will use an angle of 80 degrees to the ground. This will displace Luxo Jr. in the desired direction. There will be 2 methods of this design. One design possibility would be to anchor the rack and pinion to the framing of Luxo Jr. The other option would be to solely anchor the rack and pinion to the base of the replica model. It will compress the spring and when the energy is released, it will displace the whole base of Luxo. Both designs will have the mechanism be mounted to the base, so this will be the base in the calculations. The equations will assume that the body is rigid, accounting for only one mass. The velocity variable will be adjusted as prototypes are done on the project to see how much the model should displace. First the group will look at the force needed to displace Luxo Jr. A minimum of 45 Newton is needed to displace the model using equation (a). This is defeating gravity and accounting for the 3 kilogram mass. It is necessary for the spring to compress about an inch. Therefore, a k constant of 1771 is needed using equation (b). With an arbitrary velocity of 5 meters per second and height of 0.005 millimeters Luxo Jr will have a potential energy of 0.147 using equation (c). The Kinetic energy is then 0.375 using equation (d). The equations used for these calculations are as follows. Remember that the mass variable is 3 kilograms. Gravity is 9.8 meters per second squared.

(a) F=ma
(b) F=k*(deltax)
(c) PE=m*g*h
(d) KE=0.5*m*v^2

The main concerns with design 3 in figure 12 is that by anchoring the rack and pinion to the framing of Luxo Jr. it may cause a cartwheel effect. This is due to transferring the force through the base and toward the head. This angle relationship may push up and backwards. Another concern is the amount of space to mount the mechanism but that can be solved in the prototype sessions by allowing the mechanism to be adjustable in placement. This is accomplished by allowing the jumping mechanism to be bolted onto the base of the lamp rather than 3D print on the base to allow for adjustability. The team will also use angled shims on the bottom of the mechanism between it and the base to adjust for a forward displacement.

Design 4

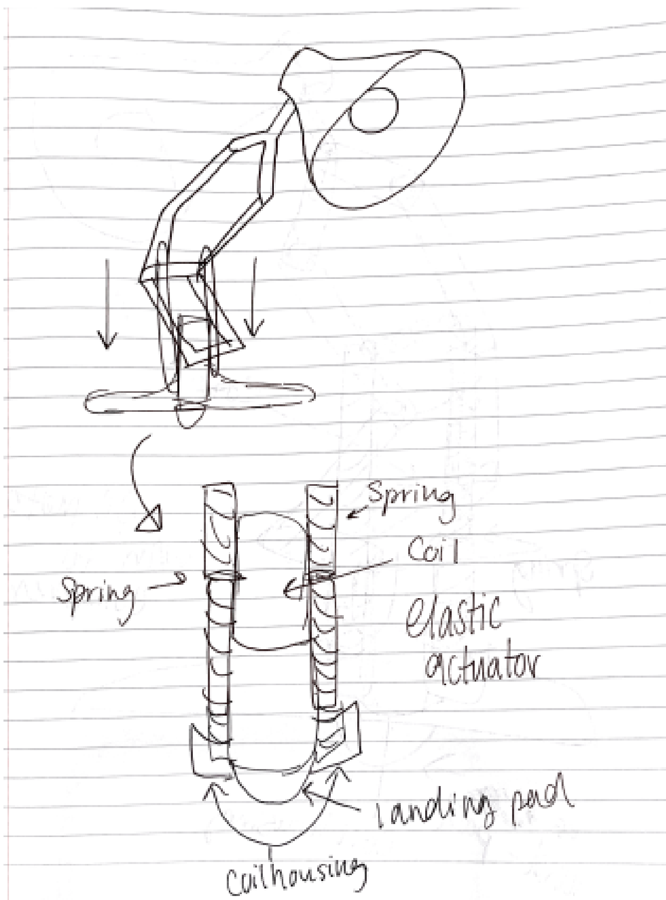

Figure 11. Luxo Jr. lamp design 4. *This figure shows the fourth design option for the Luxo Jr. Lamp.*

Design 4 includes an elastic actuator positioned within the base of Luxo Jr. This actuator would have two springs connected in parallel that attach to the Luxo Jr. model on either side at its middle joints. Within the actuator would most likely be a DC motor that would compress the springs. These springs would compress and subsequently release the body of Luxo Jr. Also included within the actuator would be a voice coil that would compress with the springs. The DC motor would run and compress the springs and coil, and then release, causing the Luxo Jr. to jump. The base also would have a landing pad on the bottom which would push out when the springs and coil are released, pushing Luxo Jr. off of the ground and also helping to stabilize the lamp during landing. The actuator and landing pad would be at a slight angle to allow for forward displacement. A possible issue that could arise with this design is the possibility of the 3D printed Luxo Jr. not being strong enough or moveable enough to withstand the compression and bending of its joints. This could cause Luxo Jr. to break while jumping. This problem could potentially be fixed by reinforcing the joints in a way that will allow them to properly and freely move.

III. Methodology

J. Fish Bone Diagram

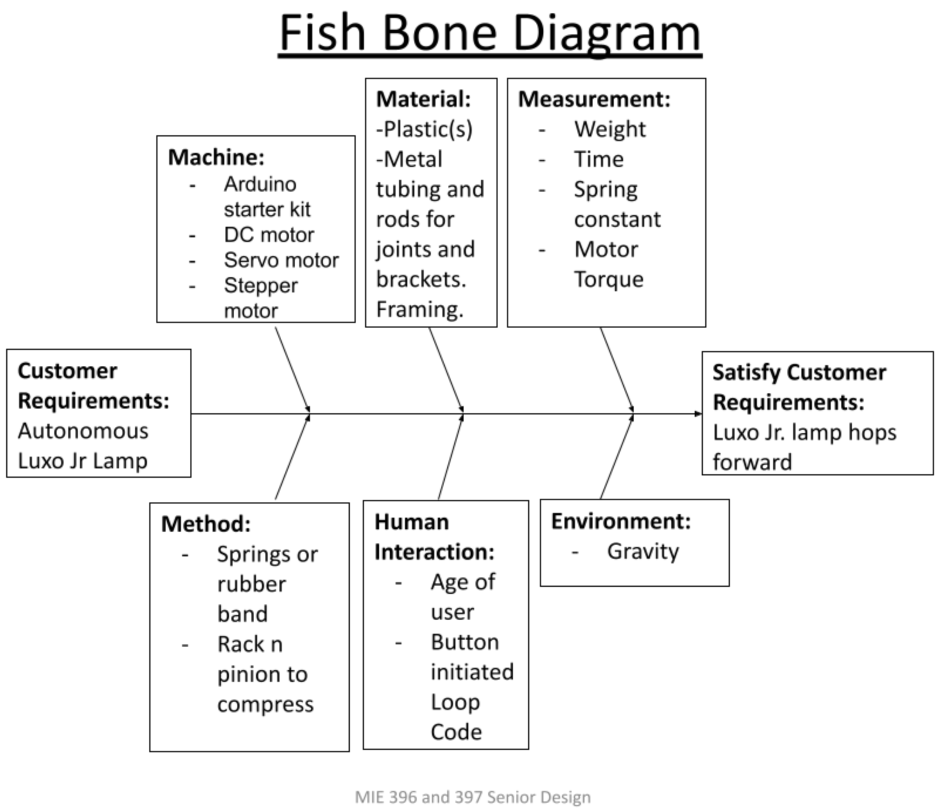

Figure 12. Fish Bone diagram. *This figure shows the fishbone diagram which provides a graphical representation of causes and effects.*

K. Preliminary Calculations

This paper has discussed that the lamp has a human-like jump. A jump starts with coiling down and then extending itself to accelerate the body up in the air and forward. This requires the evaluation of the physics of the model, researching materials to use to withstand this demand, and the model achieving air with forward progression.

One of the preliminary calculations which the group has found to determine what methods apply is that once the team defines the kinematic structure of the lamp and approximates the dynamics of the lamp movement, then the group will have to calculate the required motor torque [$T_{min}(Nm)$] which will be used as well as the required angular velocity [$\omega_{min}(rad/s)$].

The equation to determine the motor torque is shown as:

$$T = F * r \quad (1)$$

where 'T' represents the armature or gross motor torque, 'F' represents the force, and 'r' represents the radius of the armature.

The equation to determine the angular velocity is shown as:

$$\omega = \Delta\theta/\Delta t \quad (2)$$

where 'ω' represents the angular velocity, '$\Delta\theta$' represents the change in angular rotation, and 'Δt' represents the change in time.

The third preliminary calculation which the group has found to determine what methods apply is that if the total energy of the entire jumping device stays constant both before as well as after take-off, the spring coefficient can be obtained from equation:

$$m_1gh_1 + 1/2k\omega\Delta x^2\eta = m_1g(H + h_2) + m_2gH \qquad (3)$$

where 'm_1' represents the mass of the lamp head, 'm_2' represents the mass of the base, 'h_1' represents the height of the upper dual struts, 'h_2' represents the height of the lower dual struts, 'H' represents the jumping height of the device, 'k' represents the spring coefficient, 'Δx' represents the spring elongation, 'η' represents the spring efficiency, and 'g' represents gravity.

Another preliminary calculation which was used is an equation to calculate the required torque for the motor in order to compress the springs. That was done by using the following formula:

$$T = k * F * d \qquad (4)$$

where 'T' represents the torque required, 'k' represents the spring constant, 'F' represents the force required to compress the springs, and 'd' represents the distance of when the spring is compressed.

Sample Calculation (For Motor Torque)

Given: Spring constant, k = 0.47lb/in ; Force, F = 75N ; Distance of when the spring is compressed, d = 4cm

By converting the units and plugging in into equation (4): $T = k * F * d$ = (0.21+0.21)(75)(0.04) = <u>1.26 N</u>

L. Numerical Method

For the Luxo Jr. jumping mechanism, ANSYS was used to simulate how the materials would respond with the application of force. The goal for the simulation was for the gears to move along the rack when there was applied force that would pull down the top plate and compress the springs. To achieve the desired results, the first task was to assign materials to the part of the mechanism. The springs, bolts, and nuts are assigned 316 stainless steel, while the rest of the mechanism is assigned to be PLA plastic. Boundary conditions applied to ANSYS included both frictionless and fixed supports. The frictionless supports allow connecting bodies to move freely in axial directions, while remaining fixed in normal directions. The fixed supports set all degrees of freedom to zero ensuring zero displacement. For the Luxo Jr. jumping mechanism, the bolts and the backside of the rack were identified as frictionless supports. Meanwhile, the underside of the bottom plate was set to be a fixed support.

After testing the whole mechanism, the rack and gear assembly was tested by itself to see if it was capable of delivering the force in the rack. That was done by applying the desired force in the rack and extracting the moment reaction (the reaction force inside of the gear to rack) at the gear. Then, remote displacement was used to constrain the gear (instead of a fixed support) because this type of constraint provides rotational, as well as translational constraints. By doing so, the team ended up with a minimum safety factor of 2.3, meaning that this rack and gear assembly will not fail under the desired load and therefore it is valid (it can handle the force).

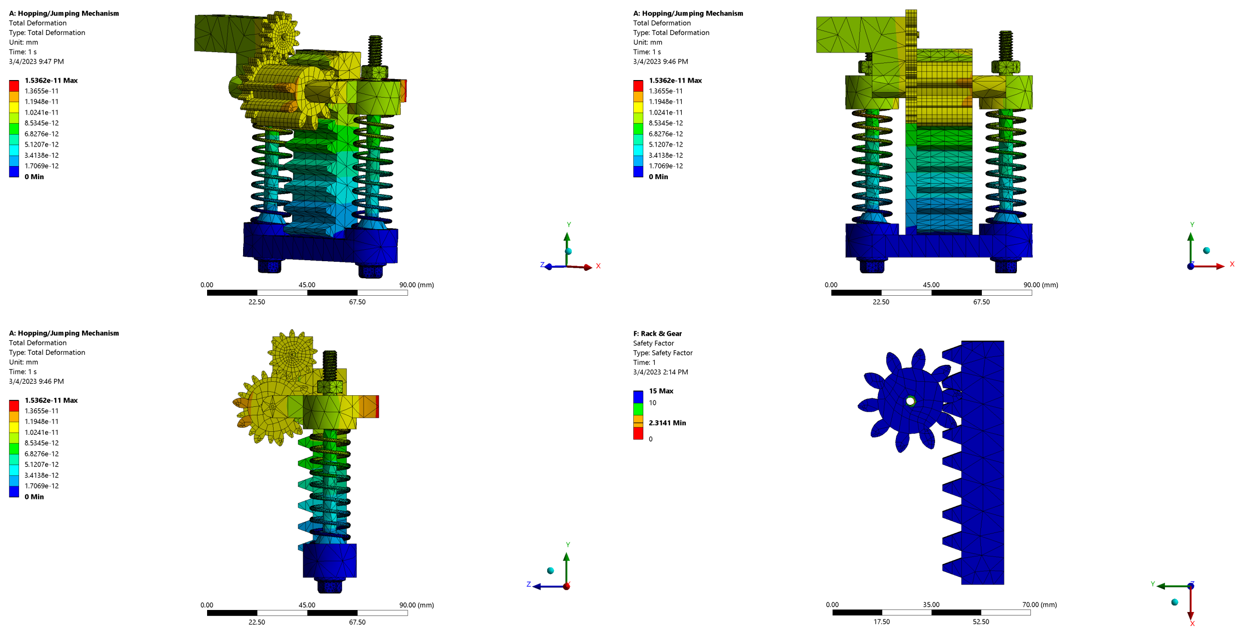

Figure 13. Ansys Simulations. *This figure shows the results from the Ansys simulations which is to predict how the hopping/jumping mechanism will work in the real world.*

M. Technical Drawings

The first technical drawing, seen in figure 14, envisioned the jumping mechanism and Luxo Jr. The task was to scale and find fitment of all our components. The team then further conceptualized the gears they'd use along with the jumping mechanism's mounting plate to attach the base of the Luxo Jr. model. This whole process allowed for the visualization of the full assembly and its scale. All the measurements were done in metric measurements.

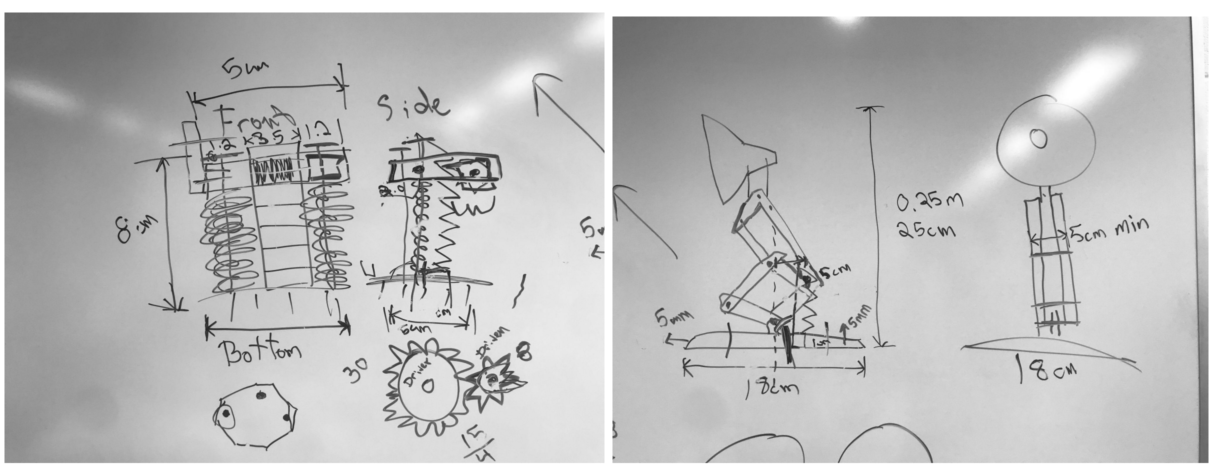

Figure 14. Technical Drawings. *This figure shows the overall scaling process to check for clearance and design parameters.*

The following figure is the wiring diagram done on Tinkercad. Tinkercad is useful because it is the theoretical solution. This allowed for less time of diagnostics using a breadboard and gave us proof faster than using a breadboard. The diagram is simple. The diagram contains a 9 volt battery, ON/OFF switch, motor, LED light, and a multimeter to measure voltage going to the motor. The motor and LED have resistors to control the voltage going to them. The motor is currently designed with 50 ohm resistors and the LED light has a 500 ohm resistor. The ON/OFF switch is used as a common ground. When the switch is in the ON position, the LED and motor is powered on. The OFF position stops the complete circuit causing no power.

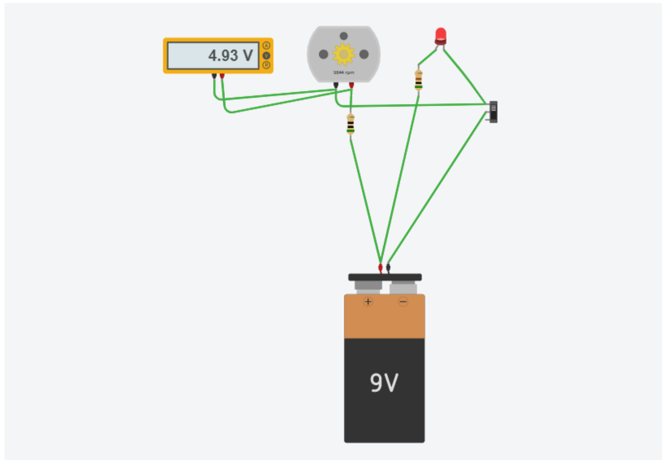

Figure 15. Electrical Diagram. *The figure is a tinkerCAD model of the electrical diagram for Luxo Jr.'s jumping mechanism.*

The following figure is a Luxo Jr. model the team found online. The project advisor said to not waste time designing this as there already were models available. The team then scaled it down to reduce weight using Solidworks scale function. Full CAD designs of Luxo Jr. model and jumping mechanism components are in the appendix.

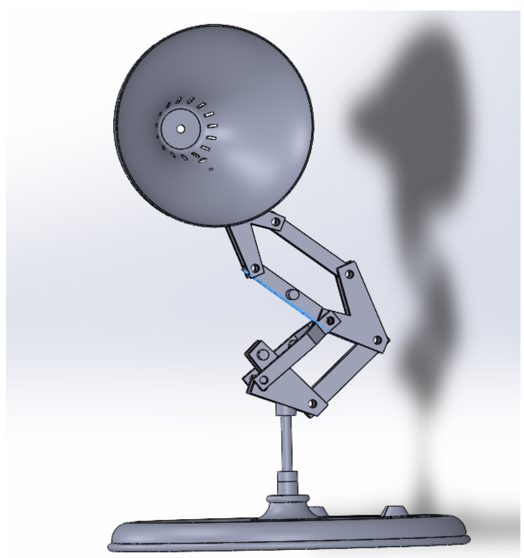

Figure 16. Luxo Jr Model. *This figure shows the Luxo Jr model in SolidWorks.*

N. House of Quality

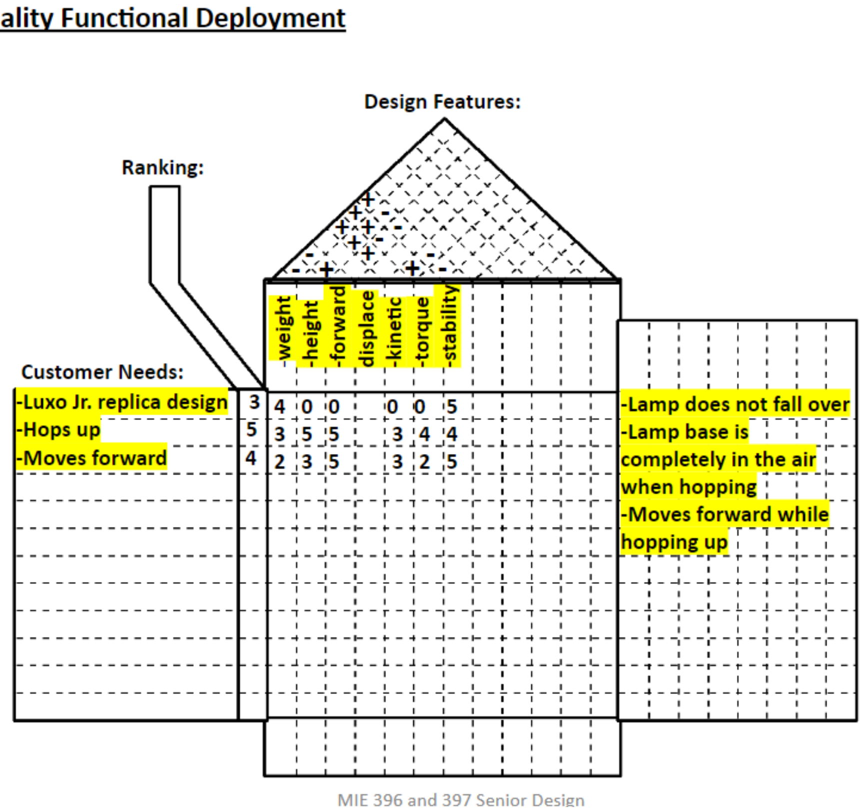

Figure 17. House of Quality diagram. *This figure shows the house of quality diagram which is a visual way to look at the deployment of high-quality functions to aid in collective decision-making.*

IV17. Preliminary Results.

O. Decision Matrix

	Ability to Hop	Ability to move forward	Stability	Ability to fabricate	Rank
Weighting Factor	0.35	0.30	0.25	0.10	1.0
Design 1	6 / 2.1	3 / 0.9	3 / 0.75	9 / 0.9	4.65
Design 2	4 / 1.4	6 / 1.8	3 / 0.75	3 / 0.3	4.25
Design 3	9 / 3.15	5 / 1.5	6 / 1.5	7 / 0.7	6.85
Design 4	8 / 2.8	2 / 0.6	8 / 2	8 / 0.8	6.2

Table 2. Decision matrix. *This figure shows the scores received by each design in order to make a decision on the best design.*

The final decision on the four designs was determined using the decision matrix. The decision matrix was used to evaluate the main objectives of a successful project. The Luxo Jr. model needs to hop, move forward, be stable and be fabricated by the team. The sponsor's main concern was to get Luxo Jr. in the air. There have been past attempts at this but they did not achieve enough displacement off the ground. This made it the highest weighted factor. Moving forward can be achieved while in motion, making it the second highest weighted factor. Stability is important as it is not desirable for Luxo Jr. to fall over. Finally, fabrication was the lowest weighted factor as the team aimed to design something that is producible, but it is not the most important aspect of the project. The decision matrix determined that design 3 was the best scoring design.

P. Preliminary Design

After considering all of the designs and objectives, it was determined that Design 3 would be created. Design 3 was designed to accomplish a hop. Displacement forward is achieved by mounting the rack and pinion mechanism at an angle of 80 degrees to the ground and behind the Luxo Jr. model in hopes that the forward weight will even out the base in the air. Both hop and move forward will be accomplished in one action. Stability is at a 6 as the team can create a larger base diameter to even out the weight distribution. Fabrication of design 3 will prove a challenge if the motor cannot compress the spring but can be solved with either a bigger motor or using gear reduction to provide more torque. In the end, the decision matrix decided that design 3 is the best option.

Q. FMEA

Though the design has not been tested in real life, there are still important possible failures to consider. It is possible that the hopping mechanisms will not be strong enough to achieve the sponsor's required displacement. It is also possible that the Luxo Jr model will struggle to remain standing after hopping. It is also important to pay attention to model joints that will have to withstand the force going through them to accelerate the model to the desired displacement.

System	Function	Potential Failure Mode	Potential Effect of Failure	Potential Cause of Failure	Current Mode of Control	Risk Assessment			
						S	P	D	RPN
Autonomous Luxo Jr. Lamp	Moves forward by jumping/hopping	Base does not completely lift off the ground	Will not achieve required displacement	-Not enough momentum -Potentially too heavy	Method selection	5	7	1	35
		Falls over	-Bending/breaking of robot frame -Electric motor failure	- Lands on base at an angle - Not enough weight at center mass	Measurement selection	5	5	1	25
		Will not achieve the required displacement	Dissatisfied sponsor/advisor	Robot is too heavy; -Not enough momentum -Not enough force -Not enough velocity	Machine selection	2	8	1	16
	Replica Model	Design	Will not look like Luxo Jr. replica design	Dimensions/ratios are not similar to the Pixar design	Measurement selection	1	2	2	4
	Controller	Starter button not powering up	-Fail to activate device -Fail to initiate jump	-Not enough power -Wiring issue -Motor/actuator failure	Machine selection	4	2	1	8

Table 3. Failure Mode and Effects Analysis (FMEA). *This table is a methodical approach to identifying potential issues, failures, and the effects these have on the system.*

R. Test Results

One of the first issues that the team ran into was having correct clearances between different parts. Collaborative brainstorming helped resolve all of the clearance issues by making decisions as a team. The first prototype's dimensions were very exact. This caused parts to not be able to slide when in contact. In order to solve the clearance issues, the team decided to make loose or very loose fits between items that slide and move. This included the rack and the gears. Once the components were able to interact with each other properly, the team found that were issues with the motor. The motor's main issue was that it was unable to push down the top plate level with the gear rack and instead pushed it at an angle causing the top plate to catch and be unable to compress. The team sought guidance from the sponsor on whether to solve this, to which the sponsor suggested trying a workaround to accomplish the objective rather than sitting on a power issue. The team followed their sponsor's advice to manually compress the springs. This process was performed by manually compressing the springs and using the motor power to hold the compressed kinetic energy, followed by removing the power from the motor which in turn caused the kinetic energy from the springs to be released and impact the top plate via the mounting bolts. The mounting bolt impact caused damage to the first top plate. This was solved by 3D printing a new top plate and using washers to distribute the surface area of the impact rather than the small surface the bolts were previously impacting. The original placement of the jumping mechanism was behind Luxo Jr. with the assumption that the impact would lift the base and tilt forward to cause the model to even out and clear the ground. During the tests, this caused just a forward tilt and the base would skid forward on the ground rather than lift. By designing a serviceable design for prototyping, we were able to easily move the jumping mechanism in front of the model. The mounting space on the base also allowed for angled shims. The team angled the jumping mechanism forward as well. This allowed the front of the Luxo Jr. model to lift up with the forward weight and impact distribution with the back of the assembly following the projectile allowing the whole base to lift off the ground and stably come back down. In the end, the team was able to accomplish a displacement of two inches forwardl and hopped, at minimum height of base, is an inch verticle as seen in figure 18.

S. Final Design

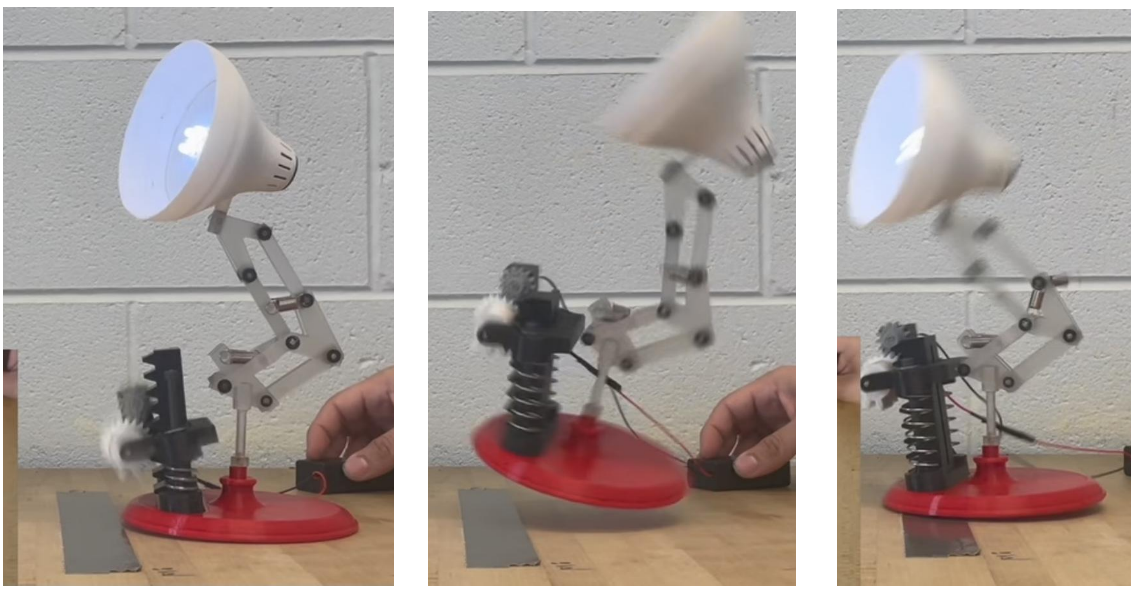

Figure 18. Luxo Jr. Final Design Test *These figures show the final design of Luxo Jr. being tested. This image also documents a successful hopping forward displacement by referencing the duct tape.*

The final design closely resembled the aforementioned design 3. However, in design 3 the hopping mechanism is located behind the body of Luxo Jr. After testing, the team found that having the hopping mechanism in the back created negative displacement. To offset the negative displacement, in the final design the hopping mechanism was placed in front of the body of Luxo Jr. and was angled in the forward direction. These adjustments improved the forward displacement of the hop. The new placement also allowed the weight distribution to tilt the robot forward and then back to allow the base to completely displace off the ground. The springs used in the hopping mechanism have a spring constant of 0.47 lbs/in. The top plate of the hopping mechanism holds the 6V motor that is attached to the 9V battery. The hopping mechanism is angled via an angle insert that is placed inside the slot on the base under the hopping mechanism. The final design is primarily 3D-printed. The gear attached to the motor shaft and the body of Luxo Jr. were printed out of resin, while the rest of the lamp was printed out of PLA plastic, not including fasteners and electrical components. To prevent the gear attached to the shaft from slipping, the hole in the center of the gear had to be printed slightly smaller than the diameter of the shaft and then melted onto the shaft. If the hole was the same size as the shaft, the shaft would spin without spinning the gear because the shaft of the motor is a D-shaft. There needs to be resistance along the flat profile of the shaft, so melting the gear allows for a near-perfect fit. Since the 3D-printed parts are easily modifiable, the back panel of the lampshade was removed to fit a switch that would turn the lamp on and off. The lampshade had a circular disk that held in place 4 white LED lights. Behind the circular disk in the lampshade houses are the electrical components for the lights, which include two 3V lithium CR2032 cell batteries and the wiring. This allowed the lamp to become a lamp with lighting and also contributed to a weight distribution that contributed to the base clearing the ground.

T. Cost Analysis

The most time spent in the project was the constant conceptualization of the jumping Luxo Jr. via research, running the Ansys simulations to check for failure in the jumping mechanism, and physically fabricating our 3D printed conception. Although, the team never went over time, just about 30 hours a week was spent collectively. Therefore, the team used the work time provided therefore being under budget. In the bill of materials, which is shown in Table 4 below, the team only spent 70.77 dollars on complete assembly materials. Therefore, the jumping Luxo Jr. prototype can be inexpensively printed and modified to achieve better results. This also gives a basis to think about the cost of manufacturability. Once a market-ready Luxo Jr. model is available, expenses can be minimized by accurately determining 3D ink expenses and exploring less expensive alternatives to hardware and components.

Tasks	Materials	
Phases or Category Title	Units	$/Unit
3D Printed Parts	20	0.375
Small Springs	4	0.2
Small Washers	20	0.08
Small Dowel pins	8	0.18
Threaded Insert	2	0.04
Mini Switch	1	1.1
CR2032 Batteries	2	0.8
Led Diode Lights	4	0.03
Motor	1	11.99
100 Ohm Resistor	1	0.1
9V Alkaline Battery	1	6.22
Battery Holder, I-Shape	1	1.21
Straight Ejector Pin	2	11.22
Steel Dowel Pin	1	4.43
Springs	2	5.07
Total	70	70.77

Table 4. Cost Analysis. *This table shows the cost to produce the final model of Luxo Jr. and its hopping mechanism.*

U. Lessons Learned

(S.K) During the design process of the Luxo Jr lamp and the hopping mechanism, something Sebastian Kowal learned was when 3D printing parts from an assembly, the holes in any part must have a larger dimension than actually desired. This is because when 3D printing a part, the holes in a part come out to be smaller than anticipated. The team used a tolerance of +0.20 mm for all the holes in the parts for the hopping mechanism. However, once the parts of the mechanism were 3D printed, the team realized that a tolerance of +0.20 mm for the holes in each part was too small. The team learned that higher tolerances for the holes in some of the parts of the hopping mechanism must be used, depending on how tight of a fitment between each part is desired. For example, the top plate holes that will be used to insert the dowel pins of the hopping mechanism will need a tolerance of at least +0.50 mm because a loose fit between the holes and the dowel pins is required so there is no friction when the top plate holes slide down the dowel pins. Also, the top plate hole that attaches to the rack of the hopping mechanism will need a tolerance of at least +0.50 mm because a loose fit between the hole of the top plate and the rack is required so there is no friction when the top plate slides down the rack. After learning this lesson, the top plate of the hopping mechanism will have to be reprinted with the proper tolerances.

(A.A) In terms of lessons learned, there are a lot of things which were gained from the Senior Design process and from Ahmed's work on this project. One of the things which Ahmed has learned is that in order to start tests in Ansys, he has to make sure that everything is functioning properly in SolidWorks first. For instance, when he had some issues in Ansys regarding compressing the springs, and that was because the springs were not compressing in SolidWorks since they were treated as rigid bodies and not flexible. Therefore, once the springs were successfully compressing in SolidWorks, then the Ansys results made sense given that every part of the assembly was treated as it is whether it was rigid or flexible.

(K.G.) By taking the Senior Design courses, Kali has learned a lot about the design processes and analysis in SolidWorks and Ansys, especially in the first semester of the course. Through the class and working on the project, Kali learned about coming up with designs and making decisions on ideas with different methods such as houses of quality, fish-bone diagrams, and decision matrices. Through creating pieces of the Luxo Jr model, Kali learned many SolidWorks skills, such as how to scale parts to different sizes, and generally improved her ability to use the software. Kali also learned that it is necessary to add certain tolerances when 3D printing in order for the pieces to actually be able to fit together after printing, as measurements are not typically exact when printed. Kali also learned through research about the different types of actuators and other mechanisms and how they can work to create a jumping robot. By taking this course, Kali also learned and improved her technical writing skills and learned what is expected in a technical report. Through the manufacturing and test process, Kali improved her skills with certain tools such as drills and soldering irons.

(D.L) Throughout the course of this Senior Design project, Danielle has identified how bottlenecks can add constraints to a project. There is a long list of tasks that need to be completed and each one builds off the task before it. The team had to think critically to come up with designs before moving forward with CAD. However, the CAD model needed to be completed before ANSYS could be run. A hiccup in any aspect of the project can stall forward progression in other avenues. For example, ANSYS has taken longer than the team expected it to, so the ANSYS is behind the projected schedule. This experience has highlighted the importance of getting ahead of issues and reaching out. While critical thinking is required, reaching out to new people and new resources are sometimes better soon than later. Exhausting time in the beginning stages of the project, leaves less time for the later tasks because the deadline remains the same. This project demonstrated the benefits to working with 3D printed prototypes. Everything that was 3D printed was easily modifiable, low in cost, and easy to assemble. This project also reinforced my knowledge of circuits and soldering.

(G.B) Senior Design has really shown Gabriel how to work in a team. Things learned were to hold accountability for tasks to be done. Life could get in the way of a project and cause setbacks. Gabriel learned to continuously work and put in more effort to keep the project moving forward. Every individual's contribution in the team is what makes the project move forward. By holding ourselves accountable, this endured the tasks were completed on time. In the design process, Gabriel was reminded of tolerances from his past internship. This was ignored in the prototype but in the assembly process it was learned to always take tolerances into account. This is also due to the type of design. This is a sliding and gear driven design. Since there is sliding, whereever the slide is occurring, the parts that interact in the sliding movement should have a loose fit. This is achieved by removing material where the sliding parts mate to one another. Another recent discovery was that of gear backlash. The prototype did not account for backlash which is causing the gear on the rack and pinion design to bind. This is caused by having no backlash, or in other words, no play between the gear and the rack. This can be achieved by spacing the gear away from the rack and adjusting until there is enough play to where the gear does not bind. The final design also reminded Gabriel of importance of how Luxo Jr, was designed to be assembled. By making so many parts of our design as their own part to be bolted on rather than as a unit with another part, this allowed the design to be modifyable and serviceable. By taking the service angle in the design process, it allowed the whole design to be fixable by allowing assembly to be easily assembled and disassembled in under 10 minutes.

V. Statement of Individual Contributions

(S.K) Last semester, Sebastian designed Design 1 as a concept design for the Luxo Jr. lamp, but Design 4 was the winning concept design. During the design process of the Luxo Jr. lamp and the hopping mechanism, Sebastian Kowal was tasked with designing the hopping mechanism of the Luxo Jr. lamp. Sebastian contributed by designing the top plate part and the bottom plate part of the hopping mechanism for Luxo Jr. on SolidWorks. Sebastian also built the main gear part and the rack part of the hopping mechanism for Luxo Jr. on SolidWorks. Sebastian constructed the hopping mechanism assembly for Luxo Jr. on SolidWorks. Finally, Sebastian found a few of the parts (compression springs, dowel pins and screw inserts), from McMaster, that needed to be ordered for hopping mechanism assembly.

(A.A) In terms of individual contributions, so far Ahmed's main focus for the project is Ansys. Ahmed has been doing simulations on the base of Luxo Jr. Lamp as well as the hopping/jumping mechanism. On one hand, in terms of Luxo Jr. Lamp base, the results which Ahmed got verify that the base which will be used will function in its intended environment from the material that it would be made out of and the load that would be applied to it. On the other hand, in terms of the whole hopping/jumping mechanism, the simulations are still in process. Ahmed has also tested the rack and gear assembly by itself under the desired load to see if it would be capable of delivering the force in the rack. In addition, Ahmed has been filling out the meeting minutes and uploading them to Box as well as Blackboard.

(K.G) In the first semester, Kali researched and read through many scientific reports of previous attempts at creating a jumping Luxo Jr. lamp and other jumping robots. After this, Kali designed a possible mechanism for the team to move forward with, Design 4. In the design process Kali mainly worked on the Luxo Jr. model. Kali worked to scale all of the pieces for the model to be the desired size that the team decided on in SolidWorks. Kali also adjusted hole sizes to have tolerances in order to 3D print. Along with this, a new base was also designed in SolidWorks for the mechanism to be able to be attached to the model of the lamp. Kali sourced the materials necessary to assemble the model of Luxo Jr. Kali assembled and maintained the Luxo Jr. model throughout testing. Kali participated in the testing of the hopping mechanism and recorded most of the attempts and tests.

(D.L) Last semester, Danielle designed Design 2 as a concept design, but once we decided to move forward with Design 4 Danielle helped with the ideation process. The help included into the ideation process included finding a scale and size of Luxo Jr. that would appropriately fit the team's design. Danielle was able to find and recommend to the CAD team parts from McMaster. After the CAD was created, the majority of Danielle's contributions to the project has focused on simulating the jumping mechanism in ANSYS. While using ANSYS, Danielle had made several discoveries: how the different supports affect the simulation, how mating and gear ratios in the CAD can affect the simulation, and how pressure versus force act differently when applied to the mechanism. Boundary conditions have been tested and materials have been applied. However, ANSYS is still in progress for this project. Danielle has worked with her teammate, Ahmed, and TAs, and will continue to work with them until ANSYS is resolved. Outside of the technical work, Danielle has taken on responsibilities such as organizing meetings with advisors, emailing advisors and sponsors, creating the bi-weekly presentations, etc.

(G.B) In the beginning of the project, Gabriel led group meetings by addressing tasks and using meeting minutes to document the deliverables expected. After the house of quality, FMEA, and decision matrix was completed by the whole team, Gabriel moved on to conceptualize the jumping mechanism in the second semester by scaling the Luxo Jr. model and jumping mechanism for fitment. This led to scaling down the Luxo Jr. model from a pre-made CAD model. This then allowed us to visualize the placement of the jumping mechanism as seen in Figure 14. Once scaling was completed, Gabriel helped Sebastian with the CAD work by advising the design changes and improvements. Gabriel also used a service approach to the design. This means that the design would be easy to service for repairs and modification. This lead to the jumping mechanism to be bolted to the rest of our assembly that includes the base and the Luxo Jr. model. By making things bolt on, any failures were easy to replace single parts rather than having to print out whole units. Priority was taken to make sure the individual parts fit together properly in the assembly and accounting for the hardware we'd be using on the mechanism like the mounting bolts and thread inserts. Gabriel also designed the wiring diagram.

V. Conclusions / Future Work

The Luxo Jr. team had a difficult task, making a monopod model hop and move forward in the same motion. Something that the team saw frequently throughout the research portion of this project was that oftentimes jumping mechanisms included bending legs. Therefore, the team came up with many designs that would transfer a force in the direction we want the motion of our project. The team made CAD designs on Solidworks that would be put in Ansys to be proven to not fail and finished by 3D printing and assembling. This all provided valuable learning experiences to each team member, who were all relatively new to 3D printing, SolidWorks and Ansys software. The team also practiced technical writing, critical thinking, teamwork, and design considerations such as tolerances and gear backlash. The Luxo Jr. lamp being 3D printed allowed for easy modification for prototyping, low cost, and simple assembly. The current prototype does hop and move forward meeting the project's objectives. To further the lamp into a robot, the team should consider a higher power motor, better rack and top plate alignment, and a controller once previous issues are resolved. Overall, the Luxo Jr. project provided a great opportunity for the team members to gain hands-on experience in the design process and develop skills that will be valuable in their future careers.

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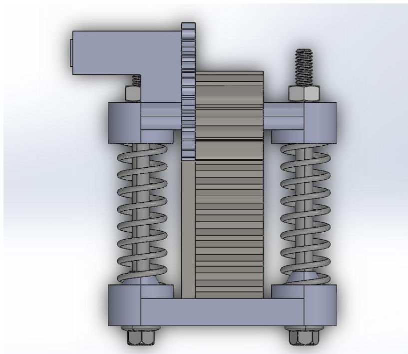
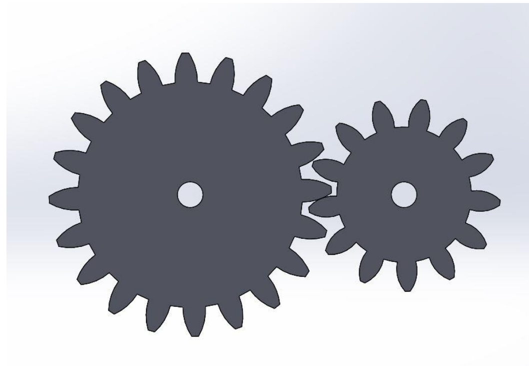
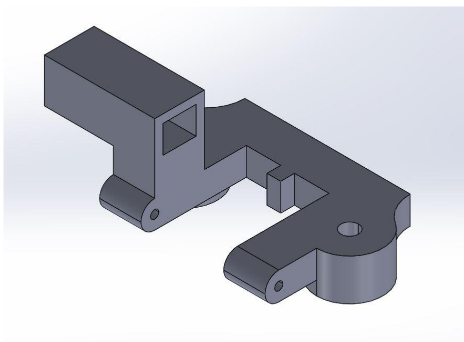
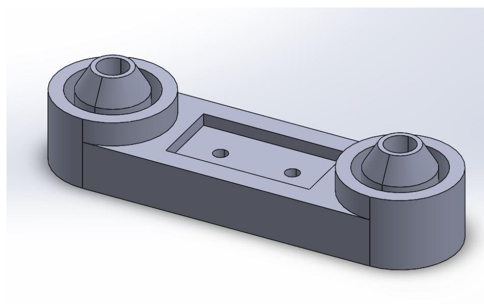
Appendix

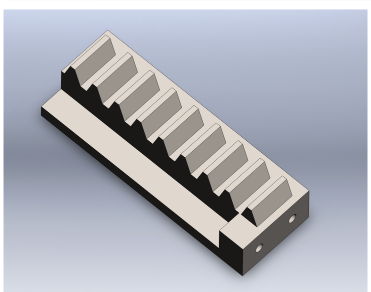
Jumping Mechanism CAD

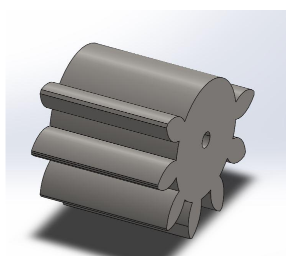




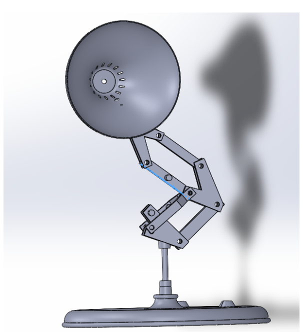


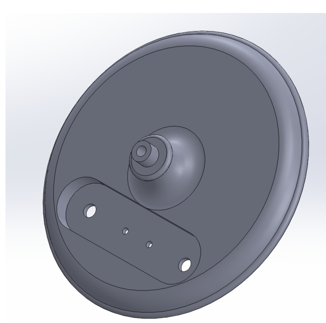






Luxo Jr. Model CAD





Gantt Chart

Project #	Main Assignment	Specific Task	Who Contributes?	Who Owns Task?	Planned Start Date	Internal Due Date	Note
Final Project Report Format	Title Page	Project Title	Everyone	Ahmed Al Khuridah	11/30/22	11/8/22	Done!
		Team Number	Everyone	Ahmed Al Khuridah	11/30/22	11/8/22	Done!
		Team Members	Everyone	Ahmed Al Khuridah	11/30/22	11/8/22	Done!
		Abstract	Everyone	Gabriel Barba	11/30/22	11/8/22	Done!
	Separated Sections	Table of Contents	Everyone	Danielle Lee	11/30/22	11/8/22	Done!
		List of Figures	Everyone	Everyone	11/30/22	11/8/22	Done!
		List of Tables	Everyone	Ahmed Al Khuridah	11/30/22	11/8/22	Done!
		Nomenclature	Everyone	Ahmed Al Khuridah	11/30/22	11/8/22	Done!
	Introduction	Introduction	Everyone	Sebastian Kowal	11/30/22	11/8/22	Done!
		Problem Statement	Everyone	Gabriel Barba	11/30/22	11/8/22	Done!
		Sponsor Background	Everyone	Danielle Lee	11/30/22	11/8/22	Done!
		Literature Survey	Everyone	Kali Giancana	11/30/22	11/8/22	Done!
		Design Criteria	Everyone	Sebastian Kowal	11/30/22	11/8/22	Done!
		Codes and Standards	Everyone				
	Technical Content	Assumptions	Everyone	Sebastian Kowal	11/30/22	11/8/22	Done!
		Metrics	Everyone	Gabriel Barba	11/30/22	11/8/22	Done!
		Proposed Solutions	Everyone				
	Methodology	Fish Bone Diagram	Everyone	Everyone	11/30/22	11/8/22	Done!
		Preliminary Calculations	Everyone	Ahmed Al Khuridah	11/30/22	11/8/22	Done!
		Calculations	Everyone				
		Experimental Method	Everyone				
		Numerical Method	Everyone				
		Technical Drawings	Everyone	Gabriel Barba	1/17/23	3/5/23	Done!
		Algorithms	Everyone				
		House of Quality	Everyone	Everyone	11/30/22	11/8/22	Done!
	Preliminary Results	Selected Designs	Everyone	Gabriel Barba	11/30/22	11/8/22	Done!
		Final Decision	Everyone	Final Decision	11/30/22	11/8/22	Done!
		FMEA	Everyone	Danielle Lee	11/30/22	11/8/22	Done!
		Future Work	Everyone	Everyone	11/30/22	11/8/22	Done!
	Appendix	Gantt Chart	Everyone	Ahmed Al Khuridah	11/30/22	3/5/23	Done!
		CAD Drawings	Everyone	Gabriel Barba	11/30/22	3/5/23	Done!
		Simulations	Everyone				
		Software Flow chart	Everyone				
		Code	Everyone				
		Project Charter	Everyone	A.A & G.B	11/30/22	3/5/23	Done!
	References	References	Everyone	Everyone	11/30/22	11/8/22	Done!

Project Charter

1. SPONSOR: UIC Robotics and Motion Laboratory

2. PROJECT TITLE: Luxo Jr. Lamp

Final
Date: April 28, 2023

3. GOAL(s)/ OBJECTIVE(s):
1. Create a Luxo Jr. lamp that moves forward by jumping/hopping
2. The robot should resemble the Luxo Jr. lamp
3. The hops can be remote controlled or open-loop

4. DEFINITION(s) OF DONE:
1. 3D Solidworks assembly
2. ANSYS static structural analysis
3. Microsoft 365

5.a. KEY METRICS:	
Metric	**Description**
1. Hop	Base of the lamp must be clear of the table.
2. Forward	Move forward as it hops.
3. Stable	The model does not fall over.

6. PROJECT TEAM:	**Primary Name/Phone #s:**	**Back-up Name/Phone #s:**
Sponsor	Dr. Pranav Bhounsule	
Faculty Advisor	Dr. Mathew Alonso	
Project Team and function	ME38	

7. KEY ASSUMPTIONS and NECESSARY CONDITIONS:
1. Gravity will be taken into account
2. Friction between the base of the lamp and the ground will be taken into consideration
3. The lamp will be considered as a rigid body.
4. The lamp will consist of a linear spring system.

8. TIMELINE/SCHEDULE:			
Major Project Milestones	Plan date	Latest Best Estimate	Completion date
CAD	01/17/2023	03/05/2023	02/10/2023
ANSYS	02/10/2023	03/05/2023	03/04/2023
3D PRINT	03/04/2023	03/18/2023	03/10/2023
Parts list	03/27/2023	03/31/2023	03/31/2023
Cost analysis	04/01/2023	04/14/2023	03/14/2023
Final Report	04/21/2023	05/03/2023	04/28/2023

9. RISKS:		
Risk Description	Risk Owner	Plan to address
1. Do not complete/late completion of milestones	G.B	Assign additional members on each task and set more achievable deadlines
2. Compression not achieved	A.A	Uses ANSYS to achieve proper results
3. Motor does not adhere to the mechanism system requirements	G.B	Find motor with necessary output

10a. DOCUMENTATION:			
Document #/Name	*	Person(s) Responsible	Description
1. Specifications	ANSYS	A.A & D.L	Details of system requirements
2. Quantitative Analysis	Bill of materials	K.G	List of parts and quantities
3. CAD design	Solidworks Assembly	G.B & S.K	Part drawings
4. Final Product Drawings	Solidworks Assembly	G.B & S.K	CAD assembly

11. PROJECT CHARTER APPROVALS:	
Ahmed Al Khuridah	date: 12/09/2022
Gabriel Barba	date: 12/09/2022
Kali Giancana	date: 12/09/2022
Sebastian Kowal	date: 12/09/2022
Danielle Lee	date: 12/09/2022